Stormwater Management Modeling in "Sponge City" Construction: Current State and Future Directions

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In response to urban pluvial flooding and pollution, the Chinese government proposed a "sponge city" policy in 2013 that aims to improve urban stormwater management and promote sustainable urban development. However, at present, sponge city construction is still in its exploratory stage. It is still not clear which models are capable of simulating the six key processes (i.e., "retention," "infiltration," "storage," "purification," "discharge," and "utilization") of sponge city practices. Its various benefits (e.g., social, economic and environmental benefits) have not yet been systematically investigated in the context of the sponge city. In this study, we reviewed and compared 19 urban stormwater management models (including 13 hydrological models and 10 decision-support tools, as there are 4 overlap ones) and investigated their application in China. Firstly, we examined the mechanisms behind the hydrological models and compared the abilities of the models to simulate various processes. Secondly, we analyzed what kinds of benefits can be addressed by these decision support tools (DSTs). Finally, we discussed the applications and limitations of the models in various climate zones in China. The findings suggest that none of the models consider the impact of climate change on the sponge city practices (SCP) and none of DSTs can simulate the negative performance of SCP. Furthermore, the lack of sufficient databases in China limited the applications of many of the models. Additionally, we found that the hydrological processes corresponding to "storage" were given more attention in southern China, and "infiltration" of stormwater was of greater concern in northern China. In the context of sponge city construction, this paper provides suggestions for future model development of urban stormwater management in China, such as the development of a stormwater database and the incorporation of long-term climate change impacts into the model.

Keywords: stormwater management, sponge city, green stormwater infrastructure, model comparison, stormwater utilization

1 INTRODUCTION

Rapid urbanization increases impervious surface area and reduces opportunities for stormwater infiltration, altering the urban hydrological cycle (Oudin et al., 2018; Hou et al., 2019; Rosenberger et al., 2021; Wang and Palazzo et al., 2021). In the context of climate change, extreme rainfall events have increased in frequency, resulting in greater urban flooding potential, non-point source

pollution, and more frequent discharges from combined sewer overflows (Hou et al., 2020; Mishra et al., 2021, Yang et al., 2021). Due to the inadequacy of conventional stormwater management systems, countries have begun to explore novel and more sustainable stormwater management techniques such as low impact development (LID), best management practices (BMPs), and green infrastructure (GI) in the United States, water sensitive urban design (WSUD) in Australia, sustainable drainage systems (SUDs) in the United Kingdom, low impact city design and development (LIUDD) in New Zealand, as well as the active, beautiful, clean (ABC) water program in Singapore (Chang et al., 2018; Zhang et al., 2019; Kazantsev et al., 2020; Islam et al., 2021). In 2013, the Chinese government proposed its own urban water management programme, the national "sponge city" initiative, meaning that cities can promote infiltration, retain, store, and purify stormwater like a sponge to utilize stormwater resources and alleviate the problems of flooding, water shortages, and pollution (Li H et al., 2017; Wang et al., 2017). Such SCP have significantly impacted urban hydrological processes and stormwater-resource utilization in China (Suppakittpaisarn et al., 2017; Traver and Ebrahimian, 2017; Li C et al., 2019). They can increase the permeability of urban surfaces and infiltration, alleviate the negative impacts caused by stormwater runoff (e.g., flooding and non-point source pollution), and also replenish groundwater (Fanelli et al., 2017). Moreover, through SCP, stormwater resources are collected and treated in sustainable, cost-effective ways for urban public and residential applications such as firefighting, road cleaning, and toilet flushing (Sartor et al., 2018; Grytsenko et al., 2020). "Sponge city" has been mentioned in the sixth IPCC report as one of effective practices. Chinese government also strongly promotes it in the new urban planning and defined six words to mark the functions of sponge city (i.e., "retention," "infiltration," "storage," "utilization," "purification" and "discharge") (Xia et al., 2017). The six processes have the specific Chinese words for each of them, which are proposed in an official document issued by the Chinese State Council (i.e., *Zhi* for retention, *Shen* for infiltration, *Xu* for storage, *Yong* for utilization, *Jing* for purification, and *Pai* for discharge) (Liu H et al., 2017). They are used to describe the process from rainwater dropped from the sky to it is discharged through the surface or pipes. However, the practices lack the scientific instructions for the successful implementation.

