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# Sponge City Practice in China: A Review of Construction, Assessment, Operational and Maintenance

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Abstract: As the global climate change and the rapid progress of urbanization, the frequent occurrence of flooding disasters and non-point source pollution seriously threaten the sustainable development of modern cities. To alleviate these problems, China started to pilot construction of the “Sponge City” (SPC). Over a decade, it has attracted public attention, supports, and participations. The paper presents a literature review of sponge city construction (SPCC) process (planning, design and construction) as well as the assessment of SPC, including: operation, maintenance, and effectiveness.

Research gap and future works are also proposed. The paper offers some tactics for SPCC, including: 1) in the planning and construction stage of SPC, the goals and systematic plans should be formulated according to local water-environmental conditions the drainage plan should cover the strategy to dispose runoff volumes at sources and the ultimately goal for flood mitigation. The drainage design involves the combination of various green and grey infrastructures; 2) It is important to identify monitoring methods and hydrological models which can be used to assess the performance of a SPC. With adequate field data, all models and methods should be calibrated for not only runoff quantity and quality control but also the alleviation of urban heat island effects, including the base flows and local groundwater table; 3) Based on the regional field data, it is necessary to standardize regional design parameters, construction material specifics, and maintenance scheme and schedule that would significantly affect the facility's infiltrating and filtering processes, therefore, a regular maintenance program should be initiated to monitor the operations of the as-built facilities according to local climate conditions. The paper evaluated several maintenance methods for ten typical facilities to provide a reference for the operation and maintenance of facilities in SPCC.

Keywords: Sponge city construction (SPCC); Systematic remediation; Assessment; Operation and maintenance

## 1. Introduction

In recent years, the rapid population growth, urbanization and high-intensity human activities have caused many extremely serious environmental problems all over the world (Fang et al. 2019). Among those problems, the impact of urban stormwater runoff on the urban environment and the life of urban residents become more and more serious (Nguyen et al. 2019). In an urban area, pervious vegetated ground surfaces have been progressively replaced with impervious pavements. Urbanization is a process which significantly reduces the soil infiltration volume and causes an increase in stormwater runoff flows and volumes (Hou et al. 2019). Over the years, urbanization induced floods have caused life losses and property damage. The public has become more aware of the deterioration of urban water environment. (Chan et al. 2018). To alleviate the urban flooding problems, 30 cities in China were selected to initiate a pilot project to build sponge city (SPC) since 2015 (Gong et al. 2018b).

SPC is an innovative idea and new methodology that provide a comprehensive solutions to improve urban water environment (Ma et al. 2018). It should be constructed based on the main characteristics and problems of different types of cities. For example, for industrial cities, the primary issue maybe the water environment problems caused by industry pollution. Besides, the SPC planning and design should be based on the differences in the city's climate characteristics, soil types, and zoning. Generally, the concept of SPC is similar to, but more informative than, the low impact development and sustainable approach developed for urban drainage systems (Bae and Lee 2020). Besides, SPCs focus on improving the capacity to deal with severe weather conditions and water environment and ecological problems. However, the ongoing construction of resilient cities in many countries focuses on the capacity of hazards withstanding and self-recovery. It is emphasized that resilient cities pay more attention to the ability to learn, adapt and self-organize in crisis, which means that cities have the ability to adapt to natural disasters and learn from them, so as to maintain the original structure and key functions (Chuang et al. 2020). Therefore, there are still differences between SPCs and resilient cities. The concept of SPC integrates the source LID/green infrastructure (including green roofs, bioretention, rain gardens, permeable pavements and other decentralized storage facilities), and midway drainage network optimization (from traditional drainage-based network upgraded to a sustainable drainage system that maintains a benign hydrological cycle. The water quality, water volume, landscape potential and ecological value of the runoff are comprehensively considered in the design), and the flood control system at the end, which systematically solves the urban water environment, water safety and water ecology issues. In fact, it is a comprehensive platform, characterized by natural accumulation, infiltration, and purification with the construction of cross-scale water ecological infrastructure as the core. Through the construction of a regional urban flood control system, biodiversity protection, habitat restoration and the construction of a green travel network, the SPC ultimately comprehensively solve a series of “urban diseases” such as floods and droughts. In

China, all urban renewal projects are issue-oriented, with specific targets for developing solutions using the concept of SPC. Often the solution lies in how to reduce the risk of flood inundation and how to enhance the water quality in natural water bodies such as rivers and lakes. (Dong and Gao 2019). On the other hand, the development of a new town is usually goal-oriented, with a regional, comprehensive drainage planning and design (Yang et al. 2019). The difference between the concept of SPC and the traditional approach is shown in Figure 1. According to the concept of “source reduction, process control, and systematic remediation,” sponge city construction (SPCC) is planned systematically, and the methods of “infiltration, detention, retention, purification, reuse and discharge” are used to achieve the goal of comprehensive SPCCs (MHURD 2014). The SPCC mainly includes four components, including: (1) the runoff volume reduction system at the source, the minor and major conveyance drainage systems, and the outfall flood control system to reduce the flow release. Coupled “grey-green infrastructures” is an important method for the construction of SPCs. The grey drainage system is designed to collect and remove stormwater to ensure the safe level of traffic service, including stormwater conveyance networks, storage systems, and pumping stations (Qiao et al. 2020). The green infrastructure is designed to take advantage of filtering capacity of plants, soils, and sand filters to dispose surface runoff, including bioretention systems, infiltrating beds, green roofs, and permeable pavements. A green drainage facility is a cascading flow system to drain impervious surfaces onto porous surfaces for the purpose of water volume reduction and water quality enhancement, infiltrating runoff serves as a base flow to replenish and conserve local groundwater table to maintain healthy water ecology (Mao et al. 2017). As for the public participation, the level of awareness of people was still low. When a SPC was constructed, the project fails to effectively identify stakeholders and their concerns in the early stage, and the lack of effective communication with the public during the construction process also greatly ignored the importance of public participation and awareness, but the public acceptance of SPC concept and implementations was still very impressive because people think that SPCC can improve environmental benefits (Gong et al. 2018a).

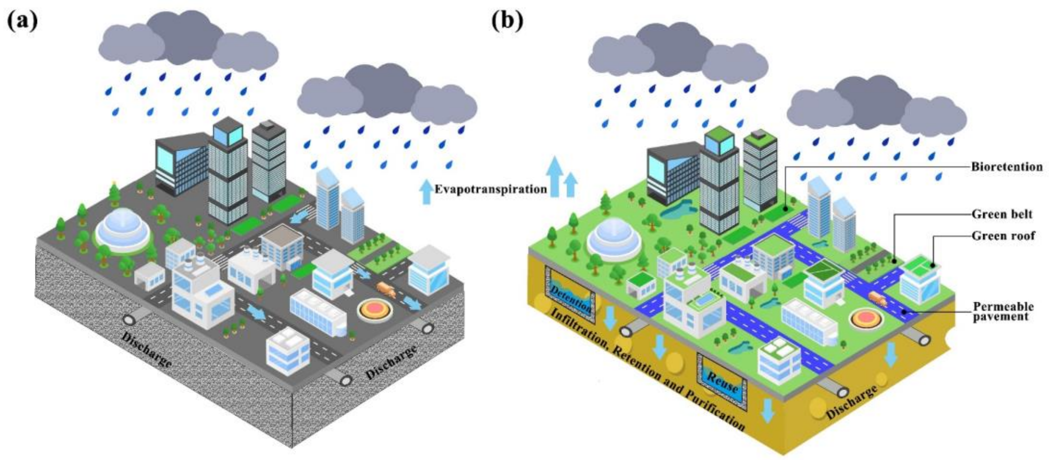


**Figure 1**. Different hydrological processes in (a) traditional quick-drainage and (b) SPCC

To further understand the proposed grey-green coupled drainage system, the Ministry of Housing and Urban-Rural Development (MHURD) in China has recommended the "Assessment Standard for Sponge City Effectiveness" since August 2019 (MHURD 2019a). The above standard procedure set forth the criteria and methods to evaluate the performance of a Sponge City (MHURD 2019b). The SPCC is required to preserve the natural ecological pattern and protect the natural hydrological conditions by controlling runoff releases (Wu et al. 2019). The assessment of runoff control effect includes not only on-site runoff volume disposal, but also peak flow reductions at the system outfall point, the added benefits on stormwater quality enhancement include runoff pollutant concentration and solids load reductions (MHURD 2019b). At present, the assessment approach consists of collecting long term rainfall-runoff field data and then calibrating the continuous hydrologic numerical simulation. The filed-based experience will further be utilized to improve the design and construction standards for SPCC." (Randall et al. 2019).

Upon the completion of SPC facilities in a city, it is necessary to implement the operational standards and regular maintenance program. On-site maintenance work includes monitoring of clogging effects through the internal components such as filtering layers and media underneath the porous basin and replacements of external components such as outlet structures, measuring instruments, data logging facilities, and power supply systems (Macedo et al. 2017). Therefore, in order to better the construction and operation of a SPC, it is important to foresee the pivotal factors that sensitively affect the effectiveness of a SPC. Maintenance tasks required for various SPC facilities may vary considerably, from a regular weed, litter, and solids removal, to a complete replacement of filter media in the sublayers underneath the porous basin. These tasks can be carried out by a regular maintenance program or the due inspections after a severe storm event. (Flynn et al. 2012).

