Review

A new model framework for sponge city implementation: Emerging challenges and future developments

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A B S T R A C T

Sponge City concept is emerging as a new kind of integrated urban water systems, which aims to address urban water problems. However, its implementation has encountered a variety of challenges. The lack of an integrated comprehensive model to assist Sponge City planning, implementation and life cycle assessment is one of the most challenging factors. This review briefly analyses the opportunity of existing urban water management models and discusses the limitation of recent studies in the application of current integrated models for Sponge City implementation. Furthermore, it proposes a new Sponge City model framework by integrating four main sub- models including MIKE-URBAN, LCA, W045-BEST, and MCA in which environmental, social, and economic aspects of Sponge City infrastructure options are simulated. The new structure of Sponge City model that includes the sub-model layer, input layer, module layer, output layer, and programing language layer is also illustrated. Therefore, the proposed model could be applied to optimize different Sponge City practices by not only assessing the drainage capacity of stormwater infrastructure but also pays attention to multi-criteria analysis of urban water system (including the possibility of assessing Sponge City ecosystem services for urban areas and water-shed areas) as well. Balancing between simplification and innovation of integrated models, increasing the effi-ciency of spatial data sharing systems, defining the acceptability of model complexity level and improving the corporation of multiple stakeholders emphasizing on possible future directions of a proper Sponge City design and construction model.

1. Introduction

Concerns about water resources sustainability have increased worldwide due to population growth and urbanization problems (Carle et al., 2005; Lee Joong and Heaney James, 2003). According to United Nations (2010) statistics, approximately 80% of the world's total population is predicted to reside in urban zones by 2030. Studies on the complexity of urban water systems and new kinds of sustainable urban water management concepts are becoming prolific in hydrological scientific research (Salvadore et al., 2015). Today's conventional urban water management systems, where all components are constructed independently, do not possess the capabilities for functioning effectively especially in terms of urbanization and climate change requirements (Butler and Schutze, 2005; rauch et al., 2005). Examples of a diversified approach to achieve an integrated urban water management system (IUWM) include Best Management Practices (BMPs) in the United States, Water Sensitive Urban Design in Australia, Sustainable Urban Drainage System (SuDS) in the United Kingdom, and Sponge City in China. The objectives of these systems are to (1) pay good attention to all components of the system so that they work well, (2) implement water systems in both centralized and decentralized contexts, and (3) create multiple ecologically friendly services in urban zones including: water resources conservation, flooding disaster mitigation, relevant amenities and micro-climate improvements (Bach et al., 2014; Brown et al., 2009; Nguyen et al., 2018).

Integrated urban water models have been developed and their focus is on interactions amongst all components of urban water systems management. The transition to integrated urban water models specifically focuses on the interactions between urban water systems, which should be the priority of urban development and societal factors (Rauch et al., 2017Deletic et al., 2019). As early as the 1970s, research in integrated urban water systems was undertaken in Glatt Valley, Switzerland (Gujer et al., 1982) but the research did not document any modelling results. At the first INTERURBA conference in 1993, emerging research on integrated urban water models was initially reported that marked a milestone in the development of such integrated models (Lijklema et al., 1993).

Integrated urban water models are essential tools for planning and management of urban drainage systems. In 1971, US Environmental Protection Agency (EPA) developed the Storm Water Management Model (SWMM) which is the one of most popular tool for the evaluation of stormwater management systems (Deng et al., 2018). A range of commercial stormwater models such as Mike-Urban, InfoWorks, and DAnCE4Water, which were built based on SWMM, are commonly used worldwide. Although, the models have brought benefits for planners and policymakers, these models encounter many challenges because urban water systems are, in fact, very complex. Moreover, the lack of understanding of interactions between all components, that is, understanding the whole system, and the expense of data requirements and limitations in computational hardware have affected the model's performance (Candela et al., 2011; rauch et al., 2005; Vanrolleghem et al., 2005). Having the insufficient understanding of model uncertainties also contributes to the model being at risk of failure (Dotto et al., 2011). However, with the recent advances in software package capabilities and technologies, these models have performed better in recent years. Integrated models gained momentum by combining and improving conventional single model packages in the past few decades (Bach et al., 2014).

Sponge City (SC) implementation promises many benefits for our society in general and urban areas in developing countries in particular (Chan et al., 2018; Jia et al., 2017; Li et al., 2017; Mei et al., 2018; Zhang and Chui, 2019; Zhang et al., 2018). The Sponge City implementation process consists of four phases (Fig. 1). Phase 1 is analysing regional context including water issues and existing water management to identify the demand for Sponge City implementation. The next phase is developing scenarios based on climate change scenarios, population growth scenarios, and water demand scenarios. Phase 3 indicates the selection and development of modelling software to simulate the performance of Sponge City measurement. The final phase is the planning and implementation of Sponge City.

To obtain the promising benefits of Sponge City, planning and development of Sponge City measurements is important. However, it is a difficult work as an urban water system is highly complex and uncertain in the future, with a variety of aspects to be scrutinized, including urban development, urban water infrastructure planning, and measurement feasibility evaluation. An interdisciplinary approach that is developing an integrated Sponge City model to deal with interdisciplinary planning problems is necessary. Sponge City construction in China owns its unique aspect compared to other concepts (e.g., SuDS, WSUD, BPMs) as the Sponge City not only addresses stormwater but also tackles flooding disasters, water restoration, and water purification. Nevertheless, the simulation and evaluation tools to predict the comprehensive Sponge City's performance are still limited. This necessitates the novel development of an integrated model to assess the efficiency and sustainability of this new kind of urban water management scheme -Sponge City- where social, environmental, and human health associated factors are taken into account. This model should be sufficient for representing real urban water environments, and be able to make these integrated approaches for the Sponge City concept to be feasible. Sponge City models should be able to integrate the sub-models and include the following: (1) identify suitable areas for Sponge City construction; (2) compare green infrastructures, urban development, and climate change scenarios; (3) simulate the best ways to reduce stormwater runoff, mitigate flooding and improve water quality; and (4) ensure that the Sponge City is environmentally friendly. Doing so will make life easier for all the stakeholders and communities and will assist the implementation of Sponge City in a large-scale.

A range of papers illustrates the development, barriers, and opportunities of integrated urban water models. Bach et al. (2014) reviewed 30 years of research and the adoption of integrated urban water models and classified these models into four groups according to their degrees of integration. The review paper also mentioned that user-friendliness, administrative fragmentation, model complexity, and communication are crucial factors, which have affected the uptake of integrated urban water models (Bach et al., 2014). Zomorodian et al. (2018) analyzed the feasibility of System Dynamics (SD) application on addressing the complexity of integrated urban water management modelling. Salvadore et al. (2015) compared 43 hydrological modelling approaches and identified a blueprint for future urban hydrological modelling development. The study defined that the high degree of uncertainty will be reduced by the application of remote sensing data, measurement model parameters and spatial calibration methods. Recently, some integrated

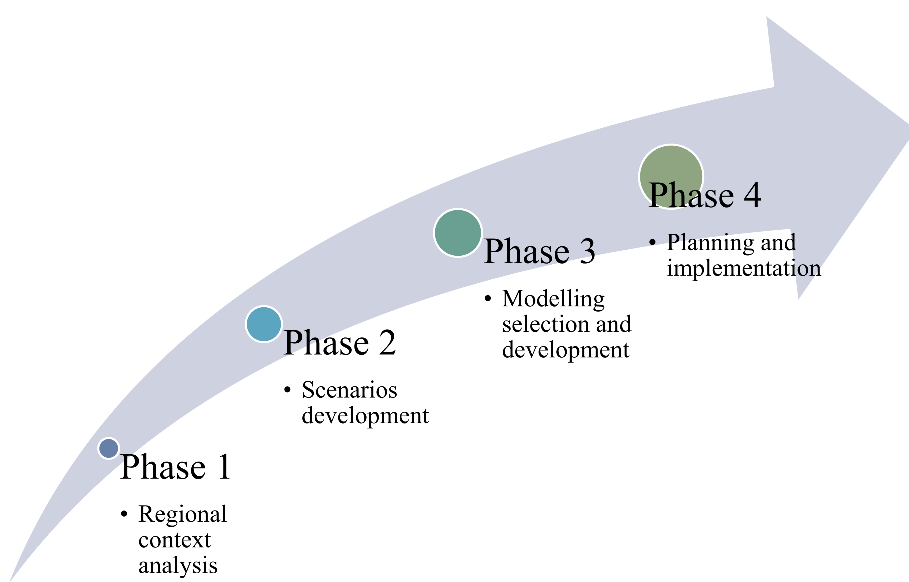

Fig. 1. Summary of Sponge City implementation process.

models were developed for assessing the Sponge City performance. SWMM and the Analytical Hierarchy Process (AHP) method, for example, served to quantify the benefits of LID practices in the Sponge City (Li et al., 2019). An energy analysis and GIS model were combined for application to selected pivotal areas for Sponge City construction (Zhao et al., 2018). Besides, spatial data like Landsat-8TIRS was used to evaluate the effects of LID practices in Sponge City on thermal landscape (Hou et al., 2019). An integrated model named Uwater was innovated by the integration of SWMM and spatial data management tools in GIS, which is capable to evaluate drainage capacity of the stormwater system and design Sponge City infrastructures (Deng et al., 2018). All these studies provide useful approaches to integrated modelling development and their application to water management. However, there is still a lack of studies with an integrated view on the development of a comprehensive integrated model for Sponge City implementation.

