

Review

Framework, Procedure, and Tools for Comprehensive Evaluation of Sustainable Stormwater Management: A Review

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Abstract: To better evaluate and enhance the performance and benefit of sustainable stormwater management (SSWM) in developing countries, this study proposes a comprehensive evaluation framework based on thorough literature review. This framework re-classifies evaluation goals and indicators into four aspects—stormwater system, integrated management, social engagement, and urban development. The purpose of this review is to provide a guideline for decision makers to choose appropriate goals and indicators according to different regional context. Meanwhile, a structured procedure for comprehensive evaluation of SSWM is proposed to guide a well-organised decision-making process. Furthermore, pros and cons of eight decision support tools, as well as their functional focus, are compared, aiming to provide references for SSWM in developing countries. Outcomes presented in this review are expected to support decision makers in the process of screening optimal SSWM strategies and monitoring SSWM projects.

Keywords: comprehensive evaluation framework; stormwater management; decision support tool; sponge city

1. Introduction

In recent years, rapid urbanisation and high-density construction have caused continuous expansion of impervious areas, leading to significant changes in the hydrology and ecosystem in cities [1,2]. These changes include reduction of stormwater infiltration, generation of massive stormwater runoff, decrease of groundwater recharge and continuous aggravation of non-point source pollution, all leading to major challenges in urban stormwater management (SWM) [3,4]. Given these challenges, traditional engineering solutions for SWM are increasingly recognized as not appropriate because they are not environmentally sustainable. As an opposite approach, green infrastructure-based sustainable stormwater management (SSWM) has been suggested as an alternative adaptive strategy for mitigating the long-term impacts of urbanisation and climate change like more frequent occurrences of extreme conditions of floods, droughts, heatwaves and other threats to human and nature [5,6]. Therefore, a holistic and integrated view of SSWM is needed to achieve best management practices.

In developed countries, a number of SSWM concepts have emerged in recent decades, including sustainable urban drainage systems (SUDS), stormwater best management practices (BMPs), green infrastructure (GI), low impact development (LID), and water sensitive urban design (WSUD) [7]. Although these concepts vary in scope and context, they generally aim to minimise the negative impacts

posed by excessive urban stormwater and attempt to restore natural hydrological processes through measures such as green roofs, rain gardens, permeable pavements, wetlands, and other measures. Both academic and practical research reported that these SSWM approaches can provide environmental, economic, and social benefits [8,9]. SSWM can further contribute to other aspects, such as enhancing aesthetic appearance of built areas, public health improvement, recreational value, and ecological protection [10]. Establishment of a comprehensive evaluation framework for SSWM is needed to assist decision makers in identifying primary functions, operational performances, and extended benefits of to multiple aspects. Additionally, a reliable and suitable comprehensive evaluation process and methods can streamline the assessment process and dramatically reduce the associated time and cost in decision making. Successful lessons and experience can be drawn from developed countries and help other regions to develop SSWM strategies more scientifically.

It is commonly agreed that SSWM should integrate stormwater systems with environment, economics, society, and other aspects of SSWM [8,11]. However, effective implementation of SSWM might be challenging in rapid urbanizing regions, particularly in developing countries [12,13]. Furthermore, current SSWM approaches in many developing countries might not be systematically formed [14,15]. Comprehensive evaluation of goals and indicators of SSWM is expected to provide a common language for decision makers to facilitate the effectiveness of communication and the process of elaborating optimal decisions [16]. Some researchers have tried to develop a comprehensive evaluation system based on specific context [17–20]. For instance, Bai et al. [21] established a comprehensive assessment system to evaluate the benefits brought by different LID scenarios in Sucheng, China; Gogate et al. [22] developed a decision-making framework to assess the feasibility of SSWM options in Pune, India. However, the evaluation goals and indicators proposed in such studies vary due to different context and site characteristics. Moreover, the emphasis on the importance of SSWM from different perspectives is still growing around the world. Many other factors, which can affect the performance and added value of SSWM, need to be considered during the decision-making process. For example, the significance of relations between SSWM and spatial suitability has been more emphasised in recent years [23,24]. Lessons from developed countries, which show a broad range of evaluation goals and indicators across different dimensions, can assist decision makers in addressing the gap and in deriving a clear vision of SSWM for developing countries.

Establishment of a standard procedure for comprehensive evaluation of SSWM can further assist decision makers in formulating a more inclusive and well-informed decision. Additionally, methods of valuing various indicators can provide technical supports for the evaluation process [19,25]. Several researchers have reported different methodologies for evaluating the performance and benefits of SSWM strategies. Generally, the evaluation steps and methods in these studies are based on the conditions and the sufficiency of evaluation data of the study area [17,26]. Considering these limitations in knowledge, a systematic summary of general comprehensive evaluation steps and preferred methods for SSWM are needed in order to provide references for developing countries. Meanwhile, comprehensive evaluation of SSWM is generally time-consuming due to high uncertainty and the complexity of stormwater systems [27]. A decision support tool can assist decision makers in solving this issue effectively and provide relatively reliable evaluation results. Several review articles have addressed the classification of a wide range of existing decision aid tools, as well as their primary focuses and barriers [28–30]. Nevertheless, there are limited studies focusing on the adaptability and reliability of these tools for assisting SSWM in developing countries.

In this review, we propose a comprehensive performance and benefit evaluation framework for guiding SSWM implementation in developing countries. The selection of suitable evaluation goals and indicators is based on a thorough literature review from three tiers—namely, international, national, and context-specific tiers. The outcome will facilitate the development of suitable goals and indicators for evaluating the performance and for measuring the benefits of SSWM under varying geographical conditions. Meanwhile, a general procedure and recommended methods for comprehensive evaluation of SSWM are summarised to facilitate the decision-making process. Furthermore, eight different

types of decision aid tools are compared discussing their functional focus, adaptability, applicability, and capacity for comprehensive evaluation of SSWM in developing countries. The major aim of this comparison is to assist in screening for the most suitable tool during the decision-making process. A secondary aim is to provide recommendations for further decision support tool development.

2. Materials and Methods

2.1. Literature Search

The framework, procedure, and tools for a more comprehensive performance and benefit evaluation of SSWM summarised in this study are derived from an extensive literature review. The reviewed material includes peer-reviewed journal articles, book chapters, conference proceedings, case studies, fact sheets, and governmental reports. The searching databases include Web of Science, ScienceDirect, ASCE Library, and Scopus. Literature selected (around one hundred and fifty articles) mainly falls into six categories which are: (1) SSWM; (2) SWM performance and benefits; (3) stakeholders and decision makers; (4) evaluation methods/methodology; (5) indicator/criteria quantification; and (6) decision support tools/models. Detailed key words in each category are summarised in Figure 1.

| Sustainable stormwater management | Stormwater management performance and benefits | Stakeholders and decision makers | Evaluation methods/ methodology | Indicator/criteria quantification | Decision support tools/models |
|---|---|--|--|--|---|
| Sustainable urban drainage system Low impact development Best management practices Green infrastructure Water sensitive urban design Urban water management Stormwater control measures Urban planning and design | Performance evaluation Effectiveness Comprehensive benefits Ecosystem services Social engagement Public participation financial benefits economic benefits Urban development Urbanization Climate change | Stakeholder/ decision maker perspectives Opinions Governance Communication Policy Benchmarking Index/indicators Framework Transition Ranking | Multiobjective Cost effectiveness Cost benefit Comprehensive evaluation Multicriteria Integrated Evaluation step/procedure /process Assessment | Indicator quantification Benefit quantification Quantitative Qualitative Life cycle valuing Value transfer Monetary weight Score | Simulation Optimization Modelling Tools Softwares Decision support/aid Model integration Hydrological model Agent-based Scenarios |

Figure 1. Key words of the literature search (overlaps may exist between each category box).