Numerous studies have applied hydrological models to simulate processes and evaluate the cost effectiveness of various SCP configurations. For example, Li et al. (2018) used Hydrus-1D to investigate the operational effects of bioretention on tanks in Xi'an, Shanxi Province. Zhang et al. (2021) used SWMM and SUSTAIN to assess the cost effectiveness of SCP in Dali, Yunnan Province. Additionally, DSTs have supported policymakers or stakeholders in making better and more effective decisions. For example, the Spatial Suitability ANalysis TOol (SSANTO) was used in Melbourne, Australia to involve stakeholders in urban planning through integration of WSUD (Kuller et al., 2019), and STORMKIT was applied in the Australian state of Victoria to assist in the design of a stormwater system using minimum input requirements (Imteaz, 2015). A few

studies have reviewed or compared model applications in multiple situations. For example, Jayasooriya and Ng (2014) selected 10 models and conducted a series of comparisons relating to data requirements, model accuracy, simulation approaches etc., and Elliott and Trowsdale (2007) compared 10 models in terms of application range, calculation methods, contaminant removal, SCP devices, and user interfaces. Haris et al. (2016) reviewed 12 models to explore their functionality, accessibility, characteristics, and components.

These studies have, however, not compared the application of stormwater models in the context of China's sponge city policy. For example, how do models or algorithms embedded in stormwater models correspond to the six mandated functions for sponge city construction? The variables and parameters used as inputs to the models are not yet summarized for sponge city policymakers and other related stakeholders. Moreover, are current DSTs capable of supporting a cost benefit analysis of sponge city construction? These questions require further elucidation, hence our study has investigated the performance of 19 urban stormwater management models in terms of hydrological simulations and decision support in the context of the sponge city. Given that the six hydrological processes (i.e., "retention," "infiltration," "storage," "utilization," "purification" and "discharge," **Figure 1**) are mandated in the construction of sponge cities (Jia et al., 2017), we have analyzed hydrological simulations based on these six processes. Additionally, sponge city practices provide environmental, economic and social benefits, an understanding of which can provide support to decision making. However, their relevant benefits in China have not been systematically summarized and evaluated (He et al., 2019; She et al., 2021). Therefore, our study also aims to evaluate DST from this perspective.

2 MATERIALS AND METHODS

In this paper, we firstly reviewed the stormwater modelling and tools, which are currently assessed worldwide. Then we found the assessed their applications in China based on the published articles.

Firstly, we identified 33 stormwater models from published articles, conference papers, project websites, government technical reports and modeling guidelines. Amongst these, we selected ones simulating different SCP processes which are currently available and widely used. After manually screening, we identified 19 models, which detail information and their advantages and shortcomings are included in the Supplementary Tables. Based on their main features, we divided the models into two types: hydrological models (13 no.) and DSTs (10 no.). Amongst the 19 models, LIDRA, L-THIA LID, MUSIC, and SUSTAIN were able to model both hydrological and DST functions, hence were included in both categories. Then we compared the mechanisms and the required input variables of the hydrological models with regard to retention, infiltration, storage, utilization, purification, and discharge. We also compared the DSTs in terms of their ability to model social, economic, and environmental benefits.