At present, various researches have been conducted to focus on how SPCs alleviate urban inundation and stormwater quality improvement. Often a research report covers one or two case studies, and does not provide a comprehensive assessment of the construction, operation, and maintenance of SPCs. Therefore, this study presents a review of the life cycle assessment of SPCC including construction, operation, and maintenance, and the evaluation of current design parameters and standards. In particular, the critical factors which affecting facility's runoff control performance are also identified and analyzed. This study provides a scientific basis to evaluate the design and construction approaches to construct a SPC, based on the operations and maintenance programs implemented in many as-built SPCs in China.

## 2. Methodology

This study uses a content analysis method (Xu et al. 2019) to conduct a comprehensive review of the whole process of China's SPCCs including planning, design and construction, assessment and facility operation and maintenance. The main context of this paper is shown in Figure 2. Firstly, searching literature related to SPC and low impact development (LID) by using keywords or relevant information in existing papers. Secondly, identifying and categorizing the theme of all searched papers and removing invalid information based on in-depth analysis. Then, a comprehensive review is made from three aspects, namely SPC planning and construction, SPC effect assessment, and facility operation and maintenance according to the sorted researches, national standards and manuals. Finally, integrating all relevant information to give a complete SPCC planning, design and construction, assessment, operation and maintenance method as a guide for SPCC in China. In this study, the Web of Science database as well as China National Knowledge Infrastructure was chosen for content analysis since the concept of the SPC was proposed by China. Both databases contain the most influential related researches at home and abroad.

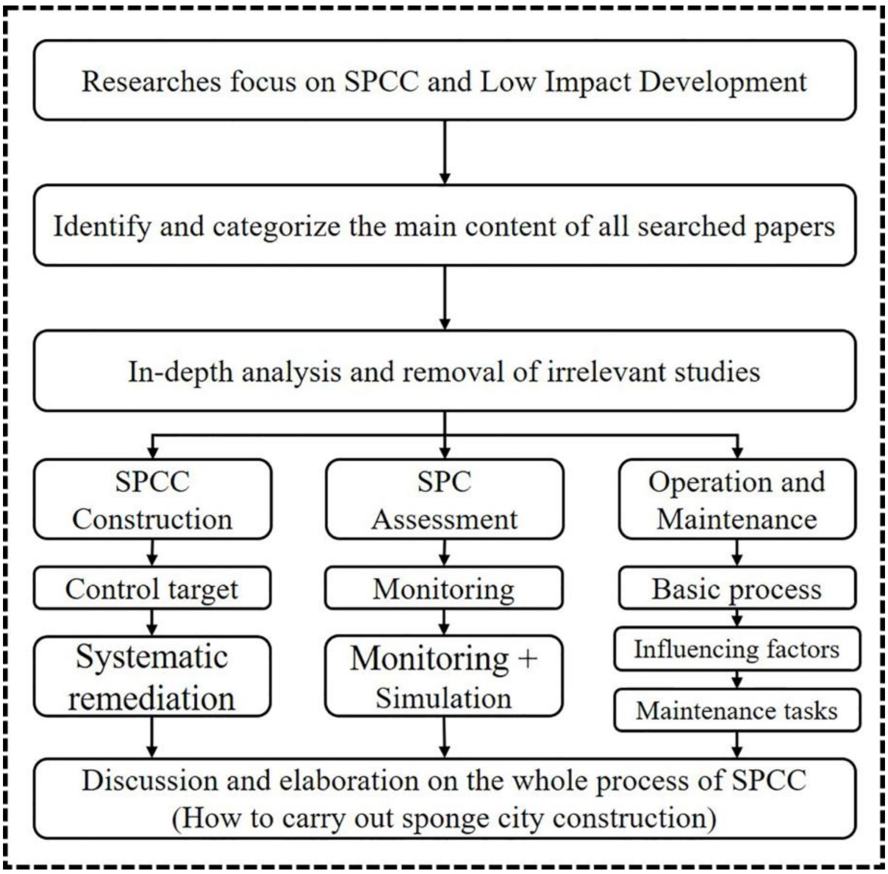


**Figure 2**. The flowchart of SPC process methodology.

We include SPC, LID or sustainable drainage system studies that are published in either English or Chinese before January 2020. We used the key words of green infrastructures, SPC construction, source reduction, process control SPC assessment, runoff quantity and quality monitor and simulation, operation and maintenance of SPC. For English literature, we added additional key words of “China/Chinese” as constraints to ensure that all researches are based on cases in China. Altogether, we found 136 papers in English and 97 papers in Chinese in the initial search.

Because the scoping review aims to summarize SPC findings, we further screened the papers based on the following three criteria: (1) we included both quantitative and qualitative research and relevant national standards but excluded the literature review or policy discussion; (2) we included research that explicitly examines the SPCC targets, methods and the relevant monitoring, modelling and maintenance works; (3) When we searched the literature, we included papers about green infrastructure, LID facility operation, maintenance, and runoff control effects. At the same time, we deleted articles that had no data or a small amount of data (which has low guidance for actual engineering). As a result, we identified 73 papers in English and 39 papers in Chinese in our scoping review.

## 3. Construction principle of SPCC

### 3.1 Control targets

The control targets of SPCC generally include runoff volume reduction ($R_r$), runoff flow reduction ($P_r$) and delay of peak time ($P_d$), runoff pollution control, and re-use of stormwater as a natural resource. Each city should determine the runoff control criteria based on local rainfall characteristics, hydrogeological conditions, runoff pollution status, requirements for waterlogging risk control, and demand for stormwater reuse, and combined with prominent local water environment issues and economic rationality. In view of the runoff pollution control and the stormwater reuse, most of them can be achieved through the total runoff control (MHURD 2014). Therefore，the water quality capture volume (WQCV) method is applied to the ratio of on-site runoff volume interception to the local annual rainfall amount ($V_{cr}$) (Guo and Urbonas 2002). All infiltrating and filtering facilities in a SPC should be sized to capture no less than the WQCV at each and every stormwater filtering facility. The annual runoff capture and treated rate is calculated as:

$$V_{cr} = 1 - \frac{D_{out}}{R_a} \quad (1)$$

Where $V_{cr}$ is the ratio of annual runoff volume intercepted by the LID device such as 0.6 to 0.95, depending on the local climate and level of urbanization, referring to the variable α in Figure 3, $D_{out}$ is WQCV representing the annual rainfall-induced runoff depth in (mm), $R_a$ is the local annual average rainfall amount in mm, referring to Figure 3.

MHURD (2014) suggest that the value of $V_{cr}$ at each city and the local annual rainfall depth be determined using Figure 3 which was derived based on the statistical analysis of long-term daily continuous rainfall data bases recorded at hundreds of cities in China from 1983 to 2012. According to the long-term rainfall-runoff analysis, the China mainland was divided into five regions, as illustrated in Figure 3, the WQCV is determined with the location of the project site and its corresponding $V_{cr}$. It is easy to see that the goals of each pilot areas are greater than or at least equal to the overall requirements of the region after SPCCs.

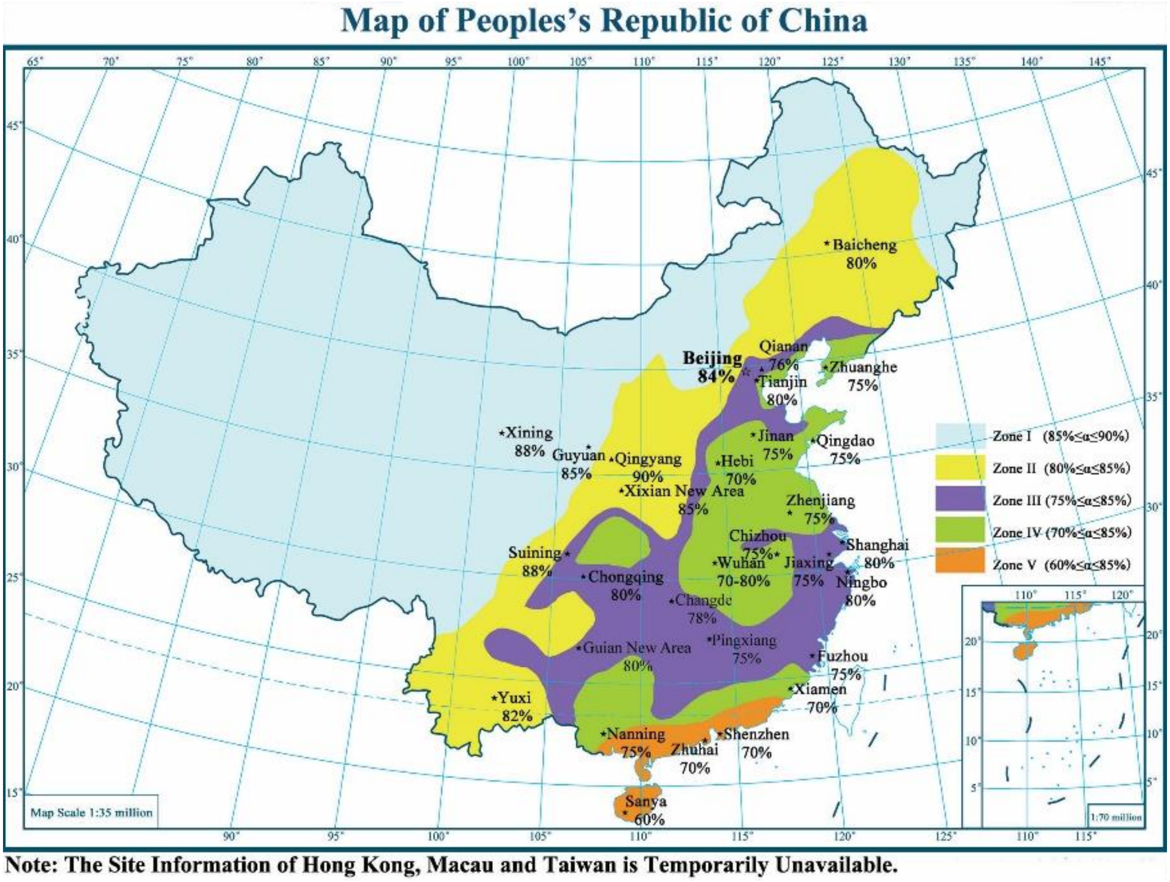


**Figure 3**. The location and corresponding $V_{cr}$ targets of thirty SPC pilot areas and the zoning map of volume capture ratio of annual rainfall in China (Base drawing redrawn according to MHURD (2014)).