2.2. Development of a Comprehensive Evaluation Framework for SSWM

The analytical procedure of developing a comprehensive evaluation framework for SSWM is of crucial importance for decision makers to gain important insights into current state and future trend of SSWM [31–33]. The adopted approach in this study for developing a comprehensive performance and benefit evaluation framework for SSWM in developing countries is illustrated in Figure 2 and can be summarised into four steps as follows:

1. Review international SWM policies and best practices. In this step, the current situation and future trend of SWM in a global perspective is identified. It is of great value to be open to the common issues, novel ideas and solutions of SWM.
2. Review national SWM practices. The significance of SSWM has been recognised by many countries in the past decades. Several countries have developed a relatively systematic and comprehensive management framework. The experience learned from different nations can help developing countries to leapfrog and accelerate the development of SSWM.
3. Review studies on comprehensive evaluation of SWM. Many studies focusing on the comprehensive evaluation frameworks of SSWM of different scales and perspectives are reported. Review of these studies helps to identify some important factors needed to be considered in developing a comprehensive evaluation framework for SSWM.
4. Develop the comprehensive evaluation framework for SSWM in developing countries. Based on an extensive literature review of related studies and current SWM situation in most developing areas, a new comprehensive evaluation framework for SSWM in developing countries in a broad perspective is proposed.

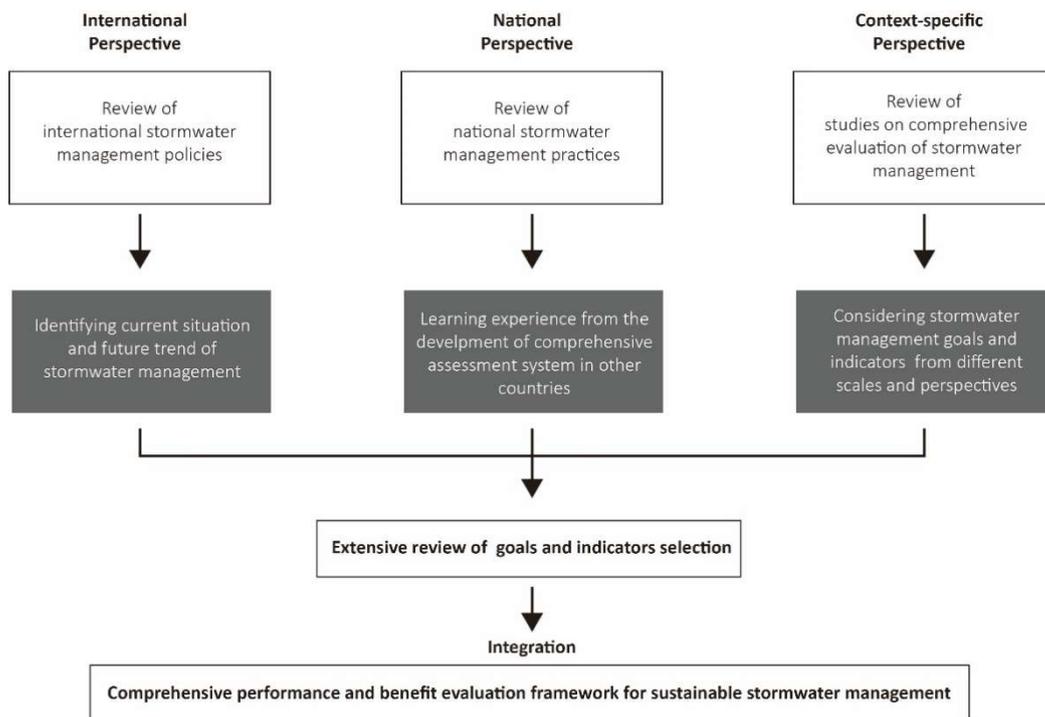


Figure 2. The structure of developing the comprehensive evaluation framework for sustainable stormwater management (SSWM).

Further, as an example for adopting this framework, the current limitations of existing assessment system and possible future outlook of Sponge City Construction (SCC) in China, launched in 2015 as the national SSWM programme [34], is discussed. China is in the process of rapid urbanisation and has various geographical environments, climate conditions and hydrological characteristics which can represent the development stages and existing conditions in most developing countries. Meanwhile, the concept of Sponge City is like that of LID, SUDS, and WSUD, the main philosophy of which is to mimic and restore natural hydrological processes in SSWM.

2.3. Summary of Procedures and Tools for Comprehensive Evaluation of SSWM

The comprehensive evaluation processes and methods for SSWM might be varying based on different site conditions. However, the essential evaluation steps and sequences are similar. Following an extensive review of comprehensive evaluation systems for SSWM, a general evaluation procedure is summarised, and the evaluation methods are categorised according to their primary focuses, required data and philosophy. In addition, adoption of appropriate decision support tools should provide scientific support for the decision-making process. In developing countries, limited decision support tools have been developed based on national condition. The applicability and adaptability of different decision support tools for assisting SCC in China might provide a reliable reference for other developing countries.

Therefore, the detailed review and summary are conducted (shown in Section 3.3) from the following four aspects:

1. Establish a standard procedure for comprehensive evaluation of SSWM;
2. Classify methods for comprehensive evaluation of SSWM;
3. Compare existing decision support tools;
4. Analyse the suitability of different decision support tools for SCC in China as an example.

3. Results and Discussion

3.1. Overview of Comprehensive Evaluation Framework Development for SSWM

3.1.1. SWM Policies of International Organisations

Comprehensive evaluation framework for SSWM is based on correct selection of management objectives and evaluation indicators, which is crucial in guiding SWM of all stages. At the macro level, SWM is included in integrated water resources management and environmental protection strategies, for which relevant international organisations have formulated a series of objectives. For example, in 2007, the United Nations (UN) issued Principles of Integrated Water Resource Management to develop and manage the demands of the finite water resources in the world effectively, equitably and sustainably [35]. In 2015, the 17 Sustainable Development Goals (SDGs) formulated by UN took effects formally, among which the specific goals and indicators articulated in objectives 6, 11, and 13 are related to SSWM [36,37]. The International Water Association (IWA) proposed 17 Principles for Water Wise Cities (WWC) which include a four-level action plan for urban water management aiming to formulate a common action plan for maximizing the benefits of SSWM [38].

3.1.2. SSWM Practices of National Governments and Institutions

From the perspective of regions, different countries have formulated corresponding objectives and indicator systems for SSWM according to national or local conditions. For instance, with the objectives of flood mitigation, controlling soil erosion and reducing non-point source pollution, the United States (US) has developed BMPs and LID for integrated management [39,40]. In 2015, the United States Environmental Protection Agency (US EPA) published a guideline to provide assistance in choosing measurable goals and indicators for SSWM in specific areas. In addition, economic evaluation of different LID programmes in Seattle, New York, Washington. and other cities showed the potential benefits of LID and provided a framework for stakeholders to assess specific LID planning and design outcomes [31]. SSWM regulations in the US have jurisdiction across communities, regions, and states to address nation's environmental problems [41]. For instance, the National Pollutant Discharge Elimination System (NPDES) programme requires permits for stormwater discharges in construction sites larger than one acre (0.405 ha) [42]. By doing this, different state governments can be authorized to develop local SWM policies and initiatives to meet federal regulations [43]. In addition, development of stormwater pollution prevention plans (SWPPPs) can aid operators in assessing and monitoring SWM practices at construction sites and stay in compliance with local requirements [44]. Originating from the perspective of surface water drainage system, combing both environmental and social benefits, Europe established SUDS to improve urban water cycle management by taking integrated measures [45]. The Construction Industry Research and Information Association (CIRIA) in the UK published a literature review of benefits brought by SUDS and methods for benefit assessment both qualitatively and quantitatively [32]. However, the US and Europe have not established frameworks to assist stakeholders in evaluating SSWM practices at a national level.

In this regard, Australia and Singapore offer more distinct and detailed evaluation frameworks. Based on historic policies related to urban water management, The Cooperative Research Centre for Water Sensitive Cities (CRCWSC) in Australia placed the development of Australian cities into six stages to guide urban transformation and sustainable urban water management [46]. Seven goals of Water Sensitive Cities (WSC) and 34 indicators under them were developed as the WSC index tool to guide cities to transform into more productive, resilient, sustainable, and liveable cities [33,47]. Meanwhile, corresponding assessment and benchmarking of goals and indicators was performed based on local context in Melbourne, Sydney, Brisbane, and other regions. In Singapore, responding to the challenges of water supply security, water shortage and water pollution, Singapore's Public Utilities Board (PUB) started Active, Beautiful, Clean (ABC) waters management programmes to convert pipelines and drainage channels into community public green spaces in order to enhance

urban liveability and help raise the public awareness to environmental protection in Singapore [48–50]. The ABC waters programme consists of four overarching objectives, including active, beautiful, clean and innovation. Under each objective, there are various indicators to evaluate and score the projects. The aim of this programme is to integrate environment, water and community into the city environment and lifestyles for SSWM [51,52].