This paper focuses on a critical analysis of the previous literature on integrated models relating to Sponge City approaches towards establishing a new Sponge City model that functions well. This paper aims to: (1) analyse the opportunities and barriers of current Sponge City-based model, (2) provide new classification of integrated urban water modelling, (3) build a new Sponge City conceptual model framework to better address the multiple sustainability objectives of Sponge City concept, (3) clarify emerging challenges and opportunities of Sponge City model development, and (4) suggest future study/research possibilities on the Sponge City model.

2. Possible application of conventional models for sponge city

2.1. Possible application of current integrated urban water models

The majority of integrated urban water models have focused on evaluating potential hydrological performance and water quality assessment of urban water management solutions while neglecting their full assessment of environmental benefits, economic benefits and social benefits such as the improvement to human health, economic growth, crime rate reduction (Zomorodian et al., 2018). Developed countries have developed their models to support their urban water management program. The United State developed many models including SWMM, MIKE, SUSTAIN, MapShed, SWAT, PondNet, etc. to support the Best Management Practices program. Some models were built by the United Kingdom such as UWOT, Sobek-Urban, and WaterMet2 to assist Sustainable Urban Drainage Systems. To improve the efficiency of the Water Sensitive Urban Design program, Australia has innovated some effective integrated models including DAnCE4Water, Urban Bests, UrbanCycle, UrbanDeveloper, and Aquacycle. DAnCE4Water is able to assess a range of integrated planning, various urban water infrastructure systems, and the dynamics of social systems (Löwe et al., 2017; Rauch et al., 2017; Zischg et al., 2019; Urich et al., 2013).

There are three general methods in which to develop integrated models: (1) modifying conventional integrated models; (2) combining existing sub-integrated models into more comprehensively integrated ones; and (3) innovating new integrated models. Integrated urban water models are normally constructed by computationally linking a sequence of two or more sub-models that illustrate the different components of urban water bodies (Rauch et al., 2002). Each integrated model has developed its own distinct approaches and methods according to Bach et al. (2014). A variety of processes are involved in urban water management and these are hydrology, hydraulics, pollution, treatment, downstream impact, storage-behaviour, water consumption, groundwater interaction and flooding; and different urban water components, i.e. water transportation network, treatment plants, decentralized technologies, receiving water bodies and built environments. All these processes need to be considered for integrated modelling (Bach et al., 2014). Integrated modelling is based on several types of model applications including life cycle assessment, operations and control, risk and impact assessment, social implications, economic issues, ecological implications, conceptual design, and strategic planning.

Sub-models of integrated urban water management (IUWM) models might include urban water treatment models, urban wastewater collection models, urban wastewater treatment models, urban rainfall and surface runoff models, river models, urban water distribution models, environmental assessment models, economic assessment models, and social assessment models. Integrated urban water models can be divided into various groups according to their functions and their integration levels. According to their function, they could be classified IUWM models into integrated urban water treatment models or integrated urban water quality models, integrated urban water supply models, integrated urban water multi-criteria analysis models and integrated urban water management models, which describe in Fig. 2.

On the other hand, according to Bach et al. (2014), integrated urban water models were divided into four groups based on different integration levels. These are: (i) integrated component-based models (ICBMs); (ii) integrated urban drainage models (IUDMs) of Integrated Water Supply Models (IWSMs); (iii) Integrated Urban Water Cycle Models (IUWCMs); and (iv) integrated Urban Water System Models (IUWSMs) (Fig. 3). While ICBMs represent the lowest level of integration, IUWSMs are the highest level and this emphasizes the importance of water flows in the urban environment. For the four groups noted above, the scope of these models is broader.

One limitation of integrated water models is that they are not able to evaluate comprehensively economic, social, environmental benefits and ecosystem services of urban water strategies, while stakeholders tend to depend on this evaluation to make their decisions (Castonguay et al., 2018) (Fig. 4). For example, ICBM models including BSM2, EPANET and Stimela are considered as a form of plant-wide integration that does not pay attention to flooding problems of urban water. IUDMs and IUWCMs such as InforWorks CS, SWMM, and MIKE-URBAN only link between urban development and urban water infrastructure and do not consider the environmental, economic and social of urban water management infrastructures (Schellart et al., 2010; Burger et al., 2014; DHI, 2009). Although the DAnCE4Water model was defined as the highest integration level model, it only considers partially the interactions between urban water infrastructure and environmental, social and economic aspects.

Moreover, there are several key barriers from case studies that applied the existing integrated water management models such as SWMM, LCA and SUSTAIN for the assessment of Sponge City implementation's performanceGao et al., 2015. They are (1) the uncertainty of spatial and temporal data, (2) the limitations in the comprehensive assessment of ecosystem services of Sponge City, (3) the lack of the assessment of long-term benefits of Sponge City measurement, and (4) limitation in simulation with long-time series data such as rainfall data. Therefore, the development of a comprehensive integrated Sponge City model will be significantly reduced these limitations, which is summarised in Table 1.

2.2. Multiple benefits assessment models for sponge city

2.2.1. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) has been applied popularly to evaluate environmental impacts related to urban water technologies including stormwater technologies, water treatment technologies and integrated urban water management system infrastructures (Bonoli et al., 2019; Byrne et al., 2017). LCA methodology has used to evaluate and compare the environmental impacts of different urban water infrastructure practices. It is important tool to identify environmental issues in terms of sustainable urban water planning. Based on the LCA results, decision-makers can provide appropriate strategies by balancing the urban water infrastructure's impacts with the environmental protection. Although the acceptance of stakeholders often needs to consider aspects of economic, social, environmental and human health implications, there is currently a lack of studies, which pay attention to urban water

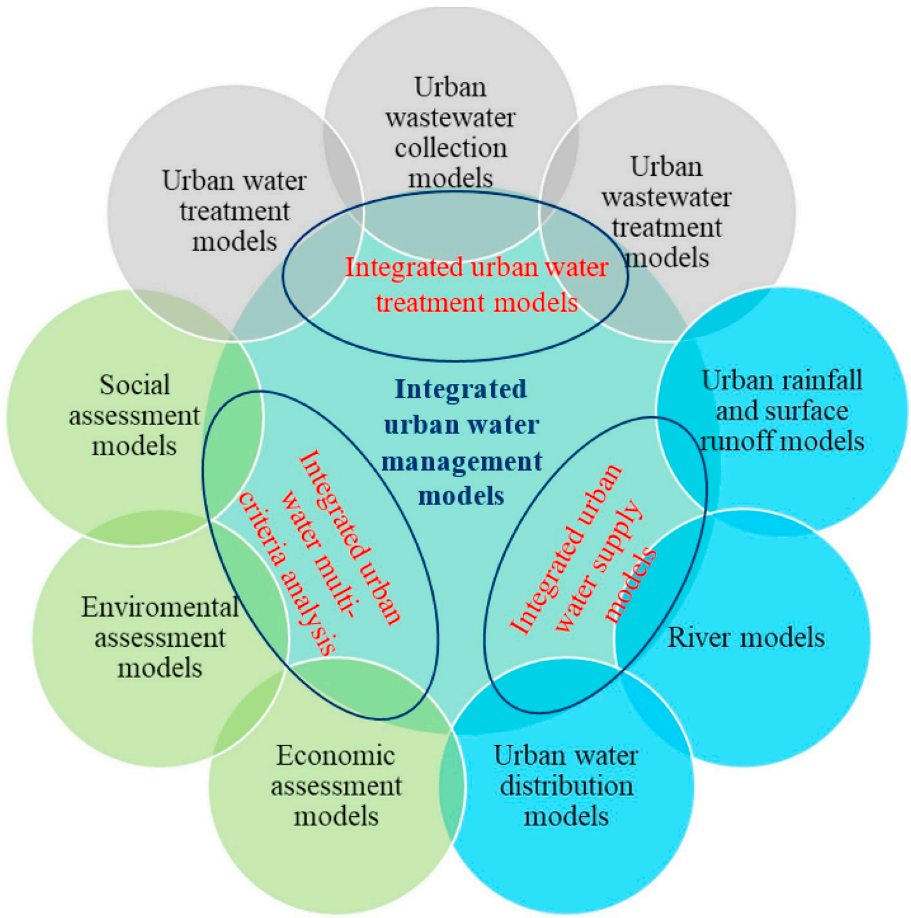

Fig. 2. Sub-models of integrated urban water modelling.