At the outfall of an urban catchment, the control of peak flow release is also a flood mediation target for SPCCs. Most of stormwater LID devices are placed at the upstream runoff sources and sized to capture the early runoff volume up to the WQCV. Often, a LID device has some effects on peak flow reductions for small to medium rainfall events. In general, the early runoff interception has a negligible reduction on the peak flows in a heavy storm event. Therefore, a sound and effect urban drainage system should be laid with the runoff volume reduction system placed upstream of the conveyance sewer and street drainage system. The sewer lines are designed for minor events (2- to 5-yr events) while the street gutters are capable of passing the major events

(10 to 100-yr events). At the outfall point, a detention storage system should be installed to control peak flow releases. The ultimate goal of SPC is to restore the pre-development water environment, and to mimic the pre-development watershed regime. In the planning of SPCCs, the runoff pollution control is also important. It is necessary to reduce solids, grease contents, heavy metals in the surface storm runoff before the entrance into the stormwater sewer system. For a combined sewer, it is important to divert the sanitary water into a treatment duration a dry weather period, and only allow the combined sewer overflows (CSO) into the sewer outlet during a wet period. The pollutant indicators to evaluate a combined sewer operation can be suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), total Phosphorus (TP) and so on. Among urban runoff pollutants, SS often has some correlations with other pollutant indicators. Therefore, SS can generally be used as a runoff pollutant control indicator since the annual total removal rate for SS of source LID facilities can reach 40%-60% (MHURD 2014). The annual total SS removal rate can be calculated by the following methods:

$$R_{ss} = V_{cr} \times R_{LID} \tag{2}$$

Where $R_{ss}$ is annual SS removal rate, while $R_{LID}$ is LID facility’s average SS removal rate (%).

### 3.2 Systematic remediation

The requirement of systematic remediation is to regard the SPCC as a system, taking the overall optimization of the system as the criterion, and coordinating the interrelationships among the sub-systems. Aiming at the multiple objectives, including public safety, water ecology conservation, water environment enhancement and water resources reuse, the SPCC is an urban renewal process to mix the existing urban areas with the proposed new developments that the entire region can be integrated to optimize the land uses among economic developments, residential needs, recreation and parks, wild life habitats, and water environment protection. All the construction and operation of the proposed drainage facilities should be planned and implemented in order to make the SPCC more systematically. For example, the newly built LID facilities can relieve the drainage pressure of the existing drainage networks through $R_r$, $P_r$, and pollution control, etc. At the same time, the implementation of SPC makes the new infrastructure of cities need to strictly follow the concept of SPC when designing and construction; while existing facilities should be problem-oriented and combined with the main issues of the city for infrastructure rebuild. Figure 4 summarizes the systematic remediation of SPCs based on the research of He (2016), Xie (2019).

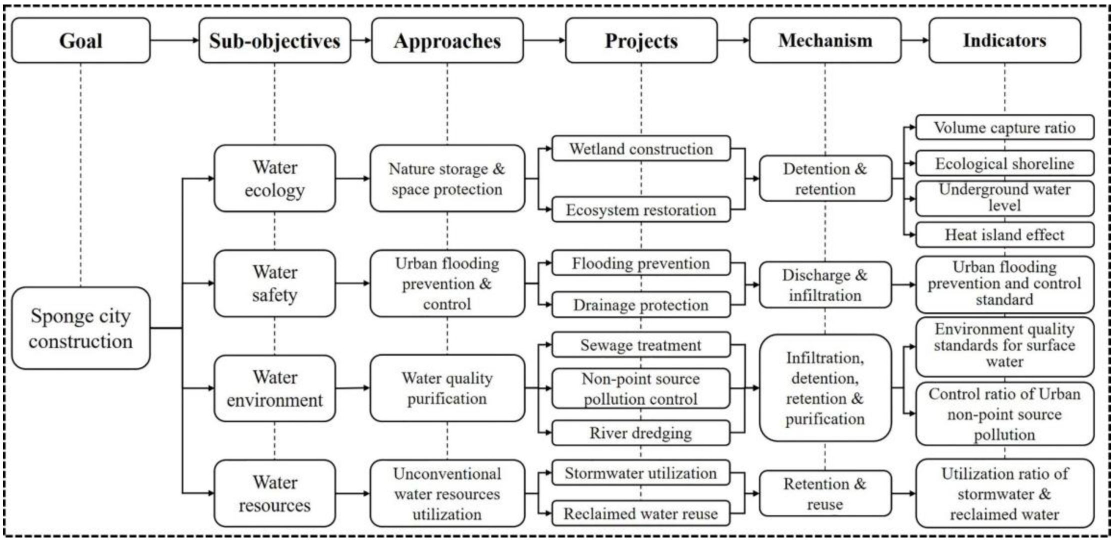


**Figure 4**. Systematic remediation of SPCCs (Base drawing redrawn and translated according to (He 2016, Xie 2019)).

To preserve the water ecology, it is necessary to create a cascading flow system to drain the impervious surfaces onto the porous surfaces, and to connect various natural ecological storage spaces to conveyance corridors, and to maintain the natural flood chain and adequate water habitats, and to assure the sufficient base flows to sustain the wet lands and wild life systems. In an urban area, the level of flood protection is critically important for public life and property safety. Therefore, a regional stormwater drainage and flood control plan must be developed with various construction stages to allocate the space and resources for building a sound flood conveyance and mitigation systems. From the perspective of water environment management, it is necessary to focus on not only the urban point and non-point source pollution, but also strengthening the sewage treatment and river dredging. Meanwhile, it is important to strengthen the unconventional water resources utilization process. And the stormwater resource can be reused by adding various stormwater storage and utilization facilities. Besides, increasing the infiltration of stormwater to replenish groundwater resources through SPCC is also important. In addition, the relevant policies, regulations, and standards for SPCCs are also public documents and have to be announced timely. The systematic remediation of urban renewal using the SPC approach can be achieved through the comprehensive combinations of the above approaches.

### 3.2.1 Runoff Volume Reduction at Source

Runoff volume disposal at the source in the SPCCs is referred to as the utilization of micro-topography design, landscape design, and other porous media infiltration techniques like LID design. It is important to lay up a strategic plan to distribute porous basins and permeable pavements at the runoff sources to promote runoff volume reductions, and also to replenish the local groundwater table. Although the infiltration technique is primarily aimed at the runoff volume reduction, it does have an added value to improve the stormwater quality enhancement through solid settling processes. Many studies have reported that upstream infiltrating and filtering facilities in a SPC can play an important role in controlling both runoff quantity and quality for frequent rainfall events (Rycewicz-Borecki et al. 2017). The control level should be determined according to the specific design parameters of each types of facility. The treated runoff volume capacity at a porous basin is calculated as:

$$V_{in} = \min[\ P, (\ WQCV + W_{in})] \quad (3)$$

$$W_{in} = K \times J \times A \times T_d \quad (4)$$

where: $V_{in}$ ($m^3$) is the runoff volume controlled by the infiltration, filtration and retention facilities; WQCV ($m^3$) is the runoff interception volume of the facilities; P is rainfall depth in (mm) during the event, $W_{in}$ ($m^3$) is the infiltrated volume by infiltration and retention facilities during a rainfall event; K (m/h) is the saturated hydraulic conductivity of the soil or media (it is calculated according to the effective retention depth of the retention zone and design emptying time of the facility and depends on the soil type or media compositions); J is the hydraulic gradient (ranging from 0 - 1); A ($m^2$) is the infiltration area; $Td_s$ (h) is the effective infiltration time equal to the rainfall event duration. Equation (3) indicates the maximal runoff treated volume cannot exceed the total rainfall amount. During a heavy event, the runoff volume produced from the tributary area is greater the WQCV. As expected, the porous basin is overtopped and also results in more groundwater recharge.

### 3.2.2 Process control

As aforementioned, a LID facility is often too small in volume to provide an adequate detention process to reduce the peak flow during an extreme event (10- to 100-yr event). (Yin et al. 2020). Therefore, it is critically important that the regional drainage plan covers the conveyance facilities to deliver the peak flow through the waterway, and the storage facilities to temporarily store the peak volume at the detention basins for release control into the downstream water body. The detention effectiveness is evaluated by $P_r$ and $P_d$. In an urban area, detention storage volumes can be provided with floodplains, parks, open space, parking areas, sport fields, and roofs. Flooding problems are two folds: (1) peak flows to overtop the waterway, and (2) excessive volumes to inundate low areas. Although the detention process can reduce the peak flows, it is important to develop a positive vertical grade to drain flood waters out of the low areas.