3.1.3. Comprehensive Evaluation Framework of SWM at a Site-Specific Scale

Scholars from various countries also worked on comprehensive evaluation of SSWM. Li et al. [53,54] proposed comprehensive benefit evaluation systems for SCC based on principal component analysis method and analytic hierarchy process, respectively. They classified the evaluation indicators into three aspects which were the environmental, economic and social benefits, under each of which corresponding sub-indicators were included to guide decision makers in choosing the most appropriate SSWM measures. Zhou [30] and Morales-Torres et al. [55] summarised the SUDS evaluation indicators relating to various related simulation models and decision aid tools, respectively. The former suggested that when formulating SSWM plans, influences of several fundamental indicators (e.g., water quantity, water quality, biological diversity) should be taken into consideration. In the latter work, the indicators were classified into stormwater infrastructure performance, benefits and costs, energy consumption and carbon emissions. Jia et al. [56] and Kuller et al. [23] considered spatial factors in multi-criteria evaluation. These included site adaptability and system space requirement to achieve a more holistic and inclusive decision-making process. In a review of selecting SSWM strategies in developing countries, Gogate et al. [22] proposed a decision-making framework and summarised four major criteria to assess SSWM options, namely: technical, economic, environmental and social indicators. Similarly, Zhan and Chui [57] put forward a life cycle benefit framework for the selection of LID measures at an urban scale in order to conduct quantitative evaluation on environmental, economic and social benefits.

3.2. Comprehensive Evaluation Framework for SSWM in Developing Countries.

The development stage of SSWM in developing countries varies dramatically based on different urban context. Generally, the primary goals of SWM are similar, addressing water-related issues, such as drinking water scarcity, flood and drought events, aquatic environment pollution, and water resource contamination [58–60]. However, this leads to the fact that the current SSWM evaluation systems in many developing countries narrowly focus on water-related goals and indicators. For instance, in Malaysia, India and China, the effectiveness of SSWM in reducing runoff and pollutants is the major indicator to assess SSWM practices, while indicators like public engagement, aesthetics and educational benefits are not well considered in the assessment criteria [61–63]. Based on the current SWM practices in most developing countries and extensive review of related policies and research, a comprehensive performance and benefit evaluation framework for SSWM is proposed in this review. This framework classifies the management objectives into the following four levels described below. The relationship between each level of objectives is illustrated in Figure 3.

- Stormwater system—focusing on the overall operation effects of the SSWM system, including surface runoff control, system performance, economic sustainability and technical innovation.
- Integrated management—emphasising the relations between SSWM and urban water management as well as other components, including environmental governance, disaster resilience and resource efficiency.
- Social engagement—highlighting the relations between SSWM system and social benefits and values, including public participation and effective governance.

- Urban development—focusing on the influences of SSWM system on future development of the city, including improvement of urban space quality and liveability, renewal of public infrastructure, and increase of city resilience as well as the corresponding indicators.

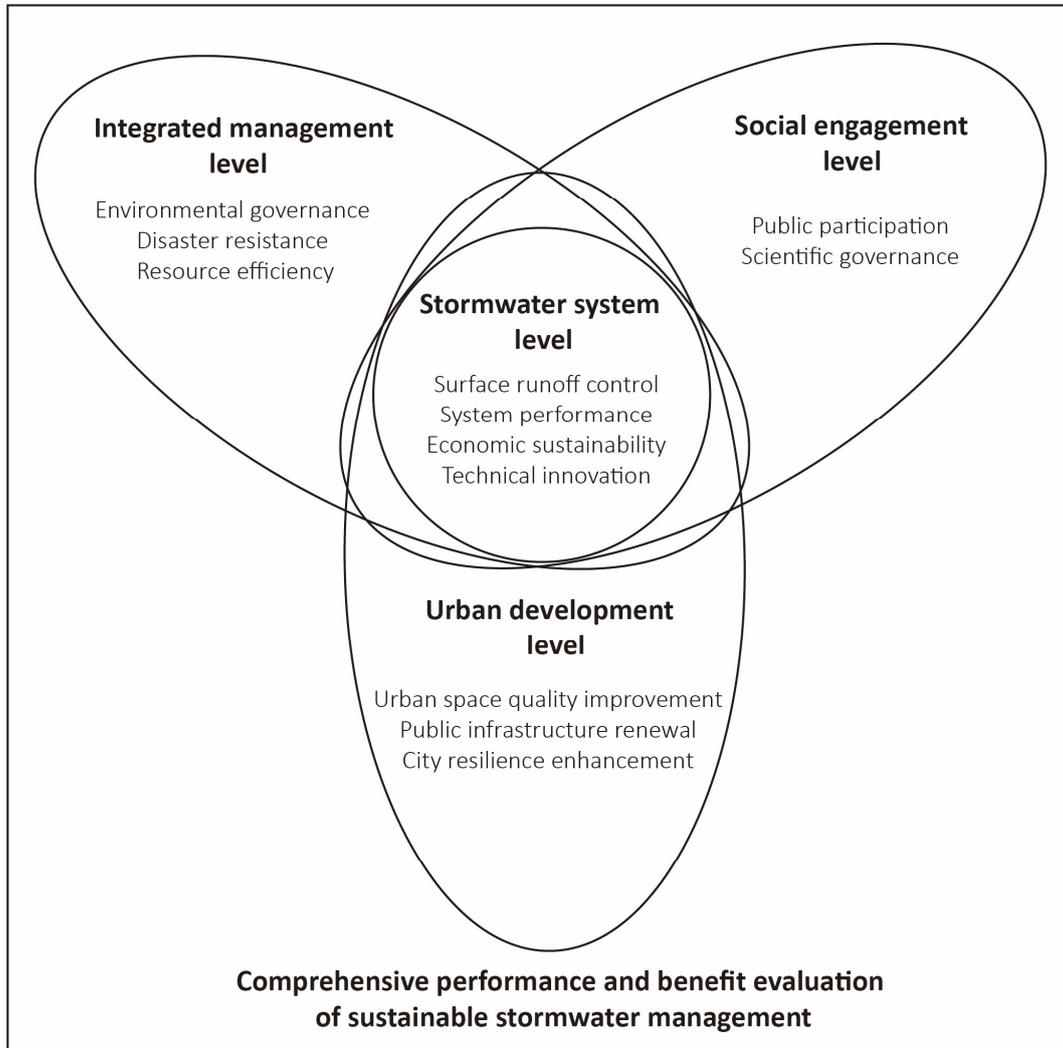


Figure 3. The relationship between each level of objectives in the comprehensive evaluation framework for SSWM.

3.2.1. Selection of Evaluation Indicators

The evaluation indicators which are needed to be considered in each level of objectives and the rationale for the indicator selection are discussed below. Based on the selected indicators, the comprehensive evaluation framework for SSWM is proposed (Table 1).

Table 1. Comprehensive evaluation framework for SSWM.