FIGURE 1 | The six hydrological processes in sponge city design.
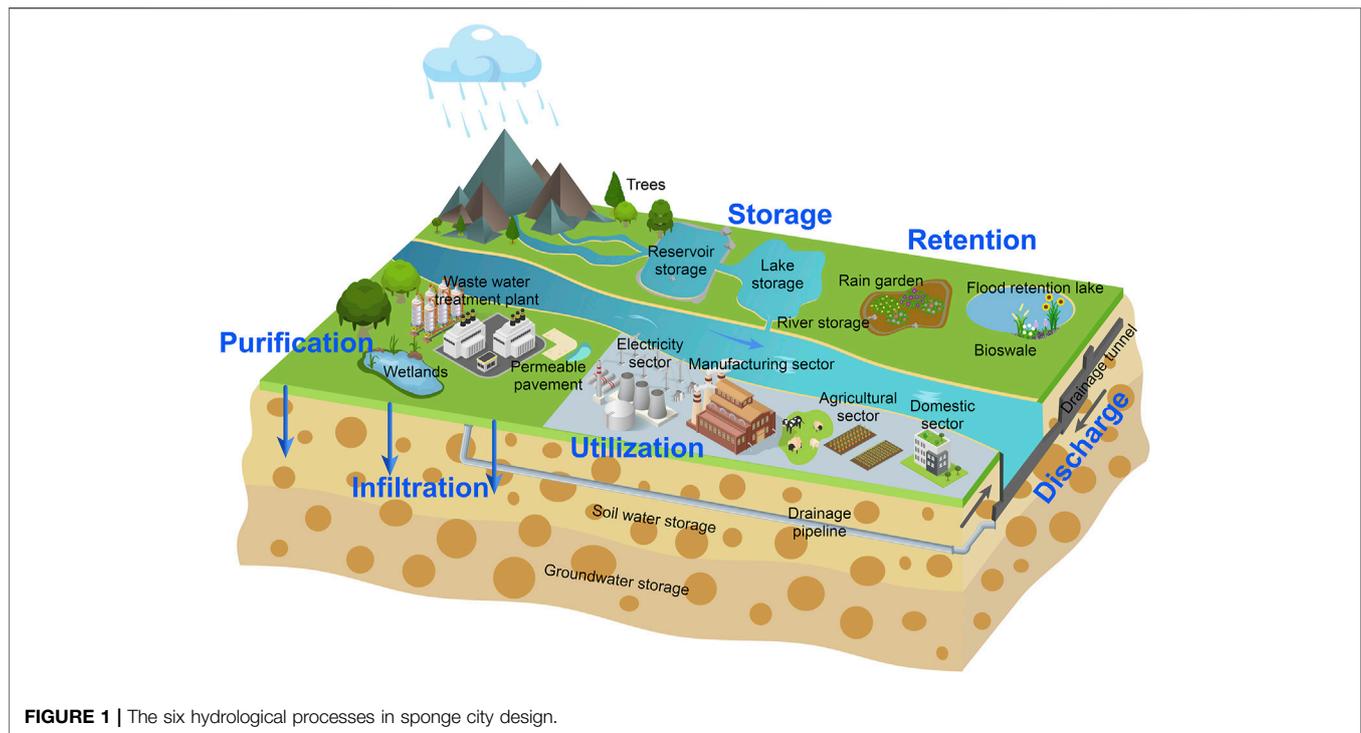
Secondly, to assess the application of these 19 models in Chinese sponge city construction, we reviewed related articles in Web of Science and Scopus, excluded the review articles. Given that LID practices were firstly applied in Beijing since 2000, articles published from January 1, 2000 were investigated. The search terms in this study were "Model name + Stormwater or Rainwater". After the manual filtering, 199 case studies were retrieved.

3 RESULTS

3.1 Hydrological Performance of Models

The internal mechanisms and input variables for simulating the six main processes of each hydrological model are summarized in **Table 1**. The mathematical algorithms associated with different processes are displayed in the mechanism row. Some processes are not explicitly described in the user manual of several reviewed models, and these are shown as blanks. The comparison of the six main processes simulated by these models is described below.

3.1.1 Retention

Retention is an important component in calculating surface runoff, and it is usually embedded in the rainfall-runoff module (i.e., SWMM, SUSTAIN, MIKE-URBAN, L-THIA LID, and MUSIC) (Zhang D et al., 2018; Liu et al., 2019). Retention is regarded as a process related to ground conditions such as slope, surface storage and roughness (Sharior et al., 2019). The input parameters of the models are similar, including slope, surface manning coefficient, storage

depth, vegetative cover and width. However, specific algorithms for retention are not separated from the runoff calculation.