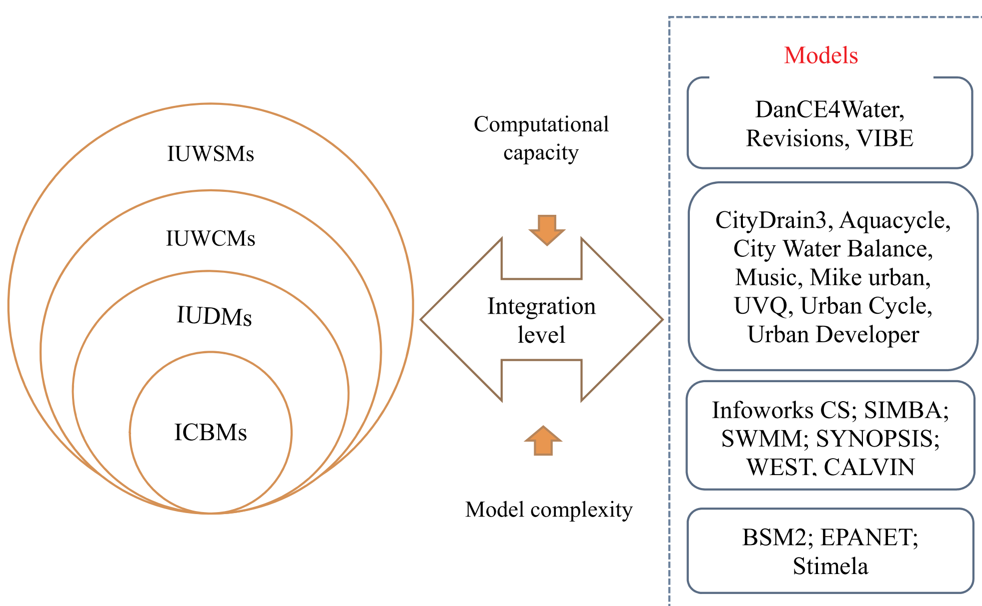

Fig. 3. Classification of integrated urban water models (adapted from Bach et al., 2014).

management practices with their assessments. The broader sustainability of LCA framework should include four steps (Fig. 5): (1) goal and scope definitions; (2) life cycle inventory analysis (LCI); (3) Life cycle impact assessment; and (4) interpretation (Byrne et al., 2017).

2.2.2. *Ecosystem services assessment (ESA)*

Sponge City promises to greatly contribute to mitigate urban water issues like flooding and water pollution which ensure the provisioning of urban water ecosystem services. The approach of urban water ecosystem services have emerged recently. Ecosystem services are considered as

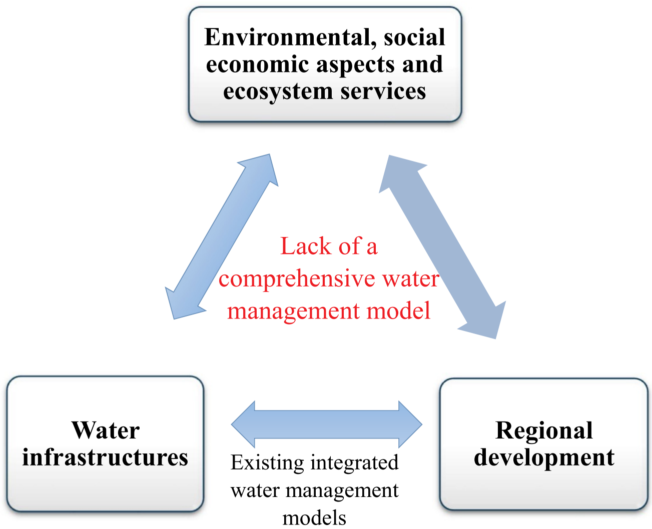

Fig. 4. The limitation of existing integrated water management models.

the direct and indirect benefits of ecosystems to human well-being (Grizzetti et al., 2016) (Fig. 6). The understanding of ecosystem services of Sponge City will assist their implementation more sustainably. It is difficult to value ecosystem services of Sponge City by quantifiable outcomes. In addition, evaluating the benefits needs substantial time and resources.

The indicators of Sponge City ecosystem services are classified into three aspects ranging from environmental aspect, economic aspect to social aspect and three ecosystem service categories including regulating services, provisioning services, and cultural services (Fig. 6). Recently, the model of Benefits of SuDs Tool (W045 BeST) was innovated to assess Sustainable Drainage Systems (SuDS) ecosystem services to support practitioners.

2.2.3. Multi-criteria analysis (MCA)

Multiple criteria analysis has been used to help decision-makers provide appropriate strategies to address complex problems like urban water issues. Depending on the series of assessment indicators that evaluate from LCA or ESA, MCA can be applied to assess the overall performance of different options and scenarios by scoring, normalization and weighting techniques. MCA is commonly used in water management to assist stakeholders engagement, conflict reduction, and community acceptance. MCA is applied widely in water policy, water planning and urban water infrastructure decisions (Hajkowicz and Collins, 2006). The MCA model is illustrated by an assessment matrix X of n options and m criteria and vector W which is dimensional weights of each criterion in each option. MCA evaluation for urban water management generally includes following steps: (1) choose feasible urban water management options, (2) select evaluation criteria like environmental, economic and social criteria (3) achieve performance measures for the evaluation matrix from expert judgements or models, (4) transform criteria with different units into a commensurate scale (from 0 to 1), (5) weight the criteria of Sponge City infrastructure options, (6) rank or score of these options, (7) sensitivity analysis, and select feasible options.

3. Conceptual model for sponge city implementation

3.1. Selection of sponge city model's features

The features of integrated urban water models do vary due to the diverse requirements at each level of integration. There are six components, which should be considered as being essential to the model's features: data requirement and availability; computational power and software development; process methods; spatial and temporal detailing; simulation configuration; and model structure (Bach et al., 2014). The key model features of the Sponge City model are presented in Table 2.

Problems concerning the model's features range from data uncertainty issues to doubtful mathematical formulation of processes given that these complex integrated models are complex and could be prone to error. Challenges in model structure and process nature (hydrodynamic, biological and physical) should be given priority in the Sponge City model's development. Data collection and data reliability are fundamental factors that encompass the requirements for building, testing and calibration (Bach et al., 2014; Deletic et al., 2012; Elliott and Trowsdale, 2007; Nguyen et al., 2007).

3.2. Selection of relevant models and variables

3.2.1. Selection of main sub-models

A comprehensive Sponge City model is able to simulate environmental feasibility, economic feasibility and social feasibility of Sponge City measurement. MIKE-URBAN is a very useful model in simulating both hydrological benefits of urban water infrastructure practices, flood extent and flood inundation that cannot be obtained from SWMM. Benefits of SUDS Tool (W045 BeST) is capable to evaluate the ecosystem services of Sponge City practices through assessing their regulating services, provisioning services, cultural services and supporting services. As well, LCA is capable to assess the whole life cycle benefits of Sponge City measurements. In addition, after achieving all aspects of Sponge City measurements' benefits, MCA can be applied to score and rank these measurements to assist decision-makers issue appropriate strategies and policies for their local context. A developed Sponge City model should consider incorporating these four existing models: MIKE-URBAN, W045BeST, LCA and MCA (Fig. 7). The in-built key innovation is created by the integration and simplification of these models and their features.