| Objective Classification | Specific Objectives | Indicators | |
|--------------------------|---------------------------------|--|---|
| Stormwater system | Surface runoff control | Runoff quantity control * (e.g., peak flow reduction, peak delay and runoff control efficiencies) Non-point source pollution control * (e.g., reduction of TSS, TN, TP, and COD) | |
| | System performance | (e.g., meeting target volume and/or peak flow reduction goals; meeting target non-point source pollutants reduction in receiving water bodies) Meet design objectives * Operational reliability # Space requirement * Site adaptability # System flexibility # System complexity # System accessibility and safety # Suitable system layout/structure # (e.g., design of planting scheme, depth of media, layer configuration and other design parameters) Conformity with technical specifications and standards # | |
| | | Economic sustainability | System maintainability # Self-sufficiency * Capital cost * Operation and maintenance cost * |
| | | Technical innovation | System operation intelligence # (e.g., adoption of monitoring sensors, wireless communications and online data platform) Adoption of innovative design and equipment # System optimisation # (e.g., structural optimisation of porous media or engineered soil to achieve the highest cost-effectiveness of the system) |
| Integrated management | Environmental governance | Restore water bodies and the ecological environment # Improve the quality of surface water * Water security and sanitation * Increase biological diversity # Restore ecological habitat # Protect areas with high ecological values # Improve groundwater quality * Groundwater recharge * Watershed wide impact * | |
| | Disaster resistance | Flood control and defense * Drought minimisation and defense * | |
| | Resource efficiency | (e.g., reduced runoff volume in underground drainages to avoid the risk of drainage damage and operational failure) Stormwater harvesting and reuse * Reduce cost of grey infrastructure * Pipe damage control * Reduce energy consumption * Reduce greenhouse gases emission * Reduce potable water supply * | |
| Social engagement | Public participation | Citizen's willingness to pay # Increase waterside activities # Increase public educational significance # Increase public activity space # Shared ownership, management and responsibility of the public # Preparedness for and response to extreme weather events # (e.g., community information sharing about flood warning) Local community participation in water-related planning # (e.g., participation of communities in developing SSWM visions) Community activities organisation # Information transparency # (e.g., A public website for updating news and events relating to SSWM projects) | |
| | Effective governance | Water-related business opportunities (industrialisation) # Assessment of professional capacities # Inter-disciplinary, inter-agency cooperation # Multiple stakeholders and policy makers involvement # Assessment of leadership capability # Multi-sectoral benefits # | |
| Urban development | Urban space quality improvement | City liveability and landscape improvement # Consider water as a major factor of urban planning and design # Activate blue-green space # Improve vegetation coverage # Improve city aesthetics # Increase recreational space # Increase property values # | |
| | Public infrastructure renewal | Construction of multifunctional water-related infrastructure # Accessibility and affordability of water-related public facilities # | |
| | City resilience enhancement | Adaptability to extreme weather events * Urban heat island effect mitigation * | |

Note: # quantitative variables; * qualitative variables; TSS—Total Suspended Solids; COD—Chemical Oxygen Demand; TN—Total Nitrogen; TP—Total Phosphorus.

1. Indicators for stormwater system evaluation

The SSWM measures can control the quantity and quality of surface runoff effectively at a site scale [5]. Such measures include rain gardens, wetlands, retention and detention pond, bioswales, green roofs, and other nature-based solutions. These have their corresponding efficiency in decreasing total runoff, delaying peak flows and removing pollutants [22]. Runoff quantity control can be quantified by calculating the total runoff reduction, peak discharge reduction and peak flow delay [64]. Non-point source pollution control can be represented by reduction of typical pollutants carried by runoff, such as total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) [65].

For operational performance of SSWM system, the primary indicators are about meeting specific design goals as well as local technical specifications and standards that are sometime dependent on the site conditions [66]. Site adaptability, including the conditions of land use, soil, topography, groundwater level etc., is another key criterion for screening appropriate BMPs. In addition, the required area for suitable BMPs are different for achieving desirable performance goals [56,67]. For instance, bioretention systems generally requires less space than detention basins and retention ponds [22]. Thus, space requirement can be considered as one evaluation indicator for operational performance objective. Moreover, reliability, stability and risk of malfunction (such as equipment breakdown and soil clogging) also influence whether the system can achieve expected performance [56,68]. The system flexibility and complexity are also mentioned as indicators for assessing the technical performance of SSWM alternatives. For example, bioswales are generally more flexible in locations, shapes and planting schemes than detention basins and retention ponds in various urban environment conditions [22]. Accessibility and safety of SSWM assets are also important evaluation indexes because they can reflect whether the system can further provide recreational and educational services [23,69]. Also, a suitable system layout/structure can improve the performance of the SSWM system. For example, different types of vegetation have different pollutant removal capacities [70]. Furthermore, design parameters like soil depth and composition of LID practices also influence the cost-effectiveness of the system [9,71].

Regards to economic sustainability, the indicators of system maintainability, capital cost as well as operation and maintenance cost of the SSWM system can generally reflect whether the system can provide economic benefits [9,17,57]. The self-sufficiency indicator means that the SSWM system can treat and supply water on site, which will increase the cost-effectiveness of the system [72,73].

For technical innovation, smarter SWM technique can effectively improve system performance (such as monitoring sensors, wireless communications and online data platform) [74,75]. System optimisation, like structural optimisation of porous media or engineering soil, can achieve higher cost-effectiveness [76]. Adoption of novel strategies, products, and approaches can also reflect the technical innovation of SWM [77]. Integration of intelligent control and incorporation of innovative design/device are individually adopted as assessment indicators in WSC index and ABC waters certification [33,52]. Therefore, intelligent operation, adoption of innovative design and equipment, and system optimisation are used as evaluation indicators in the specific objective of technical innovation.

2. Indicators for integrated management evaluation

For environmental governance, many studies have proved that SSWM can restore and enhance the environmental health [78,79]. In particular, a wide range of studies discuss the benefits relating to water body and ecological environment restoration, surface water resource quality improvement as well as water security and sanitation [46,80,81]. In addition, indicators of enhancing biodiversity, habitat restoration, protection of areas with high ecological values, groundwater quality improvement and groundwater recharge can also be considered for a comprehensive assessment [23,82,83]. Some research further showed that the implementation of multiple SSWM infrastructures can have positive impact on hydrology and water quality as well as enhancing biodiversity, protecting habitats etc. at a watershed scale [84]. Therefore, watershed wide impact can also be one important indicator when assessing the environmental benefits brought by SSWM.

A range of studies have shown that SSWM has the ability to mitigate floods and alleviate water scarcity problems by increasing water storage capacity of land and reusing harvested rainwater [85,86]. Thus, for the disaster resistance objective, flood reduction and mitigation as well as drought control and defense are chosen to be the evaluation indicators.

SSWM can maximise utilisation efficiency of natural and human-made resources. For example, stormwater harvesting and reuse are effective means of water saving. Also, on-site water recycling and reuse can reduce potable water demand [85]. Additionally, GI (such as urban trees and shrubs) in SSWM has positive effects on energy consumption reduction and greenhouse gas emission control. For example, urban trees can provide shading and cooling effect in hot summer for reducing air conditioner use, and CO₂ can be stored in biomass form, resulting in urban forests as carbon sinks [87,88]. Construction of decentralised SSWM measures, as an alternative approach to control flood and water pollution on site, can avoid large upfront costs of constructing grey infrastructure (such as dam, potable water treatment plants, and drainage systems) [89]. In addition, decentralised SSWM measures can reduce runoff volumes in underground drainages which subsequently decrease the risk of drainage damage and operational failure [14]. Therefore, reducing the cost of grey infrastructure and pipe damage control are considered as the indicators of resource efficiency.

3. Indicators for social engagement evaluation

Public participation is vital for the success of SSWM [90]. Generally, people's willingness to pay (WTP) is an indicator to measure the social value of SSWM systems [91,92]. An increase of waterside activities, public activity space, and community activities can reflect public awareness and perception of SSWM [93]. This can subsequently increase the educational value of SSWM [23]. Shared ownership, management and responsibility of the public, public engagement in water-related planning and design as well as the transparency of SSWM information are important indicators for the public to be the members of the stakeholders and decision makers [94]. The public's preparation for and response to extreme weather events from community warning is also an important indicator that should be considered in social engagement [95].

For effective governance, the indicators of the comprehensive management capacity of professionals and leaders, multiple stakeholders and policy makers involvement as well as inter-disciplinary and inter-agency cooperation of the management level have to be assessed for improving the quality of the decision-making process [96,97]. An integrated SSWM can also provide water-related business opportunities and multi-sectoral benefits [98].

4. Indicators for urban development evaluation

The SSWM contributes to public space quality by improving liveability, landscape quality, and aesthetics of the city, as well as increasing urban vegetation coverage and urban recreational spaces [23,99]. Green spaces provided by SSWM practices can consequently form the interconnection of blue and green network in the city [100]. The indicator of considering water as a major factor of urban planning and design is of vital importance in WSUD in order to minimise negative impacts of urbanisation [101]. As indicated by previous studies, a decrease of the distance to green space can result in an increase of the property price [102].

For the specific objective of urban infrastructure renewal, accessibility to and affordability of water-related public facilities (such as an increased number of public water supply facilities) supplies certain social needs relating to water [99]. Construction of multifunctional water-related infrastructure can satisfy multiple needs (e.g., water management, energy saving, and transport) for future urban development [100].

Increase of urban resilience can be achieved by enhancing the adaptability of cities to extreme weather events [103]. For example, SSWM measures can alleviate damages caused by flood events and climate change. Also, many studies have showed that the increased green spaces provided by SSWM can mitigate urban heat island effects [104,105].