As an example, the first pilot SPC, Jinan, China, the spatial and temporal distributions of storm events in the Jinan area are extremely uneven. the land forms in the Jinan changes from hilly mountains in the south to plains in the north. The upstream runoff flow starts from the mountain area with a high velocity. The downstream receiving water body is a matured wetland lagoon. The rapid developments in Jinan areas have encroached into floodplains, lowlands, and lakeshore areas. To alleviate the flooding potentials, the drainage plan applies the cascading flow system to build a SPC in Jinan areas. At the upstream flow collection points, various LID facilities are installed to dispose the runoff volume into porous media. As illustrated in Figure 5, the SPCC in Jinan fully took into account the urban drainage characteristics of the combination of slopes and plains to form cascading flow planes. The street drainage systems in the Jinan areas consist of the traditional inlets, sewers, and street gutters. However, the flood flows generated from the hilly areas are intercepted into the ditches and trenches laid along the foothills. Both street gutters and trenches are drained into the detention basin placed upstream of the natural wetlands. The proposed detention basin is designed to reduce the post-development peak flows to the pre-development and also to provide an adequate residence time to settle the solids and pollutants carried in the storm water.

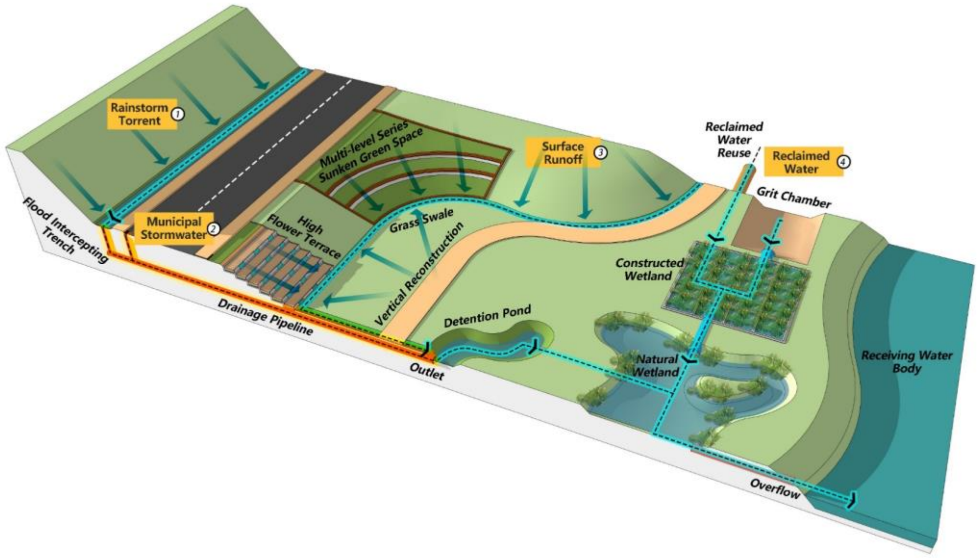


**Figure 5**. The generalization of SPCC process control method in Jinan, China.

The SPCC in Jinan set the priority to the use of rivers, wetlands and parks in the city as temporary stormwater storage space and set grass swales to transfer road runoff. However, for the intersection of the road and the river channel where could not build green infrastructures, the stormwater dustpans were constructed to intercept a large amount of runoff rainwater into the river through rational utilization of urban vertical, thereby alleviating the drainage burden on downstream sections. In addition, drainage network is a key component of the process control system. In order to alleviate urban waterlogging issues, Jinan has been improved the drainage networks by upgrading drainage standards and transferring combined sewer system to separate system. At the same time, the drainage networks were desilted, intercepted and purified to fully improve urban drainage capacity.

For the low land areas, the drainage facilities are improved with the river dredge to lower the trail water effect and also to increase the flood plain storage volume. The positive vertical energy grade line (EGL) fundamentally solve the long-concerned problem of inundation. In some areas, stormwater pumping stations were built to life stormwater over the levees and banks. Under the concept of SPC, the flooding problem in the Jinan areas has been effectively alleviated with upstream runoff disposals, midstream flow delivery, and downstream storage for flow release control. Table 1 shows the types, features and applications.

**Table 1.** Types, features and applications of each facility.

| Facility | | Main Facility Functions | | | | | | Features and Application of Facilities |
|---|---|---|---|---|---|---|---|---|
| | | Infiltration | Detention | Retention | Purification | Harvesting | Drainage | |
| Bioretention | High Flower Terrace | √ | √ | √ | √ | | | Using the interception effect of plants and soil/media to retain part of the stormwater runoff, while increasing the green space to beautify the city. |
| Bioretention | Rain Garden | √ | √ | √ | √ | | | Using the interception effect of plants and soil/media to retain part of the stormwater runoff, while increasing the green space to beautify the city. |
| Bioretention | Multi-Level Series Sunken Green Space | √ | √ | √ | √ | | √ | In addition to the features of rain gardens, Multi-level series sunken green space can also use gradients for micro-drainage. |
| Green Roof | | √ | √ | √ | | | | Reducing roof stormwater runoff, increasing urban greening rate, and mitigating urban heat island effect by reducing building energy consumption. |
| Rain Barrel | | | | | | √ | | Collecting roof runoff and further use it after purification to save water resources. |
| Permeable Pavement | | √ | | | | | | Reducing road runoff and alleviating the impact of storm runoff on urban roads significantly. |
| Grass Swale | | √ | √ | √ | | | √ | Collecting and purifying the road runoff and discharging it into the municipal piplines to form a natural urban drainage system. |
| Wetland | Constructed | | | | √ | | | One of the natural water purification system in the city with low energy consumption, which is also easy to manage, and can provide habitat for organisms. |
| Wetland | Nature | | | | √ | | | One of the natural water purification system in the city with low energy consumption, which is also easy to manage, and can provide habitat for organisms. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Flood Intercepting Trench | √ | | | | √ | During the heavy rainfall event, the mountain torrents are intercepted and discharged to nearby drainage networks. |
| Detention Pond | √ | √ | | √ | | As a stormwater detention facility, the peak flow of stormwater runoff can be retained during the temporary period. After the maximum flow drops, the runoff will be slowly discharged from the pond. |
| Drainage System | | | | | √ | Indispensable drainage measures in cities, which can be coordinated with LID facilities to reduce urban drainage risks. |

## 4. Assessment of SPC effect

According to the "Assessment Standard for Sponge City Construction Effect" published by MHURD (2018), it divides the entire contents of the SPCC effectiveness assessment into three components: (1) water ecology, (2) water safety, and (3) water environment, and then counts the area that meets the requirement in units of catchment scales. The assessment methods of specific indicators are divided into monitoring method and monitoring + simulation method. Table 2 describes the indicators for the SPCC effectiveness assessment and relevant assessment method.

**Table 2.** Indicators and the corresponding assessment method for the current SPCC effect assessment**.**

| Objectives | Indicators | Monitoring | Monitoring + simulation |
|---|---|---|---|
| Water Ecology | $V_{cr}$ | | √ |
| | $P_r$ | | √ |
| | Natural water area | √ | |
| | Ecological shoreline | √ | |
| | Underground water level | √ | |
| | Urban heat island effect | √ | |
| Water Safety | Waterlogging | √ | |
| | Flooding control | | √ |
| Water Environment | Sewage and wastewater discharged directly during dry weather | √ | |
| | SS reduction | √ | |
| | CSO | | √ |
| | Black-odor water body | √ | |

### 4.1 Monitoring

#### 4.1.1 Runoff quantity and quality

One of the most important aspect of the SPC effectiveness assessment is directly related to runoff quantity control and quality enhancement. The document of “Performance Evaluation and Assessment Measures for Construction of Sponge City ” issued by the MHURD in 2015 proposed that stormwater runoff quantitative assessments be evaluated based on field data (MHURD 2015). In addition, the representative LID facilities and key nodes are needed to monitor. The post-construction monitoring is essential for assessing SPC effectiveness, including: rainfall and runoff measurements, inflow and outflow measurements, pollutant concentration recordings before and after detention process, and data validity process. Data loggers in a monitoring system may be operated by remote or automatic on-line monitoring.

Since all LID devices are sized with WQCV, the long-term runoff volume capture ratio for the proposed WQCV is a critical parameter which should be monitored under the post-construction condition. The effectiveness of a proposed detention basin is evaluated by the long-term flow reduction ratio which should be evaluated with the flow-frequency curve using the measured after-detention peak flows. When monitoring the total annual runoff control rate at the project site, it is advisable that that inflow and outflows through a detention basin be measured for at least one-year or longer before any data analyses(MHURD 2019b).

In addition, urban flooding and runoff depth control is also the top priority of SPCC assessment. A combined approach of reviewing Closed-circuit television (CCTV) recordings and on-site inspection should be applied. The design rainfall events by screening the storm event with the maximum 1-hour rainfall depth of no lower than the design rainfall depth of the minor system specified in the national standard “Code for design of outdoor wastewater engineering” (MHURD 2016) should be monitored, and the video recording should be used to check the flooding risks. Only when the runoff depth lower than 150 mm for the road ditches and the lower points of the key flood-prone sites, and the water retreating time less than 30 minutes can it be proved that there is no flooding risk in the specific area.