Linking these four sub-models can mean that the urban water management systems interact effectively. The proposed Sponge City model above is better able to predict actual effectiveness including social benefits and environmental/ecological benefits. The last point could see a marked improvement in climate, soil and air quality, as well as better hydrological performance through water runoff and flooding disaster reduction. Appropriate Sponge City strategies are selected through the harmonisation of economic, social and environmental feasibility of Sponge City measurements. These desirable attributes of the Sponge City model proposed will require an effective support system for managing urban water problems, where decision-making is based on continuous cooperation (consensus) between modellers and policy-makers throughout the Sponge City development process (Liu et al., 2008; Makropoulos et al., 2008). Ensuring strong communication and collaboration with stakeholders helps support and build an integrated Sponge City simulation model.

3.2.2. Sponge city model framework

Modelling of the long-term performance of urban water management strategies needs to consider interactions of urban water infrastructure, urban water vulnerability, climate change, and urban water management technologies. In addition to the four main relevant models as depicted in Fig. 7, there are some sub-models, which are necessary in the Sponge City model development. These need to include: firstly, water vulnerability assessment model (Plummer et al., 2012); secondly, climate model (LAR-WG) with ability to predict time-series daily weather (Willuweit and O'Sullivan, 2013). Each sub-model is modified and tested individually prior to being integrated into the Sponge City model. This is essentially an integrated urban water management model and is shown in Fig. 8 (Saagi et al., 2017). The first step of the Sponge City model is to create scenarios based on climate, urban development strategies and urban water vulnerability index, existing urban infrastructures and new urban water management measurements. Scenarios methodology helps maximise the Sponge City model's potential

Table 1
Applying different integrated urban water modelling for Sponge City assessment.

Case study	Model (integration)	Study site	Description	Results	Barriers
Li et al. (2019)	SWMM, AHP	Guangxi, China	Simulation the benefits of Low Impact Development (LID) practices (bio-retention, grassed swale, sunken green space, permeable, storage tank) in Sponge City program	Quantified environmental, economic, social benefits of these practices	✓ Lack of assessment of long-terms benefits and performance of LID practices ✓ Lack of assessment of the effect of climate on LID measurements. ✓ Lack of comprehensive evaluation of ecosystem services of these practices.
Zhao et al. (2018)	The emergy-GIS framework based on SCS-CN model, L-THIA model and energy balance model	Shenzhen, China	Identification of appropriate areas for Sponge City construction	Selected Sponge City implementation areas based on the degree of water runoff, water pollution, heat discharge	✓Limitations in collection of precision satellite imagery data ✓The probability of deviations and errors of sub-models
Hou et al. (2019)	SWMM, GIS	Yinchuan, China	Simulation ecological stormwater processes of different LID facilities in a Sponge City	Simulated water runoff, thermal landscape, purification process of Sponge City measurements	✓ Limitation in simulation with long-time series data such as rain-fall data ✓ The precision of input data such as DEM data, pipe network needs to be higher
Deng et al. (2018)	SWMM, GIS, CAD	Yuelai, Chian	An integrated stormwater management system model to evaluate the whole life cycle of LID facility in Sponge City program	Stormwater network system construction LID facilities design and optimisation	✓ Need a huge amount of data for calibration such as long-term climate data, soil infiltration coef-ficient … ✓ Lack of the evaluation of economic, social feasibility and ecological services of LID facilities in Sponge City
Mei et al. (2018)	SWMM, Life Cycle Cost Analysis	Liangshuihe watershed	Integrated evaluation of green infrastructure for flood mitigation to support Sponge City implementation	Assessed hydrological performance assessment of green infrastructure (GI) practices Evaluated cost-effectiveness of GI strategies	✓ Lack of experimental data for calibration of the integrated assessment system causing model uncertainties ✓ Long-term benefits of GI practices are not evaluated ✓ Lack of GI practices planning and limitation in ecological services of GI practices under Sponge City program
Mao et al. (2017)	SUSTAIN	Foshan New City, China	Application of SUSTAIN model to assess the ecological benefits of aggregate LID-BMPs in Sponge City program	Planned LID-BMPs facilities for the city Evaluated the ecological benefits (e.g., water runoff control performance) of LID-BMPs and the costs of these practice	✓ The cost-effectiveness of LID-BMPs practices is not calculated ✓ Limitation in assessment of comprehensive ecological services of LID-BMPs practice including environmental and social benefits.

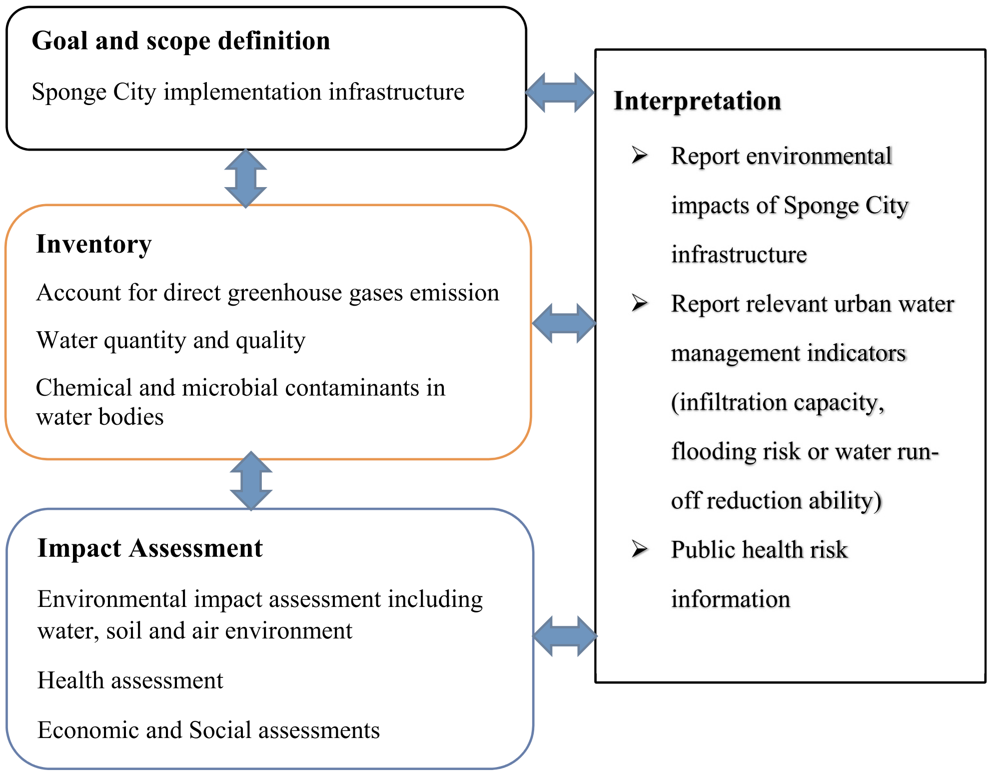

Fig. 5. LCA framework for urban water management practices (modified from (Byrne et al., 2017)).

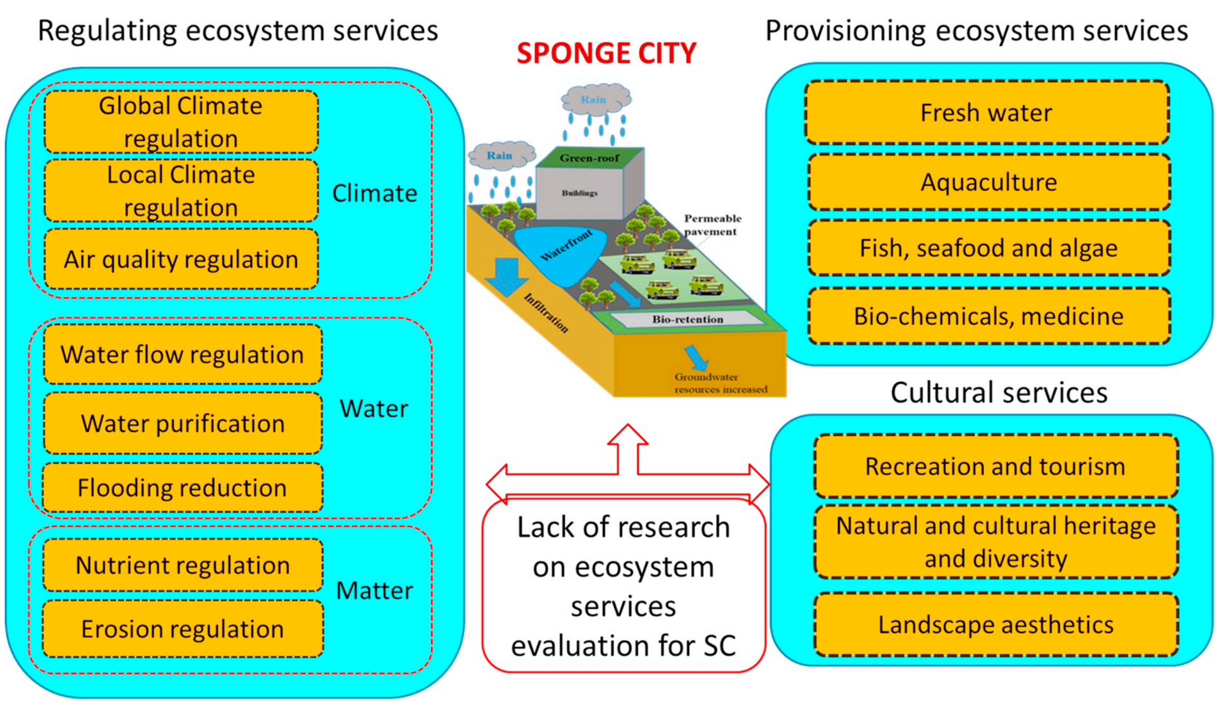

Fig. 6. Possible benefits of Sponge City implementation.