3.2.2. Adoption of the Comprehensive Evaluation Framework: SCC in China as an Example

Sponge City, as the concept of SSWM in China, has developed rapidly in recent years [60]. A robust decision-making process for SCC can help stakeholders identify optimal development strategies or monitoring programmes for existing SCC projects based on specific context and factors [106]. However, the existing evaluation system of SCC has not comprehensively represented various managing objectives and indicators that should be considered. Currently, the SCC management goals proposed by the construction guideline in China focus on total annual runoff reduction and non-source pollution control only [107]. Subsequently, the China Ministry of Housing and Urban-Rural Development (MHURD) issued the Performance Evaluation and Examination Methods for Sponge City (on provisional) (PEEMSC). The PEEMSC proposes that the performance evaluation system in China should include eighteen indicators of six categories, namely: water ecology, water environment, water resources, water security, system construction and implementation, as well as visibility and demonstration at scale [108]. In the Assessment Standard for Sponge City (GB/T51345-2018) (ASSC), MHURD assesses SCC from seven aspects, including volume capture ratio of annual rainfall, road surface ponding and local flood control, urban water quality, projects implementation effectiveness, natural ecological pattern management and ecological water front, variation trend of groundwater depth, and urban heat island effect mitigation [63]. However, most of the evaluation goals and indicators in PEEMSC and ASSC emphasise the ecological benefits brought by SSWM.

The objective and indicator setting in current SCC assessment system are compared with the framework established in Table 1. This comparison aims to summarise the limitations of the existing assessment system for SCC. Meanwhile, the evaluation objective and indicator setting in several other organisations or countries are also included in order to examine the comprehensiveness of the proposed framework.

Regarding the SSWM objective setting, UN SDGs, IWA Principles for WWC, Australia WSC index, certification criteria for Singapore ABC waters programme, and current assessment standards for SCC in China are summarised and compared under the proposed framework in parallel (Table S1). It should be noted that the UN SDGs, IWA Principles for WWC, and Australia's WSC index all consider the 12 specific objectives of Table 1. Singapore ABC waters programme does not include objectives relating to economic sustainability, effective governance, renewal of public infrastructure and promotion of disaster resilience. China adopted the UN SDGs as a universal target in 2015 [109]. Therefore, UN SDGs is chosen to be the highest achievement level for SCC. To achieve UN SDGs goals, the assessment standards of SCC should not be limited to assessing the operational capacity and the ecological benefits of SSWM systems. Instead, it should extend the objectives of SCC to cover economic sustainability, technical advancement, public participation, and renewal of urban public infrastructure.

Regarding SSWM indicator settings, the evaluation indicators for comprehensive SSWM of Australia, Singapore, and China are summarised and compared under the proposed framework (Table 2). It should be noted that indicators of system flexibility, system complexity and reduced cost of grey infrastructure are not reflected in the existing indicator setting in WSC, ABC waters programme, and SCC at a national level. However, these indicators have been emphasised in related research for site-scale evaluation. This provides a crucial insight into considering these indicators when developing stormwater management criteria in the future. The results in Table 2 also suggest that the indicator options under different objectives of WSC are more comprehensive, while Singapore's ABC waters program and China's SCC contain lower number of evaluation indicators. The evaluation indicators of Singapore's ABC waters program are relatively narrow covering specific objectives of economic sustainability, technical advancement, disaster resistance, and resource efficiency. The evaluation indicators for China's SCC under the objectives of effective governance and urban space quality improvement are also rare. Indicators under scientific governance are designed to assess whether SSWM can provide corresponding industrialisation opportunities to promote the economic development of the city only. Also, there are neither indicators (inter-disciplinary or inter-sectoral cooperation) set to evaluate professional capabilities nor indicators to promote participation of stakeholders and

leadership capabilities. The objective of promoting urban space quality lacks indicators relating to city liveability, landscape improvement, city aesthetic improvement, and property value enhancement. Indicator options under the specific objectives of system performance, environmental governance and resource efficiency are not comprehensive. In particular, indicators relating to site adaptability, system optimisation, benefits of enhancing biodiversity, value of habitat protection and energy saving benefit are limited.

Table 2. SSWM indicators—comparison between Australia Water Sensitive Cities (WSC), Singapore Active, Beautiful, Clean (ABC) waters program, and China Sponge City Construction (SCC).

| Objective Classification | Specific Objective | Indicators | Australia WSC | Singapore ABC Waters Program | China SCC |
|--------------------------------|---|--|---------------|------------------------------|-----------|
| Stormwater system | Surface runoff control | Runoff quantity control | √ | √ | √ |
| | | Non-point source pollution control | √ | √ | √ |
| | System performance | Meet design objectives | √ | √ | √ |
| | | Operational reliability | √ | √ | √ |
| | | Space requirement | √ | | |
| | | Site adaptability | √ | | |
| | | System flexibility | | | |
| | | System complexity | | | |
| | Economic sustainability | System accessibility and security | | | √ |
| | | Suitable system layout/structure | | | √ |
| | | Conformity to technical specifications and standards | √ | √ | √ |
| | | System maintainability | √ | √ | |
| | Technical innovation | Self-sufficiency | √ | | |
| | | Capital costs | √ | | |
| Operation and maintenance cost | | √ | | | |
| Integrated management | System operation intelligence | √ | | | |
| | Adoption of innovative design and equipment | √ | √ | | |
| | System optimisation | | √ | | |
| | Environmental governance | Restore water body and ecological environment | √ | | √ |
| | | Improve the quality of surface water | √ | | √ |
| | | Water security and sanitation | √ | | √ |
| | | Increase biological diversity | √ | √ | |
| | | Restore ecological habitat | √ | √ | |
| | Disaster resistance | Protect areas of high ecological values | √ | | |
| | | Improve the groundwater quality | √ | | |
| Groundwater recharge | | √ | | √ | |
| Watershed-wide impact | | | | √ | |
| Flood control and defense | | √ | √ | | |
| Resource efficiency | Drought mitigation and defense | √ | | | |
| | Stormwater harvesting and reuse | √ | √ | √ | |
| | Reduce cost of grey infrastructure | | | | |
| | Pipe damage control | | | √ | |
| | Reduce energy consumption | | | | |
| | Reduce greenhouse gases emission | √ | | | |
| | Reduce potable water demand | √ | | | |
| Social engagement | Citizen's willingness to pay | √ | | | |
| | Increase waterside activities | √ | √ | | |
| | Increase public educational significance | √ | √ | | |
| | Increase public activity space | √ | | | |
| | Shared ownership, management and responsibility of the public | √ | | | |
| | Preparedness for and response to extreme weather events | √ | | | |
| | Local community participation in water-related planning | √ | | | |
| | Community activities organisation | | √ | | |
| Effective governance | Information transparency | √ | | | |
| | Water-related business opportunity (industrialisation) | √ | | √ | |
| | Assessment of professional capacities | √ | | | |
| | Inter-disciplinary, inter-agency cooperation | √ | | | |
| | Participation of stakeholders and policy makers. | √ | | | |
| | Assessment of leadership capability | √ | | | |
| | Multi-sectoral benefits | √ | | | |

Table 2. Cont.

| Objective Classification | Specific Objective | Indicators | Australia WSC | Singapore ABC Waters Program | China SCC | |
|-------------------------------------|---------------------------------|--|-----------------------------|------------------------------|-----------|--|
| City development | Urban space quality improvement | City livability and landscape improvement | √ | | | |
| | | Consider water as a major factor of urban planning and design | √ | | | |
| | | Activate blue-green space | √ | | √ | |
| | | Increase vegetation coverage | √ | √ | √ | |
| | | Improve city's aesthetics | | √ | | |
| | City resilience enhancement | Public infrastructure renewal | Increase recreational space | √ | | |
| | | | Increase property values | | | |
| | | Construction of multifunctional water-related infrastructure | √ | | | |
| | | Accessibility and affordability of water-related public facilities | √ | | | |
| | | Adaptability to extreme weather | √ | √ | | |
| Urban heat island effect mitigation | √ | | √ | | | |

Note: WSC—Water Sensitive Cities; ABC—Active, Beautiful, Clean; SCC—Sponge City Construction.