As for runoff quality, it is required to monitor the runoff quality control capacity (SS) of the source LID facilities, the SS discharge concentration of the overflow pollution treatment facilities and the quality of the receiving water bodies in the existing standards. Monitoring of receiving water bodies and overflow pollution treatment facilities can be used to evaluate the overall level of runoff pollution control in the SPCC areas, while monitoring of individual LID facilities is used to analyze the runoff quality control efficiency of specific facilities.

Many current studies so far have analyzed the runoff quality control capacity of SPC facilities, and the indicators involved include the event mean concentration (EMC) of various pollutants and the pollutant load reduction. Numerous studies have shown that the runoff control capacity was significantly related to its scale, design parameters and the materials of each structural layer. When monitoring source LID facilities and overflow pollution treatment facilities, it is necessary to set monitoring points at the inlet, the drainage outlet at the bottom of the drainage pipes and the overflow point. Then, taking samples and detecting the pollutant concentration (SS) should be done. Source LID facilities should be monitored and took samples under typical local rainfall events, while the sampling time is evenly distributed during the rainfall process. However, overflow pollution treatment facilities should be sampled at least once each time when discharging.

The sampling section is needed to determine when monitoring receiving water bodies. On the section, the sampling vertical should be determined first and then the sampling point. The impact of tributaries and sewage is needed to consider when choosing sampling sections and at least two sections must be selected where are upstream of the confluence point and sufficiently downstream. The selection of sampling points should take full account of the number and distribution of sewage outlets, pollutant discharge conditions, hydrology and channel topography, tributary inflow, vegetation and soil erosion, and any factors affecting water quality. Sampling points should also be combined with hydrological sections as much as possible and strive to obtain the most representative samples with fewer monitoring sections and points, which reflecting the environmental quality of the region and the spatial and temporal distribution of pollutants and characteristics.

#### 4.1.2 Groundwater depth

Groundwater is an important part of water resources, accounting for about one-third of the world's total freshwater resources, and plays a positive role in improving the imbalance between water supply and demand due to its extensive distribution and easy exploitation, (Ainiwaer et al. 2019). With the rapid development of urbanization, the increase of the urban impervious area blocks the infiltration of stormwater and reduces the ability of groundwater replenishment (Tam and Nga 2018). At the same time, with the increase of the urban population and the improvement of the living standards of residents, the amount of urban water supply has increased significantly, groundwater has been over-exploited, resulting in lower groundwater levels (Kalhor and Emaminejad 2019).

The SPCC is based on the concept of "natural accumulation, natural infiltration, and natural purification", which can effectively increase the infiltration capacity and infiltration amount of stormwater, thereby achieving the goal of conserving groundwater (Ma et al. 2017). In addition to monitoring the runoff quantity and quality before and after SPCC, the effect of groundwater depth is also one of the quantitative evaluation indicators for measuring the effectiveness of SPC. Only when the groundwater level in a certain area after SPCC increased, the effect of SPCC can be reflected, which requires auxiliary analysis through monitoring. However, it should be noted that the monitoring runs through the entire SPCC process. The groundwater level of the specific area should be monitored continuously for at least 5 years before the SPCC and last until 1 year after finishing construction (MHURD 2019b).

4.1.3 Urban heat island effect

Climate change, as one of the fundamental impacts of various natural hazards, has already threatening human survival (Zarrineh et al. 2020). One of the most serious impacts caused by climate change is urban heat island (UHI) effect (Iping et al. 2019). With rapid urbanization, the UHI effect has intensified (Yu et al. 2019). For this reason, many studies around the world have spared no effort to alleviate the UHI effect through various channels (Chen et al. 2019). There are many factors affecting the UHI effect (Khamchiangta and Dhakal 2019). For example, human activities in their daily life such as industrial production and transportation have greatly increased the amount of heat emitted in urban areas; the changes in the underlying surfaces of urban areas (from permeable surface to impervious ground covers) makes the underlying surfaces absorb more solar radiation; and high-density urban buildings cause a large amount of heat accumulation in urban areas (Debbage and Shepherd 2015). A variety of low-impact development technologies have been applied in the construction of China’s SPCs, which is of great significance for improving the urban thermal environment and can effectively alleviate the occurrence of UHI effects (Li et al. 2019a). Studies have shown that source LID facilities such as green roofs can not only increase urban greening rates, but also reduce greenhouse gases (Moghbel and Erfanian Salim 2017). Plants can reduce the surrounding temperature and increase the air humidity by transpiration (Sanchez and Reames 2019).The use of permeable pavements instead of impervious ground covers can also greatly reduce the urban heat island effect caused by changes in the underlying structure (Ferrari et al. 2020).

During the SPCC, the temperature changes in the urban areas and their surrounding suburbs should be monitored. The temperature monitoring data before and after the SPCC should cover the average daily temperatures from June to September for at least the recent 5 years and 1 year, respectively. Only when the temperature difference between urban areas and the suburb decreases, it conveys that the SPCC can alleviate the UHI effect (MHURD 2019b).

## 4.2 Monitoring + simulation

### 4.2.1 Drainage system

At present, monitoring methods alone or due to the difficulty of monitoring methods are not sufficient to comprehensively assess the construction effect of SPCs. Besides, it is impractical to monitor all key nodes or source LID facilities in the catchment scale or SPC pilot areas. However, model simulation can not only play a supporting role in the design of SPCs, but also for comprehensive evaluation of SPCs through "monitoring + hydrological hydraulic model" method (Li et al. 2018a). There are a variety of models used in the SPCCs, while different models can achieve different simulation goals. The functions, principles, conditions and methods of each type of model are also variable

(Chen et al. 2018). In order to better simulate the effect of a SPC in a certain area, parameter sensitivity analysis, model calibration and validation, and uncertainty analysis are also needed (Rogers et al. 1985). The purpose of model parameter sensitivity analysis is to evaluate the impact of changes in various parameters on the simulation results of the model. It can be used to find key parameters of the model (Holvoet et al. 2005). The uncertainty analysis of parameters can understand and realize the essential difference between the real world and the characteristics of the model system more deeply (Yang et al. 2018). The calibration and validation of the model is a process of comparing the model simulation results with the monitoring data, and adjusting the model parameters to make the simulation results in accordance with the monitoring results which is to ensure that the model is accuracy and precision in practical applications (Mengistu et al. 2019).

Models and scenario analysis methods were frequently used in recent studies in the Table 3 to analyze the improvement of runoff control capacity in different spaces and scales after SPCC. Different environmental or regional conditions may result in different research outputs. The indicators include the $V_{cr}$, $R_r$, $P_r$, $P_d$ and runoff coefficient reduction ($RC_r$). All these studies have shown that after SPC, the runoff control capacity in the study area has been relatively improved.

**Table 3.** Researches on simulation the runoff control of different area by using various hydro-hydraulic models**.**

| Author (year) | Location | Annual Rainfall (mm) | Research Area (ha) | Scale | Main Results (Best Performance) [a] $V_{cr}$ (%) | $R_r$ (%) | $P_r$ (%) | $RC_r$ (%) | $P_d$ (h) |
|---|---|---|---|---|---|---|---|---|---|
| Yang et al. (2020) | Dresden, Germany | NM [b] | 85 | Project | | 27.4 | | | |
| Li et al. (2020) | Xixian New Area, China | 520 | 2365 | Catchment | | 71.6 | | | |
| Guo et al. (2019) | Qingdao, China | 709 | 1.13 | Project | 97.7 | | 56.3 | 74.6 | 0.25 |
| Randall et al. (2019) | Beijing, China | 525.4 | 13300 | Catchment | 88.7 | | | | |
| Li et al. (2019b) | Nanning, China | 1304.2 | 64.61 | Project | | 19.6 | 21.8 | | 0.05 |
| Rezaei et al. (2019) | Kuala Lumpur, Malaysia | NM | 1800 | Catchment | | | 27.0 | | |
| Li et al. (2018c) | Lincang, China | 1093 | 3.78 | Project | | 39.9 | 52.6 | | |
| Eckart et al. (2018) | Ontario, Canada | NM | 77 | Sewershed | | 29.0 | 13.0 | | |
| Kong et al. (2017) | Bazhong, China | 1108.3 | 838 | Catchment | | 25.6 | 23.8 | 25.4 | 0.17 |
| Luan et al. (2017) | Beijing, China | 525.4 | 1175 | Catchment | | 57.3 | 55.7 | | |
| Palla and Gnecco (2015) | Genoa, Italy | NM | 5.5 | Catchment | | 23.0 | 45.0 | | |
| Sun et al. (2014) | Lenexa, USA | NM | 1.7 | Project | | | | 99.1 | |
| Jia et al. (2012) | Beijing, China | 603.6 | 36 | Project | | 27.0 | 21.0 | | |

Note: [a] - Best performance means he best runoff control effect of SPCs under all scenarios in the research, while the simulation results of all the studies above were obtained from Stormwater Management Model (SWMM) developed by US EPA; [b] - NM represents parameters or conditions not mentioned in the original literature.