benefit in planning strategies and policies. The second step aims to explore urban development under various scenarios and evaluate the performance of new urban water management and Sponge City ecosystem services valuation. Thirdly, using the multiple-criteria analysis model to select the most appropriate Sponge City implementation scheme, which should ensure solving urban water issues and bring optimal water ecosystem services for urban areas. The next step is to design urban areas according to new Sponge City technologies and existing Sponge City technologies. Finally, the monitoring of post-Sponge City implementation is necessary. The Sponge City model should consider various spatial scales throughout the modelling process, including lot, parcel, patch, block, sub-catchment and catchment scale.

The most difficult challenge for Sponge City model development is to answer the question of how to incorporate sub-models into a complete

Table 2
Key model features of the Sponge City model (modified from Bach et al., 2014).

Category	Model features selection	Challenges
Data requirement and availability	Both qualitative and quantitative data, both spatial and temporal data	Difficult to collect all types of data; data uncertainty problems
Model structure	Conceptual	Model computational burden due to high level of integration
Simulation configuration	Both parallel and sequential	The inaccuracy of each sub-models affect the overall result of model
Spatial detailing	Both branched and looped	Basing on considered interactions in models
Temporal detailing	Continuous simulation and uniform time step	Huge data requirement and challenges in collection the historical data.
Process nature	Quantity: Hydrology performances Quality: Both biological and physical	Hydrology/hydraulic systems is very complex and different between watersheds.
Computational power	Multi-core processing, optimisation and scenario analysis	Uncertainties in model parameters, the big size of integration model and doubtful mathematical formulation of processes
Software development	Supermodel, interface and hybrid	Model complexity

model for testing and application. Therefore, main methods used in the development of Sponge City model could be: (i) the construction of integrated database system, (ii) the identification of the integration of multiple data sources, geo-spatial data computing, and (iii) design and visualization method (Zhang et al., 2017; Xu and Yu, 2017; Deng et al., 2018). The real-time monitoring and flood warning system can be built based on modern technologies like the Internet of Things, Big Data and Cloud Computing (Deng et al., 2018).

3.2.3. Selection of sponge city model variables

Each sub-model requires a range of variables. For example, the MIKE-URBAN database system includes data on population and technologies scenarios, land use characterization, surface characteristics, and climate information data. The inaccuracy of input data results in model uncertainties and therefore errors (Deletic et al., 2012; Bach et al., 2018; Wijesiri et al., 2016). An adequate and reliable database system is hugely important for any kind of integrated urban water management including the proposed Sponge City model. The capabilities of the variables regarding the Sponge City model according the framework in Fig. 9 can be divided into six components: (1) climate indicators, for example the history of daily precipitation, temperature, and solar radiation; (2) social indicators like population, living standards, public awareness and acceptance of water management solutions; (3) environmental indicators such as air quality, water quality, outdoor recreational activities, biodiversity enhancement; (4) urban water indicators such as water demand, water runoff parameters, Sponge City infrastructure design; (5) economic indicators such as life cycle cost, operational costs, and interest rates; and (6) geo-database including soil and elevation map, surface coverage, land use map and administration map.

Data is intrinsic in any model (Voinov and Cerco, 2010). The model formulation, calibration, and verification require relevant and sufficient data. Integrated models as Sponge City models require a huge amount of appropriate and accurate data. Environmental indicators like biodiversity or economic factors such as life cycle costs of urban water technologies are difficult to collect and sometimes make sense of. Even with the available data, it cannot be guaranteed that this is reliable and completely accurate. Therefore, data uncertainty is one of the significant challenges of integrated model implementation.

3.3. Validation and calibration process of sponge city model

The concept of the Sponge City has faced some challenges including the lack of an effective overarching model that could stimulate effective and efficient measures. Therefore, it is vital to develop this Sponge City model to assist in its successful construction. The first step of building the Sponge City model is to develop the conceptual model based on scenarios about urban water management practices, climate, and urban development data availability. The conceptual model will apply mathematical or computational methods to solve the problems noted above. The second step is to implement the Sponge City simulation model as a computer-based project. This Sponge City simulation model will predict the feasibility of relevant practices in terms of addressing urban water issues according to different scenarios. Here the validation and calibration steps are emphasized and they are the most complex tasks to get right (Bach et al., 2014; Deletic et al., 2012; Rauch et al., 2002). Model validation comprises three dimensions, these being conceptual validation, operational validation and data validation (Sargent, 1991) (Fig. 10). Conceptual validity seeks to ensure the accuracy of theories and assumptions in the conceptual model. Operational validity aims to

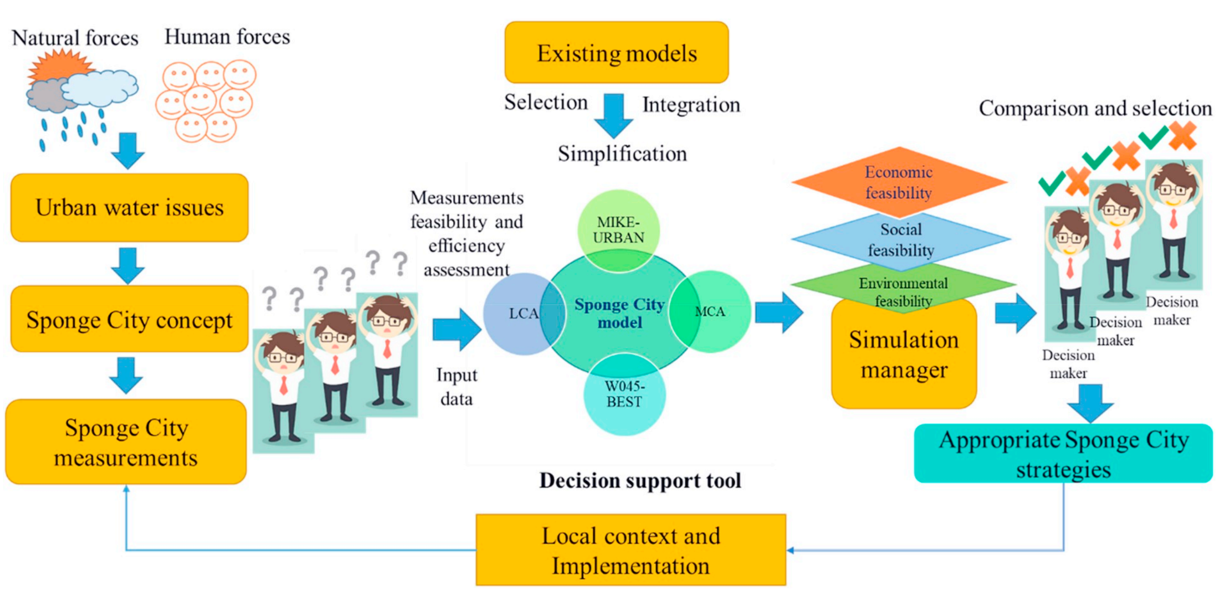

Fig. 7. Overall development proposal of the Sponge City model.