Following the above, one can see that the objectives and evaluation standards currently established by SCC mostly focus on operational capacity of the stormwater system and the ecological benefits that it can bring. Little is provided to assess whether SSWM initiatives are applied in the appropriate context such as climatic zones, site condition, economy, technology, society, governance, and urban development. These objectives and indicators have been mentioned to varying degrees in SSWM standards of other international organisations and countries. Hence, the comparison shows that the comprehensive evaluation of SSWM in China, as well as many other developing countries, should consider the relationship between SSWM with environment, economics, technology, management, and city development in the future. On the other hand, the evaluation goal and indicator setting in the proposed comprehensive evaluation framework of SSWM should cover the most goals and indicators set by different organisations and countries.

3.3. Procedures and Methods for Comprehensive Evaluation of SSWM

3.3.1. Procedures for Comprehensive Evaluation of SSWM

Undoubtedly, the establishment of comprehensive evaluation framework for SSWM will play an important guiding role in implementation of SSWM projects. Selecting appropriate evaluation goals and indicators from the framework is a crucial step when evaluating various SSWM options and monitoring of existing projects. Decision makers will be able to analyse and report the evaluation results by scoring the selected indicators directly and subjectively. However, to avoid errors and reduce subjectivity of this individual perspective evaluation method, a more objective and inclusive decision-making process is necessary. A clear procedure for the comprehensive evaluation of SSWM can reduce the evaluation time and facilitate the decision-making process. Many researchers have summarised the evaluation procedure based on different locations and contexts [17,19,22].

Based on an extensive review, the essential steps of a comprehensive performance and benefit evaluation of SSWM are summarised in Figure 4. The procedures are as follows:

1. Investigating and analysing construction site conditions (hydraulic and hydrology situation, land use type, drainage layout, etc.). The aim is to identify the existing water-related issues and appreciate the need for SWM.
2. Determining the primary goals of SWM according to site analysis. The primary goals can be set based on local management standards to meet the minimum requirement for SWM. For example, annual total runoff control rate should not be less than 75% for reconstruction project in China [17].
3. Developing different SSWM scenarios for future projects or analysing the condition of existing projects. For future projects, different SSWM strategies and layouts can be formulated to meet the primary goals. For existing projects, a detailed analysis of the project conditions can provide basic monitoring data for further evaluation of the project performance.

4. Selecting suitable evaluation goals and indicators from the proposed comprehensive evaluation framework (Table 1). It is necessary to consider data availability, relevance, sensitivity and other attributes when selecting indicators [110]. To achieve a comprehensive evaluation from various aspects, representative indicators should be selected from each objective level.
5. Using effective methods/tools to assign values or provide simulated/monitored data for the selected indicators. In this step, the objectivity of the evaluation can be enhanced, and errors caused by individual evaluation methods should be minimised.
6. Valuing and normalising the selected evaluation indicators on a unified scale. Different valuing methods might have different measurement units for the same indicator. Therefore, evaluation result of each indicator should be provided after normalisation.
7. Evaluating and scoring SSWM scenarios/projects. Performance and benefits of the SSWM scenarios/projects can be evaluated comprehensively with respect to the selected indicators from various perspectives.
8. Obtaining and reporting the comprehensive evaluation results. Inclusive and reliable evaluation results can be provided at the final step to guide SSWM construction. For future projects, the optimal design/layout can be determined by comparing and analysing the evaluation outcome of each scenario. For existing projects, evaluation results can assist in monitoring and improving the performance of SSWM systems.

3.3.2. Methods for Comprehensive Evaluation of SSWM

Evaluation indicators are classified into quantitative and qualitative variables in the proposed evaluation framework (Table 1). If indicators can be quantitatively simulated and evaluated using effective methods and tools during decision-making process, then the evaluation time can be greatly reduced, and scientific support can be offered for the scheme. Scholars have conducted extensive systematic studies on quantitative evaluation methods for various indicators. For example, when assessing the control capacity of runoff volume, total runoff reduction rate, peak discharge reduction and peak flow delay can be simulated by models [111]. In terms of complex economic benefits, life cycle assessment can be adopted to estimate the cost of the facilities, operation and maintenance at all stages [89,112]. In addition, cost-effectiveness analysis is an important method to assess varying SSWM options based on the relationship between system performance and costs [9,113].

Some indicators, like most indicators under social engagement and urban development objectives in the proposed evaluation framework, are qualitative variables. In many cases, both the quantitative and qualitative indicators need to be considered to ensure that the evaluation aspects are comprehensive. Generally, one of the most common methods for valuing qualitative variables is to use experts' opinions and stakeholders' preferences [96,114]. Experts and/or stakeholders can provide their preferences on the indicators' weights. Thereby, the values and priorities of these indicators can be represented. Another valuation method is to convert indicator importance into monetary value. However, this method might be used only for benefit-related indicators, such as the indicators of improving city aesthetics, increasing recreational space as well as increasing property values. Monetary values of various water-related benefits can be found in Gunawardena et al. [115]. In terms of social benefits, there are generally two quantitative methods to elicit people's willingness to pay (WTP)—namely, revealed preference techniques to quantify people's preferences by observing their behaviours in monetisation, and stated preference methods to reveal people's potential preferences by investigation/interviewing [57,116,117]. Following this, benefit transfer methods might be needed to predict values for specific sites from original study sites [118].

Both quantitative and qualitative indicators can be further comprehensively evaluated considering uncertainty, sensitivity, conflicting interests and complex interactions [119]. Commonly, there are two types of evaluation methods which are widely used in this step. One is multi criteria analysis (MCA), which uses statistical methods, such as analytic hierarchy process, principal component analysis and correlation methods, to weight multiple indicators. The obtained evaluation results from MCA may

be varying when using different multivariate methods with small amount of data [25,120]. This will provide decision makers a clear and straight forward comparison of the evaluation results.

When valuing the selected indicators, different measuring units need to be normalised. Common normalisation methods for MCA include linear scale method, vector normalisation and extreme value method [53]. Another approach is benefit cost analysis (BCA) which assigns monetary values to each indicator and predicts the net present value of the proposed investment throughout the lifespan. In BCA approach, all indicators need to be expressed in monetary terms and professional advices might be required from economic experts [121,122]. Finally, each SSWM scenario/project can be comprehensively evaluated and an overall evaluation score can be provided by the selected indicators. The above methods are integrated with the evaluation procedures in Figure 4.