The drainage system is mainly divided into two types: combined sewer system (CSS) and separated sewer system (SSS) (Mahaut and Andrieu 2019). For most old urban areas, the CSS is the main one (Li et al. 2010). Compared with traditional development, the SPCC provides a new way for CSO pollution control by using a combination of “green and grey” infrastructures. The decentralized LID facilities in the SPCC can effectively control both runoff volume and runoff quality to reduce non-point source pollution from the source of runoff, so as to control the load of pollutants in the sewage entering the wastewater treatment plant (Liao et al. 2015). Then, the frequency and volume of combined sewer overflow (CSO) can be alleviated accordingly. However, many newly-built urban areas in China are based on the SSS, but there is a problem of mixing stormwater and sewage pipe networks. In the dry season, there is the phenomenon of drainage of sewage from the stormwater outlet (sewage directly discharging), causing serious pollution to the receiving water body. Through the SPCC, the city can reorganize and investigate the arrangement of stormwater and sewage pipe networks and adjust the pipe network arrangement in time, so that the urban area will be constructed as a strict SSS and the problem can be systematically eliminated. Therefore, whether it is a CSS or a SSS, the SPCCs can improve both the stormwater and sewage system in the specific area. Figure 6 shows the current CSO issues and corresponding countermeasures.

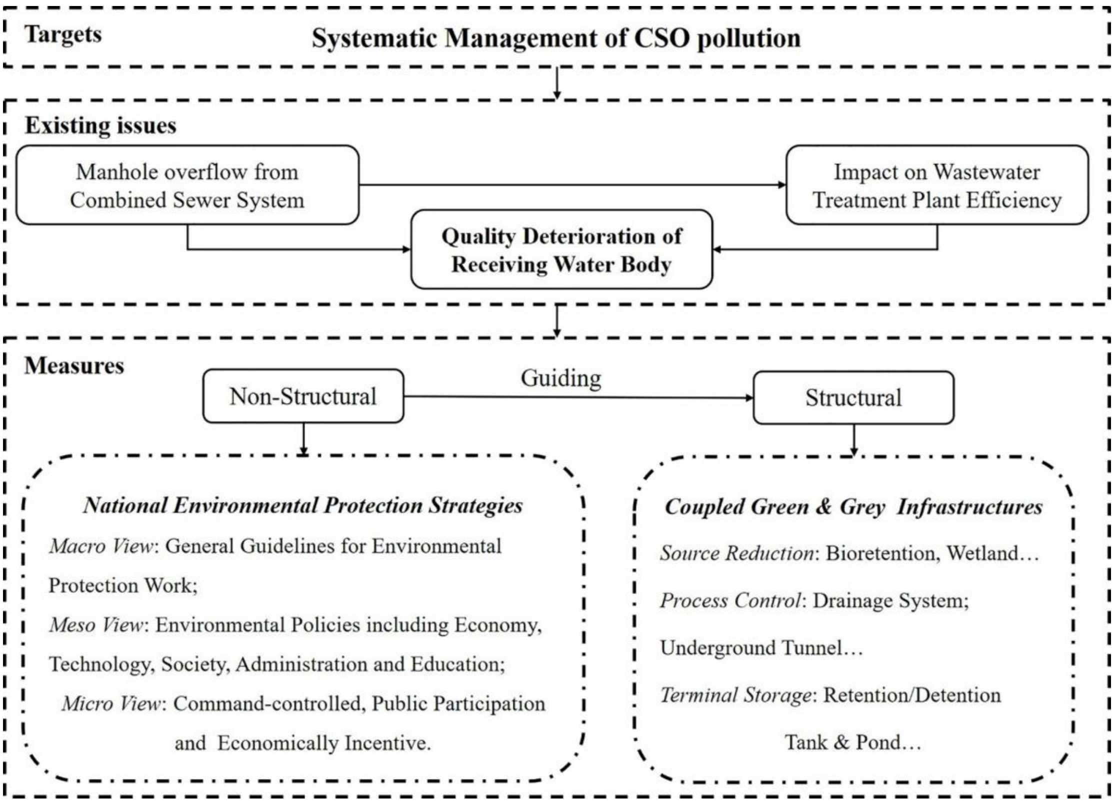


**Figure 6**. CSO issues and corresponding countermeasures based on current researches (Gong et al. 2019a, Liao et al. 2015, Meyer et al. 2013, Rathnayake and Faisal Anwar 2019, Tao et al. 2014)

Gong et al. (2019a) found that the source LID facilities, retrofitting of intercepting sewer pipes and terminal storage tank had an average CSO volume of 35% to 49%, 4% to 15% and 3% to 36%, respectively. Meyer et al. (2013) and Tao et al. (2014) pointed out that constructed wetlands can be used as an efficient way for treating CSO pollution and lower construction costs compared to grey infrastructures. Many other researches also suggested that the source LID facilities possess favorable capacity on CSO pollution reduction (Liao et al. 2015). According to the standard, the reduction of annual overflow volume shall be better assessed by model simulation. The assessment model should have the functionality to simulate rainfall-runoff, pipe flows and source reduction facilities, etc. To set up the model for simulation, the following information should be collected: parameters for the source reduction facilities, sewer network topology, including hydraulic impacts of pipe defects, operational conditions of the intercepting main sewer pipe and sewer treatment plant, catchment characteristics, terrain and continuous rainfall data of the most recent 10 years with time-steps of 1-minute, 5-minute or 1-hour.

To calibrate and validate the models, together with the projects monitored within the catchment, at least one year continuous flow time series at the municipal drainage outlet or observed water level time series at the inlet of pumping station should be collected for at least one typical catchment, with flow meters installed at the end of the municipal drainage outlet and key nodes of the network upstream. Model calibration and validation should be done by selecting monitoring data of at least 2 rainfall events respectively with the maximum 1h rainfall depth equivalent to the design rainfall depth of the minor system (MHURD 2019b). The Nash efficiency coefficient ($E_{NS}$) is used to evaluate model calibration and validation (Nash and Sutcliffe 1970). The model can be used to assess SPC effect only if the $E_{NS}$ is higher than 0.5.

The $E_{NS}$ for a given rainfall event was defined as:

$$E_{NS} = 1 - \frac{\sum_{t=1}^{T}(Q_0^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_0^t - \overline{Q_0})^2}\ , \qquad E_{NS} \in (-\infty, 1\ ]$$

Where $Q_0^t$ ($m^3/s$) is monitoring data at time t; $Q_m^t$ ($m^3/s$) is simulating data at time t; $\overline{Q_0}$ is the average value of monitoring data during the whole rainfall process.

### 4.2.2 Flooding risk

Although we can check the key flood-prone sites through monitoring, when the area is large, it is not only time consuming and laborious to investigate all key flood-prone sites in the city, but the installation of monitoring equipment will consume a lot of funds which means the economy is not reasonable. Therefore, flood simulation can be used as a more functional was to provide relevant information on the dynamics of flooding risks at a specific area and the consequences for local residents (Wang et al. 2019). It should be noted that the models need to have the capability to simulate rainfall-runoff, pipe flows, overland flow, rivers, lakes and other natural waterways. Sewer network topology and pipe defects, catchment characteristics, terrain and water quality monitoring data of the key flood-prone sites, as well as the data of design rainfall distribution for major system, with a minimum temporal resolution of 5 min and total duration of 1440 min are all need when building models (MHURD 2019b).

Table 4 shows various studies around the world that currently use different models to simulate or quantify the flooding risks in a specific area as well as the improvements after SPCC. In addition, more and more new models are being developed. They can not only save simulation time but ensure the very high simulation accuracy. Gibson et al. (2016) developed a new grid based 2D model, using a square regular grid and Von Neumann neighborhood, to simulate an area in Sheffield, UK as a case study. They found that Cellular Automata Dual-DraInagE Simulation (CADDIES) model can perform simulation work more efficiently than InfoWorks ICM which is a widely used model using triangular irregular meshes (saving 5-20 times in simulation time). Yin et al. (2020) coupled SWMM and CADDIES model for assessing the runoff control effect of LID facilities on the ground as well as in drainage system. Wang et al. (2019) combined simulation and visualization approach to simulate a pilot area of SPC which made the flooding process become more visualized. All these works tend to be useful for flooding risk evaluation in SPCC. Chen et al. (2016) used Rainwater+, one of the hydrological model which can be used for design and cost assessment, to fully analyzed LID retention capacity of several LID facilities in the case area and then the cost estimation was considered.