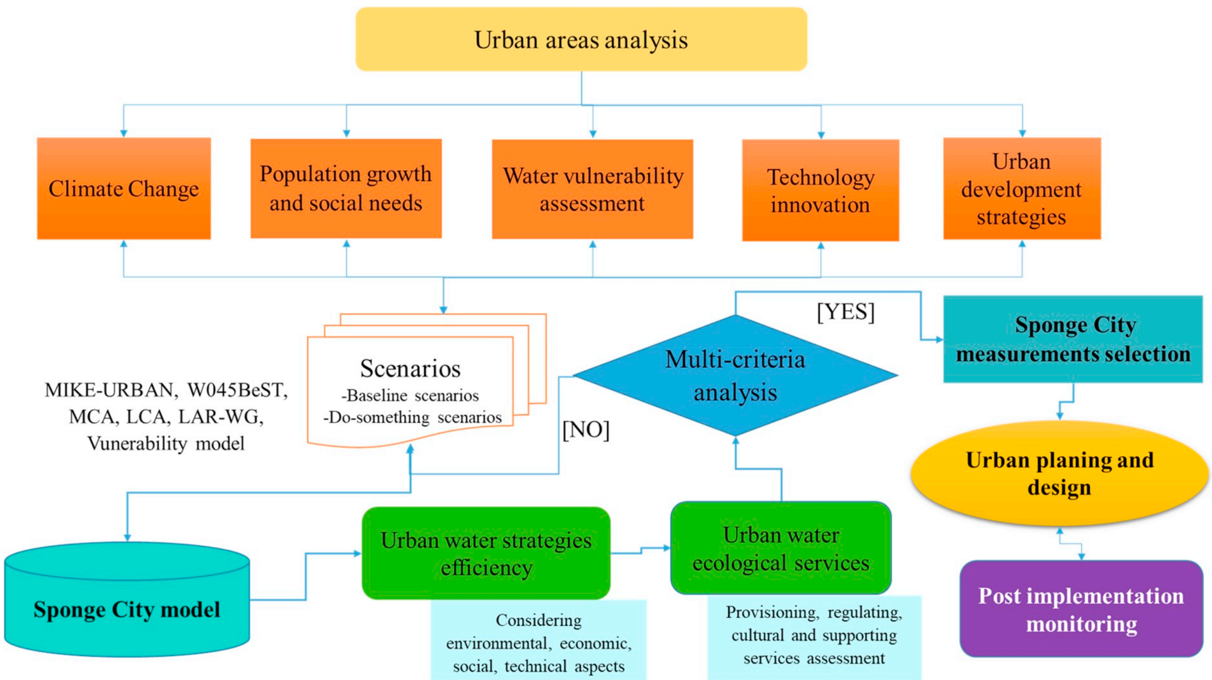

Fig. 8. Proposing framework for the Sponge City model scheme selection.

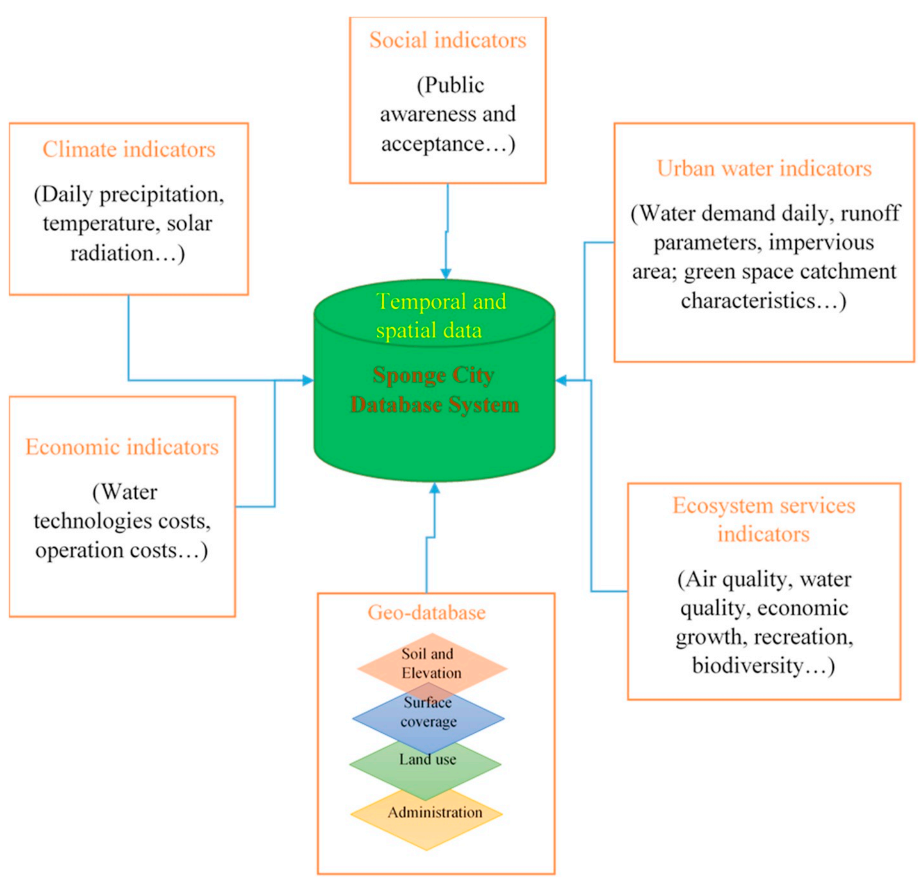

Fig. 9. Main data components of the Sponge City model.

ascertain the reliability of the model's output (Sargent, 1991). Data validity aims to ensure quantitative data is available for model testing, model calibration, and model simulation. Model calibration is defined as ensuring the accuracy of the model's output by comparing its output with actual data from measurement, observation, and collection.

Three approaches are suggested in the literature for integrating models' calibration (Freni et al., 2008; Olsson and Jeppsson, 2006; Voinov and Cerco, 2010). Firstly, a complete integrated model should be

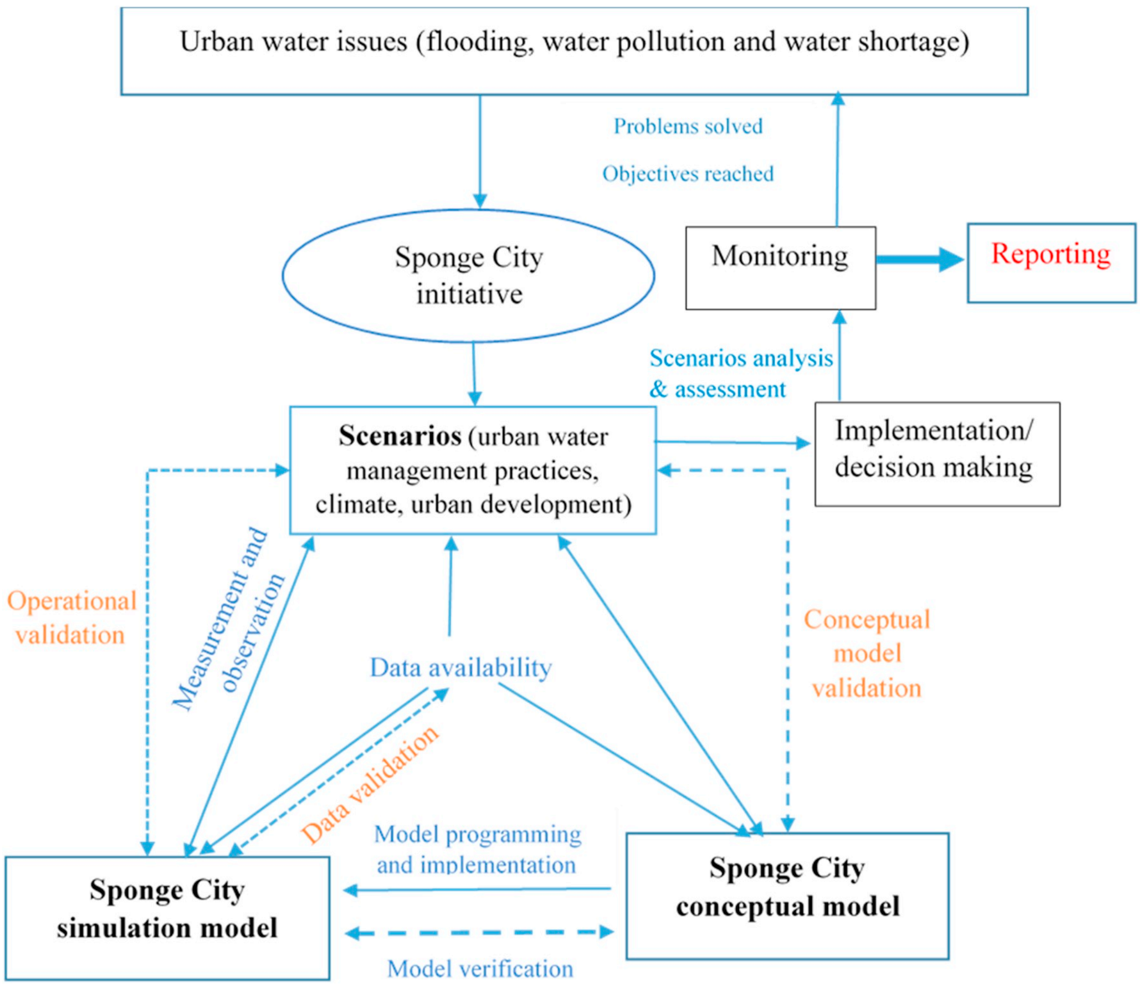

Fig. 10. A generic framework of the Sponge City model development (modified from Sargent, 1991).