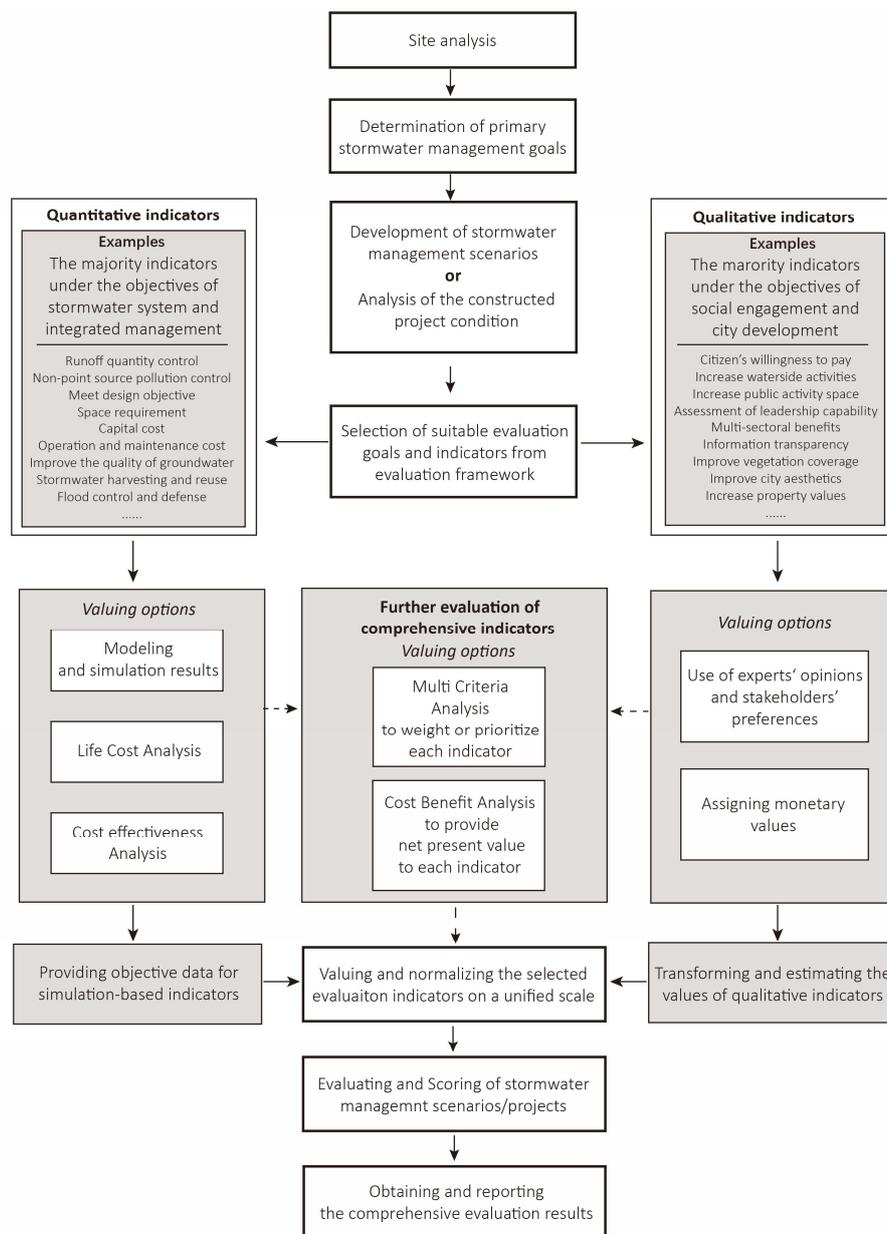


Figure 4. Procedure and methods for comprehensive evaluation of SSWM.

3.3.3. Existing Decision Support Tools for Evaluation of SSWM

Organisations across the world have developed a variety of decision support tools for quantitative evaluation of SSWM to ensure that SSWM can perform well from the conceptual stage to implementation, operation, and maintenance. However, different models have different focuses. For example, though the Storm Water Management Model (SWMM) developed by the US can simulate changes of total annual runoff and pollutant loads in SWM systems [123], other associated evaluation software is required to evaluate system optimisation and economic benefits [11]. The Australian Model for Urban Stormwater Improvement Conceptualisation (MUSIC) focuses on overall evaluation and optimisation of the preliminary concept planning of SWM systems, but the event mean concentrations (EMCs) needed by MUSIC might lead to large deviations between the simulated and observed results of runoff quality [124]. Nevertheless, MUSIC model can help Australian government, developers and relevant consultants verify their design plan quickly in complying with local guidelines and requirements that has been set in advance through MUSIC-link [125]. In recent years, many scholars have begun to simulate and evaluate Sponge City practices with various tools, including SWMM, System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), MIKE URBAN, and Infoworks. For instance, these tools have been used for the simulation of runoff volume control and pollutants removal, analysis of flood risk and evaluation of cost-effectiveness of LID measures [17,126–128].

Based on the functions and focuses of the decision support tools for SWM, scholars have adopted various methods to classify them. For example, Bach et al. [28] classified models focusing on integrated urban water management into four levels according to their degree of integration. Lerer et al. [129] classified various tools according to the types of question types (how much, where, which) that can be answered by the decision-making tools, and explained the functions, limitations and differences of tools in use. Zhou [30] compared and discussed the functions of a variety of decision-aid tools from four aspects, which are water quality, water quantity, sustainable drainage facilities and spatial planning. Jayasooriya and Ng [29] screened 10 models for detailed description based on popularity and classified them into three types according to their functions. Kuller et al. [23] proposed a new framework based on the principles of involving multiple factors, scales and stakeholders to classify decision support tools into three levels and to support better planning and implementation of WSUD.

3.3.4. Selection of Suitable Decision Support Tools: SCC as an Example

There are a variety of decision support tools that can assist decision makers in assessing the performance and benefit of SSWM. Appropriate tools can effectively facilitate the evaluation process and holistically develop SSWM strategies. However, in developing countries, limited decision support tools are developed based on national conditions. Therefore, the selection of most suitable decision support tools for context specific SSWM is necessary.

China, as the fourth largest country in the world, has huge differences in geographical environments, precipitation conditions, hydrological characteristic, and water resources utilisation between different regions. The applicability and adaptability of the decision support tools in China can provide a reference to other developing countries.

Hence, in this section, several well-known decision support tools are selected to compare their adaptability and applicability for the comprehensive evaluation of SCC. The rationale for screening appropriate decision support tools is illustrated in Figure 5. First, an extensive literature review of existing tools is conducted to screen tools that are widely accepted and used by researchers. The selection of appropriate tools in this review follows three principles: (1) Applicability in SCC; (2) the possibility of these tools to be used in SCC; and (3) the value of these tools for developing new decision support tools for SCC. A wide range of decision support tools has been developed for assisting SSWM. However, one major limitation of these tools is that they might only be applied within a specific country or region. Understanding the calculation algorithms and developing philosophies of these tools might provide critical insights into the future development of decision support tools.

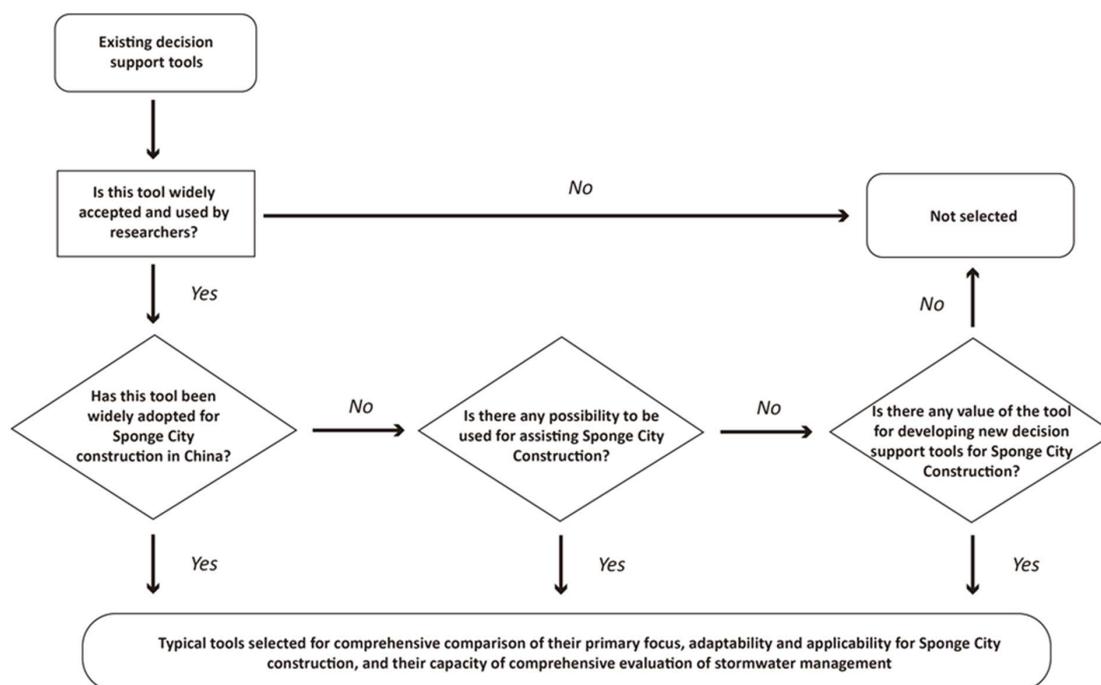


Figure 5. The flow chart of screening suitable decision support tools.

Based on the screening method of the decision support tools mentioned above, eight are selected for a comprehensive comparison of their suitability in assisting SCC (Table 3). These include SWMM, SUSTAIN, MIKE URBAN, Infoworks, MUSIC, Dynamic Adaption for Enabling City Evolution for Water (DAnCE4Water), Urban Biophysical Environments and Technologies Simulator (UrbanBEATS), and CALVIN. These tools are widely used by researchers and have the potential to be used for assisting implementation. These eight tools cover the scope of model classification proposed by Bach et al. [28], which enhances their representativeness. Comparison aspects include classification, primary focus, adaptability and applicability for assisting SCC, as well as the comprehensive evaluation capacity for SWM. Another parallel comparison of these eight tools (Table S2) is provided for assessing the capacity of comprehensive evaluation of SSWM by referring to their user manuals and related studies.