**Table 4.** Researches on simulation the flooding risk of different area by using various model**.**

| Author (year) | Location | Research area (ha) | Model Type | Rainfall conditions | Main Results |
|---|---|---|---|---|---|
| Hua et al. (2020) | Chaohu, China | 740 | MIKE URBAN | Designed | The flooding reduction improved with decreased rainfall and increased LID facilities |
| Hasan et al. (2019) | Aur River, Malaysia | 3978 | XPSWMM | Designed | Existing conditions of main drains were insufficient to control flooding. |
| Song et al. (2019) | Shenzhen, China | 3768 | IFMS Urban | Natural | 35% of the places became free from urban flooding after LID implementation. |
| (Zhou et al. 2018) | Fenghuang, China | 1850 | MIKE FLOOD | Designed | SPCC could reduce waterlogging issues in extreme rainfall events. |
| Li et al. (2018b) | Jinan, China | 3900 | FRAS | Designed | |
| Hu et al. (2017) | Nanjing, China | 5430 | Flo-2D | Designed | LID facilities could attenuate flood risks in urban watersheds. |
| Ahiablame and Shakya (2016) | Sugar Creek, USA | 8760 | PCSWMM | Long-term | |

| | |
|---|---|
| | historical rainfall |

# 5. Long term operation and maintenance of SPC

## 5.1 Basic process of operation and maintenance in SPC

Once the SPCC in a certain area is completed, it means that various types of stormwater infrastructure related to SPCs will be put into operation. Among these facilities， especially those intended to treat runoff and reduce pollutants at source，typically are designed to control smaller or medium-sized rainfall events rather than heavy storm with high return period (Gong et al. 2018b). Therefore, they may experience limitation conditions many times per year which make them under considerable pressure (Livingston et al. 1997). Without regular inspection and maintenance, the runoff control capacity and clogging process of facilities would be undoubtedly affected (Al-Rubaei 2016). Figure 7 shows the basic process of operation and maintenance of SPC facilities. First of all, accurate maintenance should be performed according to the facility types while regular check and inspection of SPC facilities are also essential. This includes the inspection of the appearance, function and effect of the facility. For example, for facilities covered by vegetation layers such as bioretention and green roofs, in addition to litter cleanup and structural layer functions test, plant growth and coverage should also be observed to meet construction requirements. Then, consider whether maintenance is required and maintenance level (e.g., bioretention is a source green infrastructure) based on the inspection results. After maintenance, facilities should be checked whether it meets the design requirements. If the design requirements are met, the content of this maintenance would be archived and the next inspection would continue as usual; if not, maintenance would be required again until the design requirements are met. Finally, according to factors such as local planning and the service life of the facility, determine whether the facility should continue to be used or enter the decommission phase.

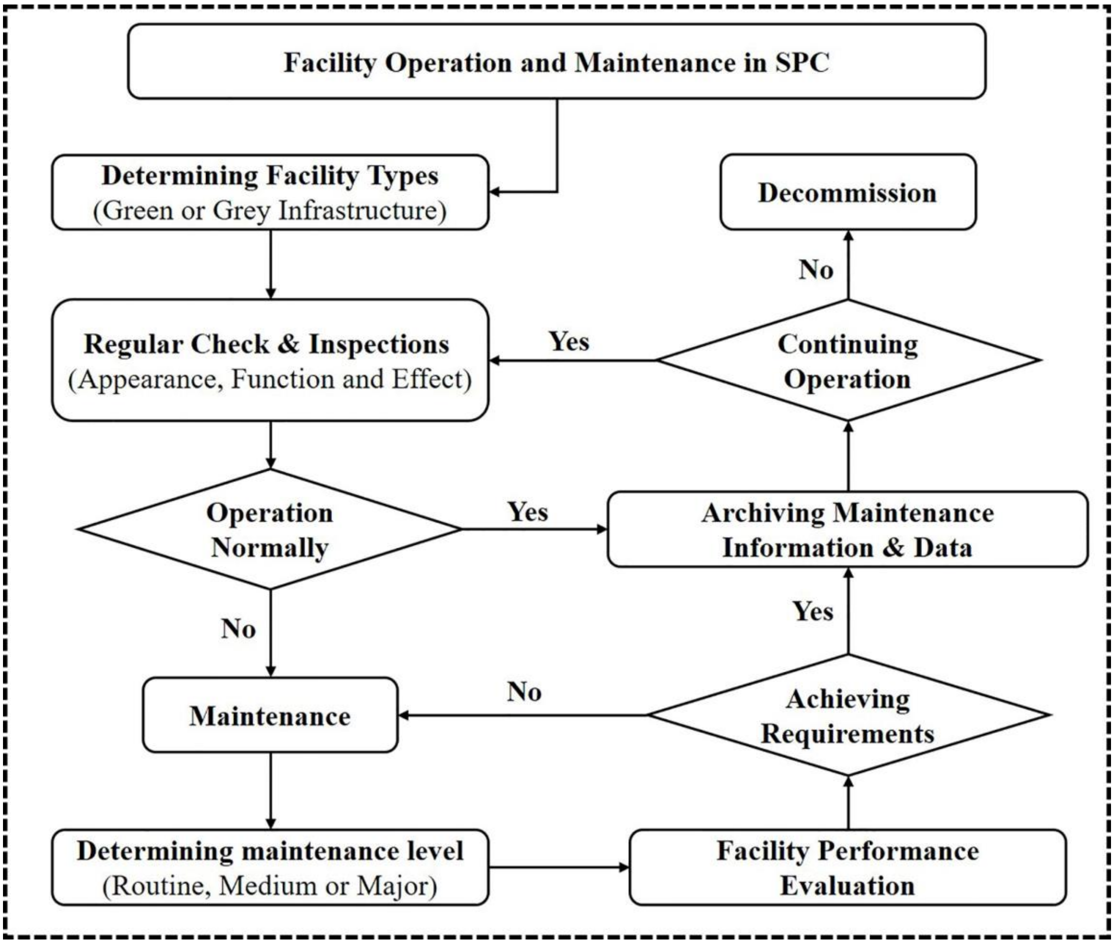


**Figure 7**. Basic flowchart of operation and maintenance of SPC facilities

## 5.2 Factors affecting the operation of SPC facilities

### 5.2.1 Different design and materials

From the above review, it can be known that SPCC can significantly reduce runoff volume, improve runoff quality, alleviate heat island effect and increase groundwater recharge. However, many researches indicated that plant species, substrate type or drainage layer materials affected the efficiency of SPC facilities in treating runoff (Gong et al. 2019b). Besides, according to the formula of section 3.2.1, if the saturated hydraulic conductivity of soil, hydraulic gradient, infiltration area and infiltration duration of a facility is different, it is no doubt that the runoff control capacity will also change. Therefore, the design parameters and structural layer materials of SPC facilities (especially source LID facilities) significantly affect the facility's runoff control capabilities. Taking green roof as an example, Table 5 shows that the facility's runoff control capacity changes correspondingly with the facility design parameters and the structural layer materials. The scale, slope, plant species, substrate type, and thickness of these studies were different, therefore resulted in different performances. However, there is no doubt that green roof plays a positive role in runoff control, as well as other types of SPC facilities.

**Table 5.** Research on runoff control of green roof with different structure layers

| Author (Year) | Location | Scale ($m^2$) | Slope (°) | Plant Types | Substrate Types | Substrate Depth (mm) | Runoff Control Capacity [a] | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $R_r$ (%) | $P_r$ (%) | $P_d$ (h) |
| Gong et al. (2018b) | Beijing, China | 0.25-2.25 | 1 | Sedum | Pastoral soil, Turfy soil, Pine needles | 100-200 | 12.4-100 | | |
| Soulis et al. (2017) | Athens, Greece | 2.3 | 0.5-30 | Sedum | Light substrate, Clay, Zeolite, Compost | 80-160 | 2-100 | 17-100 | |
| Brandão et al. (2017) | Lisbon, Portugal | 2.5 | 2.5 | Local Plants | Local Substrate | 150 | 12-100 | 97-100 | 0-19.73 |
| Lee et al. (2015) | Seoul, Korea | 1 | NM [b] | Sedum | Perlite | 150 | 13.8-34.4 | 71.0-81.6 | 2-3 |
| | | | | | | 200 | 42.8-60.8 | 79.8-91.3 | 2-4 |
| Hakimdavar et al. (2014) | New York, USA | 0.09-310 | NM | Sedum | Special Substrate for Roof Greening | 32 | 32-85 | 51-89 | |
| Speak et al. (2013) | Manchester, UK | 384 | NM | Mixed | | 170 | 65.7 | | |
| Alfredo et al. (2010) | New York, USA | 0.74 | 2 | Sedum | Light Growth Substrate | 25-101 | | 22-71 | 1-1.83 |
| Bliss et al. (2009) | Pittsburgh, USA | 1150 | NM | Sedum | Shale, Perlite, Coconut Shell | 140 | 5-70 | 52-85 | 3-4.75 |
| Stovin (2010) | Sheffield, UK | 3 | 1.5 | Sedum | Broken brick | 80 | 34 | 56.9 | |
| Van Woert et al. (2005) | Detroit, USA | 6 | 2-6.5 | Sedum | Shale, Sand, Peat, Dolomite, Compost | 25-60 | 48.7-82.8 | | |

Note: [a] - In the three columns of runoff control capacity, if the two values are connected by "-", it means the value interval. If there is only a single value, it indicates the average value; [b] - NM represents parameters or conditions not mentioned in the original literature.

5.2.2 Spatial and temporal variation

Temporal scales are mostly characterized by rainfall characteristics and changes in facility operation time. For example, peak coefficient, rainfall duration and antecedent dry weather period of a specific rainfall event can lead to different effectiveness of SPC facilities (Gong et al. 2018b) as well as the seasonal changes of annual rainfall (Brezonik and Stadelmann 2002). Many current studies also show that the operation time would also affect the performance of runoff control capacity of sponge facilities (Johnson and Hunt 2016). As for spatial scale, differences in regional parameters such as terrain, climatic conditions, soil characteristics and water holding capacity caused by different spatial location of the SPC pilots can be attributed to the effect of spatial variation on the SPC facilities. Therefore, the operation of SPC facilities is affected by both spatial and temporal changes. However, the majority of those previous studies relied on existing climatic conditions rather than future conditions. In fact, even in the same city, the climate and rainfall characteristics would produce spatiotemporal changed after many years (Tong et al. 2020), which is why the rainstorm intensity formula in each place was occasionally updated.