calibrated and optimized immediately. With a high and intricate level of integration, this approach is very difficult to get right because the model structure is very complicated. Secondly, it is important to validate and calibrate the upstream model first and then continue this validation and calibration process for downstream models. Finally, each sub-model will be calibrated separately before integration into the one model. The third approach is suitable for models with a low level of integration (Jeppsson et al., 2007). The constraints of the Sponge City model calibration are the complexity of model generation coupled with the long-term simulation objectives of the model, as the model requires a large amount of data. Many calibration methods have been applied for testing models. Modellers should choose the most suitable method for their systems that they want to build (Dotto et al., 2012).

3.4. Mapping model uncertainties

Some models or software packages are still used although certain uncertainties exist among them (Schellart et al., 2010), for example where the output of such models, may not always be reliable. Although it is vital to solve the sources and outcomes of uncertainty in urban drainage models, only little research addresses these sorts of problems in urban water management modelling (Harremoës and Madsen, 1999; Schellart et al., 2010;). Advanced urban water management models need to identify uncertainties from different perspectives. Uncertainties in hydrological models are caused by input data, model parameters and model structure uncertainties in the Sponge City concept (Guzman et al., 2015). The models without sufficient uncertainties being properly accounted for have led to incorrect simulation and this then has serious implications for strategic management and planning where errors occur (Mannina and Viviani, 2010; Voinov and Shugart, 2013Ahyerre et al., 1998). Accurate model predictions might be achieved if the measured and observed data are enhanced (Dotto et al., 2011). There are three main components causing model uncertainties and these are model input uncertainties, model structure uncertainties, and model calibration uncertainties (Deletic et al., 2012) (Fig. 11).

Firstly, the highest level of integration in the Sponge City model requires a vast temporal and spatial scale of data and where components of sub-models are intricately linked, as these may result in model input uncertainties. Secondly, the uncertainty comes from the model structure itself where any inaccuracies in the scale and selection of key processes selection could lead to conceptualisation errors being inherent in the models. The application of wrong equations or numerical methods and boundary conditions create inaccurate outputs and solutions. Finally, calibration uncertainty is also another source of uncertainty. It is due to the errors in measurement or monitoring of both input and output data, and this affects the selection of variables for the calibration process and related method (Deletic et al., 2012; Dotto et al., 2014; Seppelt et al., 2009). To evaluate overall uncertainty, the Generalised Likelihood Uncertainty Estimation (GLUE) method developed by Beven and Binley (1992) has been applied in many studies (Freni et al., 2009; Mannina et al., 2006; Thorndahl et al., 2008). Attempts to mitigate model's uncertainties are model simplification, detail reduction, maximum applying of computational or equation resources and selecting an appropriate calibration and validation method (Jamali et al., 2018).

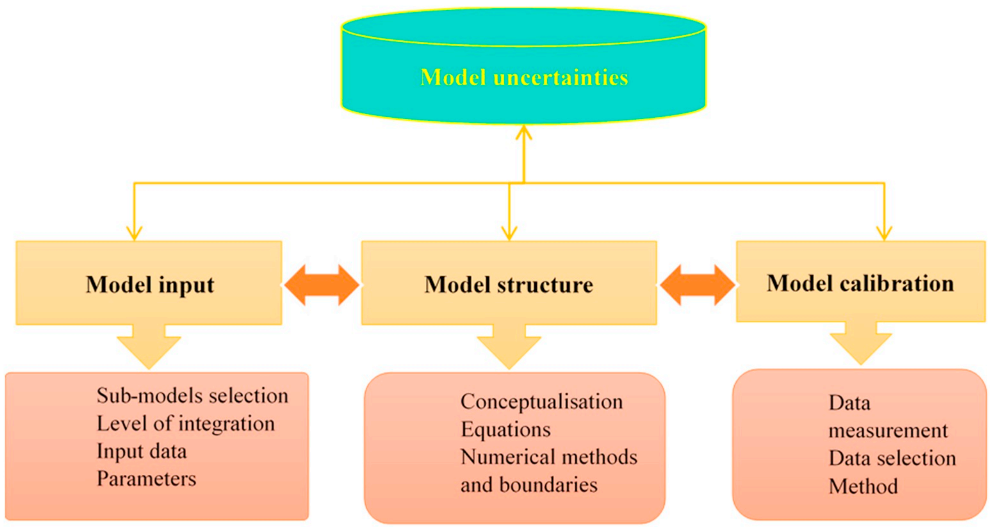

Fig. 11. The main components of uncertainties in the Sponge City model (modified from Deletic et al., 2012).

3.5. *Proposed the model's structure*

The new model is built for multiple stakeholders including researchers, engineers, policy-makers, and other practitioners to assist them to provide appropriate decisions for urban water infrastructure implementation. The model is able to assess the efficiency of water infrastructures including LID practices and Green Infrastructure practices. Both economic, social and environmental aspects of these practices will be estimated. The model-based Sponge City concept is developed based on the structure language of MATLAB with the idea of simplification and integration. Simulink function in MATLAB software is used to support developing Model-Based Design and Testing, which is a useful tool for simulation, automatic code generation and model verification. There are five layers in the integrated model including sub-model layer, input layer, module layer, output layer, and programming language layer which is illustrated in Fig. 12. Each component of the system is designed throughout the identification of the component's function. Then, the corresponding modules are formed from their functions. It creates the simulation process of the whole system.

Key aspects that need to consider for the Sponge City model development include database construction, data integration, temporal and spatial data computing, visualization process (Deng et al., 2018). The post-implementation monitoring system is built by the cooperation of the Internet of Things, Big Data, Cloud Computing technologies and the related standards of water infrastructures (Deng et al., 2018).

4. Challenges in building a comprehensive sponge city model

There are seven challenges associated with integrated urban planning models (Lee, 1973) that are also considered as the barriers of integrated urban water models according to the vision of integrated modellers (Tscheikner-Gratl et al., 2019). These challenges include (1) hyper-comprehensiveness, (2) complicatedness, (2) grossness, (4) hungriness, (5) mechanicalness, (6) wrongheadedness, and (7) expensiveness. The main challenges of a Sponge City model that the paper want to highlight here are:

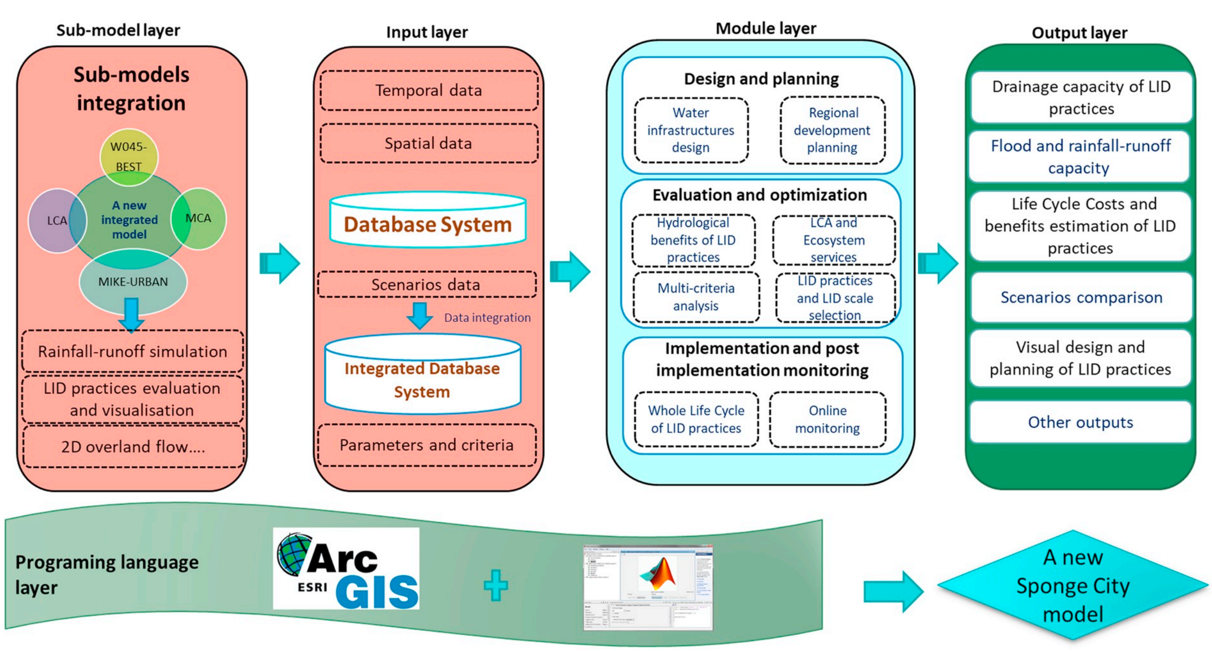

Fig. 12. The possible structure of the Sponge City model.

4.1. Model complexity

The Sponge City model should be able to simulate urban water strategies, efficient hydrological performance and the assessment of urban water and environmental indicators. The multiple objectives of the Sponge City model originate in model's complexity due to high level of integration or too much linkage in the model and the remarkable amount of simulations creating the errors of model's computation and coding processes so that modellers need to take into account these errors. The complexity of Sponge City creates a huge amount of data availability requirements and uncertainty problems in the model that should be addressed by sensitivity and uncertainty analysis to improve the effectiveness of integrated models (Bach et al., 2015; Schellart et al., 2010). For this reason, it is crucial to determine the adequate degree of integration and simplified solutions for each model being implemented to ensure issues regarding uncertainty are minimized.

4.2. Limited knowledge about urban water systems

Urban water networks are complicated systems, which are incorporated by various processes including storage, infiltration, transport and distribution of water, and their interactions (García et al., 2015). The process of each urban water management system is different. These factors lead to the limitations in understanding the interactions between water cycle components and their performance, which threatens the success of any hydrology simulation model. A comprehensive understanding of urban water systems is extremely important to prevent major problems such as flooding, water pollution and water shortages (Marlow et al., 2013). Especially, integrated urban water management practices have emerged intending to build in future sustainable urban water systems. Therefore, the implementation of any water infrastructures should consider climate change, population growth, and regional development scenarios. At present, hydrological advances such as new technologies for recording and predicting rainfall in urban areas can support and manage urban water resources.

4.3. The lack of stakeholders' involvement

Single tools or models for urban water management like ICBMs might be easy for practitioners to use if the interfaces are properly set up. Integrated modelling aims to simulate a range of processes and components in the system with a spectrum of temporal and spatial data (Tscheikner-Gratl et al., 2019). This generates complex links and interactions in integrated models which affects the stakeholders' adoption due to a poorly established interface (Marsalek et al., 1993). Another significant problem causing integrated models to not be entirely user-friendly is the lack of training to transfer the models due to limited time and rising costs. Therefore, building a user-friendly interface model that is suitable for both users either with an immediate level of model application skill and/or an advanced modelling professional is essential that helps improve stakeholders' involvement and participation in the modelling process (Bach et al., 2014; Heusch et al., 2010). Until now, a variety of integrated models like SWMM, DAnCE4Water, and URBAN-MIKE have been developed to solve this problem.

4.4. Model's cost-effectiveness

The monetary investment is a fundamental factor in any project development, and the Sponge City model requires substantial investment costs. Modellers are still required to cover all the costs associated with model development if they cannot obtain government funding or the backing of policy-makers. The required costs and efforts need to be able to create and manage huge data requirements; model calibration and building an integrated Sponge City model but the costs involved might exceed the value of the output (Ahyerre et al., 1998). For this reason, the integrated models work better as research models but not as practical ones (Bach et al., 2014). To increase the cost-effectiveness of the Sponge City model and retain the interest of practitioners, all uncertainty issues in model development have to be solved or minimized (Diaz-Granados et al., 2009; Sriwastava Ambuj et al., 2018). Despite the integrated model's development costs, it does play an important role in assisting decision-makers in making investments and the development of strategies that support various regions.

5. Future perspectives on the integrated sponge city model

For Sponge City modelling development, several future perspectives are emphasized here:

(1) Uncertainty analysis and the assessment of integrated Sponge City modelling should be carried out in parallel with the model's development, testing, and application so that practitioners can rely on the model's output and thereby make good policy decisions. Global Assessment of Modelling Uncertainties could be applied to negate any uncertainties and improve the accuracy of modelling results (Deletic et al., 2012).

(2) The availability of online spatial and attribute data-sharing systems constitutes a fundamental factor in integrated modelling development. The lack of spatial and temporal data creates incomplete knowledge of how integrated models work. Spatial and attribute data-sharing systems can be established based on remote sensing and GIS systems. Remote sensing data should be used increasingly in the upcoming decades because such data are more reliable. A better application of remote sensing data might reduce model uncertainties. The spatial data and measurement data should be incorporated into the integrated Sponge City model.

(3) Inter-disciplinary work on integrated sponge city modelling research is an important factor when it comes to building an integrated comprehensive Sponge City model. Sponge City implementation is a challenging task that requires a multidisciplinary effort to address complex issues and unforecastable future. A reasonable explanation for the lack of integration in urban drainage models is that the responsibilities in urban water management have been broken up or isolated from each other (Rauch et al., 2002). Sponge City simulation and system analysis include interdisciplinary fields of research such as environment, society, and the economy. An effective Sponge City model should incorporate the multi-science field approach. Therefore, reliable simulations of complex interactions in the Sponge City model will address stakeholders' requirements in solving urban water management problems.

(4) A further effort needs to focus on developing an online - integrated urban water management tool for the best management and operation of the Sponge City concept. This online tool helps decision-makers use the integrated models more conveniently. Obtained results from modelling work could enhance the knowledge in how to implement and develop integrated urban water management practices, and how to estimate the effectiveness of investing in urban water development projects.

(5) There are some areas for Sponge City model development including the linkage between automatic calibration models and the Sponge City model to deal with the uncertainty problems (Elliott and Trowsdale, 2007). In addition, enhancing the adoption of the Sponge City model by improving the model's communication system is very important (Bach et al., 2014). By being transparent and fully informed, these model developers will be able to convince decision-makers about the cost-effectiveness of integrated models and provide accurate and comprehensive results. Further research into the spatial-temporal dynamics of urban rainfall for predictions and improving the spatial simulation of ecological/environmental processes of the

Sponge City is essential (Fletcher et al., 2013; Hou et al., 2019). Moreover, an effective Sponge City model is likely to support flood and hydrologic warning systems in releasing more precision information for the community.

6. Conclusions

The uptake of integrated models to deal with environmental problems has increased in recent times. Recently, many models have been developed and now are incorporated a wide range of urban water management practices to address water issues. However, there is a lack of an effective overarching model that supports the Sponge City implementation due to its multiple objectives and complexity. Therefore, it will necessitate to build the Sponge City model based on the current conventional integrated urban water management models. This paper critically highlights the importance of the comprehensive Sponge City model where the combined format can properly assess the challenges that include the model's cost-effectiveness, ambiguous data, etc.

In this paper, a novel framework for the Sponge City model was identified to simulate the efficiency of urban water management practices. The framework of the Sponge City model developed here was based on integrating four important sub-models, i.e. MIKE-URBAN, W045BeST, LCA and MCA. The model is likely to predict the multi-benefits of urban water management measures in terms of environmental, social and economic requirements, compares their cost effectiveness, and then identifies the most appropriate urban water management plan.

Applying the Sponge City model requires different scenarios being taken into account and a large amount of required data. In this way, it will demonstrate that urban water management practices, urban development patterns and the dynamics of natural processes including hydrological systems are working properly or where changes need to be made. Uncertainties associated with this model can be overcome through the improvement of spatial data-sharing systems, the development of efficient computation and software design, and inter-disciplinary work.

Finally, the novel model framework described in this paper will assist modellers to develop a comprehensive Sponge City model for future applications. The Sponge City model development specifically focuses on assisting the Sponge City program, but in the future, it should be broadened in scope.

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