The comparison demonstrates that all the eight tools can evaluate the runoff quantity control in terms of whether the stormwater system meets the designed objectives and the operational reliability of the system. Nevertheless, the comparison shows that although SWMM, Infoworks, SUSTAIN, and MIKE URBAN are widely applied in SCC, their capacity of comprehensive evaluation is limited. For example, Infoworks and MIKE URBAN mainly focus on the flood control and the performance of drainage system. There is a lack of studies on the applicability of CALVIN, UrbanBEATS, and DAnCE4Water. However, the philosophy and algorithm adopted by these tools are inspiring to the future model development for SCC. For instance, the water shortage loss function adopted by CALVIN can predict overall urban water use in the future based on population growth projections and urban water demands [130]. This method gives insights into how to guide SCC in drought areas in China. The stochastic procedural algorithm adopted in UrbanBEATS can conceptualise various characteristics of urban environment to achieve a better water infrastructure planning [24]. This provides insights into how to establish links between SCC and urban planning and design. The developing philosophy of DAnCE4Water involves various transitions of urban water management in one single model. It considers interactions between water infrastructure, city development and societal need to predict possible future scenarios of urban water management [131]. This provides some ideas of exploring consequences of SCC under deep uncertainties in the future. The use of MUSIC for SCC is limited, but it is applicable when the long-term climate data can be provided.

For the comprehensive evaluation capacity of these tools, MUSIC, UrbanBEATS, and DAnCE4Water can simulate comprehensive results from a range of different perspectives.

From the tool comparison in the proposed comprehensive evaluation framework (Table S2), it is further revealed that all the eight decision support tools cannot measure most qualitative indicators under the objectives of social engagement and urban development. For these indicators, methods like using experts' opinions, stakeholders' preferences and assigning monetary values that mentioned in Section 3.3.2 can be used as valuing options. Furthermore, methods like MCA and BCA can be adopted for evaluating both qualitative and quantitative indicators to provide comprehensive evaluation outcomes. A set of related tools were reported by Linkov and Moberg [132] and Pannell [133] to help decision makers in selecting best solutions for environmental problems, but very few of these tools focus on SSWM. In this regard, tools like E²STORMED which is based on MCA to quantify decision criteria of SSWM [55] and INFFEWS which is based on BCA focuses on assessing water sensitive outcomes economically [134] have been developed in recent years to provide integrated and robust evaluation of SSWM. However, these two tools generally have limited hydrologic simulation ability and their applicability need to be widely tested. For SCC in China, there has been an increasing trend in using MCA rather than BCA as the final step to weight the indicators, score strategies or projects, and provide relatively objective evaluation outcomes [17,120]. The limited use of BCA in SCC is mainly because the research on monetary values of various benefits brought by SCC is relatively limited.

Development of more integrated tools is therefore needed. Instead of focusing on hydrologic models only, future tools should adopt broader approach to embrace measurement methods of diverse indicators such as social engagement and urban development. For instance, a simplified MCA or BCA can be added as a function in future tools to assist in making more inclusive decisions. Furthermore, better user-friendliness, transparency, multi-stakeholder involvement, and data collection are also important to enhance the capability of effective communication of future tools across various disciplines.

Table 3. Comparison of eight decision aid tools in assisting SCC.

| Classification | Tool Name | Primary Focus | Adaptability and Applicability in SCC | Comprehensive Evaluation Ability of SSWM | Main References |
|----------------|-------------|--|--|---|-----------------|
| IUDMs | SWMM | Hydrological and hydraulic simulation of SWM performance | Widely used in runoff quantity control performance assessment | Evaluation of flood control and defense Has to be integrated with other tools or methods | [11,17,21] |
| | Infoworks | Hydrodynamic simulation of flow by drainage system | Widely used in flood control simulation | Evaluation of flood control and defense Performance of underground drainage network | [128,135,136] |
| IWSMs | CALVIN | Integrated water cycle management for California river basin | None This model is based on the flood and drought characteristics of California. However, the urban water shortage loss function applied in CALVIN can provide critical insights into SWM simulation in drought area in China. | Evaluation of flood control and defense Evaluation of drought mitigation and defense Analysis of total water system including the relations to surface and groundwater reservoirs, canals, rivers, water demand and supply Economic value evaluation | [130,137,138] |
| IUWCMs | MUSIC | Conceptual planning and design of WSUD | Limited Mainly due to built-in climate data which is only for Australia and New Zealand. But the size and performance of SSWM measures in China can be simulated with adequate climate data. | Calculation of groundwater recharge; Evaluation of stormwater harvesting and reuse rate Providing platform for stakeholder engagement Life Cycle Cost Analysis | [125,139–141] |
| | MIKE URBAN | Hydrodynamic simulation of flow by drainage system | Widely used in flood control simulation | Evaluation of flood control and defense Performance of underground drainage network Calculation of water demand and supply | [126,142] |
| | SUSTAIN | Planning and optimisation of BMPs | Widely used BMPs selection and optimisation | Evaluation of flood control and defense Evaluation of SWM systems site adaptability Cost-effectiveness analysis | [143–145] |
| | UrbanBEATS | Spatial planning and design of WSUD placement | None The stochastic procedural algorithm adopted in UrbanBEATS is inspiring. The algorithm considers varying demographics, land uses and other urban characteristics in determining WSUD placement. It provides critical insights into how to integrate SWM into urban planning and design. | Calculation of space requirements of SSWM systems Evaluation of site adaptability of SSWM systems Evaluation of self-sufficiency of SSWM systems; Evaluation of stormwater harvesting and reuse rate; Calculation of potable water supply Economic evaluation module; | [24,146] |
| IUWSMs | DAnCE4Water | Conceptual planning and design of urban water system scenarios | None The philosophy of integrating urban water system, urban development and the societal system is inspiring. Creates a dynamic simulation and interaction environment between water infrastructure, city development and society to explore possible future scenarios of urban water management. Provides critical insights on how to identify the most robust and suitable SSWM strategies to plan against future uncertainties. | Evaluation of self-sufficiency of SWM systems Evaluation of urban heat island effect mitigation Information transparency Evaluation of stormwater harvesting and reuse rate Providing platform for stakeholder engagement Simulation of future urban development scenarios | [131,147] |

Note: IUDMs—integrated urban drainage models; IWSMs—integrated water supply models; IUWCMs—integrated urban water cycle models; IUWSMs—integrated urban water system models. The classification method is adopted from Bach et al. [28].

4. Conclusions

This study conducts an extensive review on comprehensive evaluation of SSWM and proposes a new evaluation framework for assessing the performance and benefits of SSWM in developing countries. In particular, the existing SSWM evaluation systems in the US, Europe, Australia, Singapore, China, India, and Malaysia provide critical insights into developing this evaluation framework. The framework proposes four management objectives and the corresponding evaluation indicators in a broad perspective based on the current development situation in most developing countries. This can assist decision makers in improving the quality of SSWM implementation in the future.

Establishment of comprehensive evaluation framework for SSWM does not mean that all the objectives and indicators suggested in the framework should be adopted. Instead, it should be regarded as an evaluation guide at early stage to assist stakeholders and decision makers in screening and selection of optimal SSWM strategies based on their respective geographical and operational context. Considering various national circumstances in developing countries, suitable objectives and corresponding indicators in the proposed framework can be selected based on local characteristics. Then benchmarks for different SSWM strategies and existing projects monitoring programmes can be achieved during the decision-making process.

This review further summarises the procedures for comprehensive evaluation of SSWM. Different types of evaluation methods are also classified to provide recommendations for decision makers on how to screen optimal SSWM strategies and improve the performance of existing projects. Moreover, eight decision support tools are compared in this review to assess their adaptability and applicability in developing countries. Lastly, future development of assessment tools for SSWM in developing countries should also take various factors into consideration. These factors include built-in climate data, user-friendly interface, and the ability to assess multiple indicators from various perspectives, so that researchers and practitioners with different educational and professional backgrounds can participate in the decision-making process. Thereby, the science-based development of SWM systems in developing countries can be accelerated in the future.

Further research is necessary to enhance the applicability and feasibility of the proposed comprehensive evaluation framework. In addition, selected decision support tools in this study mainly focus on hydrologic models and future study should try to explore broader approach for measurement methods of more diverse indicators, especially qualitative ones. Therefore, development of more integrated tools is needed for the implementation of comprehensive evaluation of SSWM.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/12/5/1231/s1>, Table S1. Stormwater management objective comparison between international and national organizations.; Table S2. Decision support tools comparison under comprehensive evaluation framework for Sponge City.

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