Sun et al. (2019) indicated that rainfall distribution significantly affected the hydrologic performance of bioretention system under a given rainfall. Macedo et al. (2019) showed that the efficiency of bioretention varied between dry and wet season under subtropical climate. The performance of green roofs also changed with spatial and temporal variation (Hakimdavar et al. 2014). In view of the above problems, it should be known that SPCC must be tailored to local conditions, and targeted construction must be carried out in strict accordance with local actual conditions. The same construction method cannot be applied to all other cities.

### 5.2.3 Maintenance frequency

Studies show that facilities have significantly improved runoff control capacity after regular maintenance (Macedo et al. 2017). Therefore, the maintenance frequency is bound to affect the performance and effectiveness of SPC facilities (MHURD 2014). Erickson et al. (2013) indicated that maintenance should be considered at the conception stage. Silva et al. (2015) suggested that when green roofs are stabled after construction, maximum twice a year for fertilization and weeding of invasive species are recommended, while proper maintenance should also be carried out before and after storm events. Johnson and Hunt (2016) found that when bioretention system operated for 11 years, the phosphorus and Zn concentrations in forebay were 7 and 5 times higher than normal level, respectively, which means more frequent maintenance was need. Therefore, it is easy to see that the maintenance frequency is not constant during the operation of the facilities, and the operation status of the facility needs to be occasionally checked to determine the current status and maintenance frequency.

5.3 Summary of the maintenance tasks

Successful operation of facilities depends on maintaining facilities' best condition, this leads to proper maintenance method. Besides, maintenance should also consist construction and management, adapt to local conditions, cost-effective and sustainability. Table 6 shows the maintenance measures of ten typical SPC facilities based on several published researches or manuals and the practical experience (Al-Rubaei 2016, CRWP 2008, DEC 2017, Flynn et al. 2012, Livingston et al. 1997, TDEC 2015). Numerous maintenance measures are divided into routine, non-routine and major movements. Different maintenance measures need to be performed in different cycles to distinguish the importance of different levels. It should be noted that the cycle of each type of maintenance measure would change according to local climatic conditions, but high-level maintenance also needs to contain all low-level movements. When rainy season comes, comprehensive inspection of the SPC facilities is needed to ensure the normal operation.

In addition, operation and maintenance plan shall be prepared according to the characteristics of the city or facilities, and the requirements for operation and maintenance in the design stage shall be fully considered; the plan shall include at least the specific requirements for various types of facilities inspection, operation, and maintenance, as well as relevant contents of safety management and funding guarantee. Moreover, safety and professional technical training for operation and maintenance staff should be carried out regularly; security equipment and supplies related to facility operation and maintenance should also be provided and at the same time increase public participation.

**Table 6.** Facility classification and basic maintenance items.

| Facility | Types | | | | | Basic Maintenance Items for Each Facility | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Routine | | | | Non-routine | | | | | |
| | | | | | | | | | | Medium | | Major | | | |
| | Green | Grey | Source | Mid | Terminal | Litter Cleanup | Desilting | Plants Conservation | Soil Erosion | Runoff & Soil Pollutants | Conductivity | Drainage Clogging | Surface Collapse | Structure Damaged | Facility Failure |
| Bioretention | √ | | √ | | | √ | | √ | √ | √ | √ | √ | √ | √ | √ |
| Green Roof | √ | | √ | | | √ | | √ | √ | √ | √ | √ | √ | √ | √ |
| Permeable Pavement | √ | | √ | | | √ | | | | √ | √ | √ | √ | √ | √ |
| Rain Barrel | √ | | √ | | | | √ | | | | | √ | | √ | √ |
| Grass Swale | √ | | | √ | | √ | | √ | √ | √ | | √ | | √ | √ |
| Drainage pipeline | | √ | | √ | | | √ | | | | | √ | | √ | √ |
| Permeation Tube | √ | | | √ | | | √ | | | | √ | √ | | √ | √ |
| Stormwater Wetland | √ | | | | √ | √ | | √ | √ | √ | √ | √ | | √ | √ |
| Detention Pond | √ | | | | √ | √ | | √ | √ | √ | √ | √ | | √ | √ |
| Storage Tank | | √ | | | √ | | √ | | | √ | | √ | | √ | √ |

## 6. Future works and directions

For SPCC development, several future perspectives are emphasized here:

(1) One of the key problems in the SPCC is how to combine the grey infrastructures with the green LID facilities. The SPCC should fully consider the functions of green facilities, such as delaying and reducing the peak runoff (drainage intensity) to reduce the load of grey facilities. At the same time, the comprehensive monitoring of grey facilities should not be neglected, and the two should be combined organically. However, in the current SPCC, the runoff control and ecological function of green facilities are overemphasized, while the capacity of grey facilities to cope with heavy rainfall is ignored, which makes the effect of SPCC poor. Therefore, in the following construction, the relationship between green and grey facilities should be coordinated. In addition, attention should be paid to the coupling mode, method and proportion of grey and green facilities, so that the SPCC can achieve the optimal state of environmental and economic benefits.

(2) Although the existing hydrological and hydraulic models can better simulate the runoff conditions in the SPC study area after parameter calibration and validation, when the study area is large, the calculation time of the mechanism model will be greatly increased and the calculation speed will be lower. Therefore, when the monitoring data is sufficient, the data-driven model can be considered to replace the mechanism model for related hydrological and hydraulic simulations. The data-driven model has a flexible

model structure and is more adaptable to the different characteristics of hydrological regulations from different places. Since data-driven models need to learn how to fully represent the potential relationships between different variables, the number of parameters is generally more than that of mechanism models, so the demand for observational data is much larger and the data needs to have higher accuracy. However, when the monitoring data can meet the requirements, the data-driven model can better simulate the hydrological conditions of the study area in a shorter time and will be an effective substitute for the mechanism model.

(3) At present, all aspects of China's water industry and regulatory departments involve massive amounts of information, and most of the information is currently limited to departments or enterprises, and it is impossible to obtain all relevant public management information in a timely and effective manner. By introducing an intelligent management platform, it can effectively improve the efficiency of data utilization in all aspects of the water industry, improve management methods, and achieve the goal of efficient collaborative management, thereby enhancing the effect of SPCC.

However, the construction of Smart Water is still in the initial stage of practical exploration. The construction goals of Smart Water in different regions are different, and the level of understanding is uneven, mainly reflected in the emphasis on the construction of hardware equipment and facilities, and the neglect of the construction of digital management software, Besides, the emphasis on real-time monitoring, while ignoring data mining and "Smart" application construction leads to leads to the lack of

SPCC effect. The Smart Water system should be established around smart control, information sharing, precise management, and decision-making, which can provide support for the entire process of planning, design, construction, operation and maintenance of the water industry.

## 7. Conclusions

SPCs take LID as the starting point, connecting all parts of the city's water system. Different from the LID in the United States and the water sensitive urban design (WSUD) in Australia, the SPCs in China are based on the water environment capacity of the urban receiving water body, water safety risks and overall water balance. It considered the water problems from the source LID to urban drainage infrastructure construction in the middle and end with systematic control effect, integrating urban ecology, municipal administration, landscape, urban planning, water conservancy and other professional departments, and systematically solve the four major issues of urban water environment, water ecology, water safety and water resources. Avoiding the incoordination of the work objectives between the various departments involved in the water system management in the urban development process. The proposal of SPC is of absolute innovative significance for the management and development of urban water system.

The case of SPC represents the direction of water system management in future cities which is also the future cities of the whole world, that is: for the urban water system, each subject/field should not only be responsible for its own part, but should be managed as a whole, and an ultimate goal should be decomposed into multiple sub-systems. Assigning tasks to various professions, and let them manage together in order to produce the best results. This is also the most worth learning place in other countries. This paper gives a comprehensive review of SPCC from the aspects of planning, construction, assessment and subsequent facility operation and maintenance by using content analysis method. According to the discussion, the conclusions are as follows:

(1) At the background of global climate change and increasing urbanization, the SPCC in China can indeed solve water safety (alleviate urban waterlogging), water environment (runoff pollution reduction) and water ecology (significant increase in $V_{cr}$) issues while increase stormwater reuse and further inherit water culture through systematic source-mid-terminal construction and the combination of green and grey infrastructures.

(2) The comprehensive construction assessment of SPCs should be carried out through "monitoring + hydrological hydraulic model" method. The content involves the runoff quantity and quality control effect, changes in groundwater depth, mitigation of urban heat island effects and urban flooding and CSO control.

(3) Facility design parameters, structural layer materials, spatial and temporal variation and maintenance frequency significantly affect the facility's sponge effect. Long-term maintenance of facilities is also one of the essential links in the SPCCs. Different facilities should be targeted for regular maintenance based on their characteristics and

life cycle.

(4) Although 30 national pilot cities have completed SPCC and corresponding assessment, it does not mean that the SPCC is coming to an end. Under the guidance of pilot cities, China still need to summarize and promote typical cases of SPCC. On the one hand, shortcomings in urban infrastructure construction need to be improved as quick as possible. On the other hand, it is necessary to accelerate the transformation of urban construction concepts and make China’s future move toward a more harmonious, environment friendly and sustainable way.

However, due to the lack of relevant local information for operation and maintenance, it is not possible to conduct a more comprehensive review and definition of the maintenance methods and cycles of facilities. Besides, the policies and regulations related to SPCs have not been reviewed. Finally, many cities in China are undertaking the smart city constructions. Therefore, combining the SPCCs with smart cities, setting up a SPC smart management and control platform that integrates online monitoring, operation, maintenance and early warning is also important. These issues are all needed to be carefully considered in future research.

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