The retention process in the RECARGE and HEC-HMS models include interception and surface depression. The former calculates surface depression as a function of zone thickness and storage layer thickness based on the water balance model (Tu A et al., 2020), while the latter uses an empirical equation to estimate the interception and surface depression as an empirical value may vary with different surface conditions (Roy et al., 2013; Gebre, 2015). The SWAT model can estimate retention based on soil profile water content or accumulated plant evapotranspiration (Elçi, 2017; Cheng et al., 2021). The LIDRA model considers retention as tree canopy interception, which is related to rainfall depth (Horton, 1919). Retention cannot be simulated in Hydrus-1D because the model only considers the longitudinal movement of stormwater in the soil layer and ignores its horizontal movement on the surface. GIF Mod and P8 lack specific algorithms to calculate the retention process.

3.1.2 Infiltration

With the exception of GIF Mod, all other models can simulate infiltration. LIDRA, MUSIC and Hydrus-1D use specific methods related to soil properties to calculate infiltration, whilst the others estimate infiltration based on algorithms embedded in the surface runoff modules. The most widely used methods are the Green-Ampt method and the Soil Conservation Service (SCS) curve method. SWMM, SUSTAIN, HEC-HMS and MIKE-URBAN have several methods to calculate infiltration (see below). StormTac calculates infiltration as a residual of the water

TABLE 1 | Comparison of the mechanisms and input variables of hydrological models in terms of the six mandated processes in sponge city design.

Model name	Types	Retention	Infiltration	Storage	Utilization	Purification	Discharge
SWMM	Mechanism	a process related to the ground conditions such as slope, surface storage, and roughness	Horton infiltration equation; Green-Ampt method; SCS curve method	1. Function Area = A × (Depth)B + C to describe how surface area varies with depth; 2. Tabulated area versus depth curve	LID facility storage layer	power function, exponential function, saturation function, exponential wash-off function and rating curve wash-off function	Manning equation
	Input variables	slope, manning coefficient, impervious rate, storage rate, width	Horton: max and min infiltration rate, decay constant, drying time, max infiltration volume; Green-Ampt: suction head, conductivity, initial deficit; SCS Curve: SCS number, conductivity, drying time	storage area; volume or depth	storage depth	pollutant initial buildup, street sweeping interval, street sweeping availability, last swept; buildup: pollutant, function, buildup rate constant, power/sat. constant, scaling factor, time series, normalizer; wash-off: pollutant, function, coefficient, exponent, cleaning efficiency, bmp efficiency	seepage rate value (in/hr or mm/hr)
SUSTAIN	Mechanism	a process related to the ground conditions such as slope, surface storage, and roughness	Horton infiltration equation; Green-Ampt method; SCS curve method	1. Function Area = A × (Depth) B + C to describe how surface area varies with depth; 2. Tabulated area versus depth curve	LID facility storage layer	VFSMOD algorithms for sediment interception	Manning equation
	Input variables	slope, manning coefficient, impervious rate, storage rate, width	Horton: max and min infiltration rate, decay constant, drying time, max infiltration volume; Green-Ampt: suction head, conductivity, initial deficit; SCS Curve: SCS number, conductivity, drying time	storage area; volume or depth	storage depth	pollutant initial buildup, street sweeping interval, street sweeping availability, last swept; buildup: pollutant, function, buildup rate constant, power/sat. constant, scaling factor, time series, normalizer; wash-off: pollutant, function, coefficient, exponent, cleaning efficiency, bmp efficiency	seepage rate value (in/hr or mm/hr)
MIKE-URBAN	Mechanism	the catchment editor can perform the retention related to surface conditions	Kinematic Wave and Linear Reservoir: Horton infiltration equation UHM: SCS curve method RDI	Kinematic Wave: surface storage RDI: snow storage, surface storage, unsaturated zone (root zone) storage, and groundwater storage	LID facility storage layer	—	—
	Input variables	storage depth, vegetative cover, surface roughness, surface slope, swale side slope	Horton: minimum and maximum infiltration capacity, infiltration time constant for wet and dry conditions SCS: curve number, initial abstraction depth, initial antecedent moisture condition	height, porosity, conductivity, clogging factor	storage volume parameters	—	—

(Continued on following page)

TABLE 1 | (*Continued*) Comparison of the mechanisms and input variables of hydrological models in terms of the six mandated processes in sponge city design.

Model name	Types	Retention	Infiltration	Storage	Utilization	Purification	Discharge
RECARGA	Mechanism	surface depression water balance model	Green-Ampt method	—	—	—	van Genuchten equation
	Input variables	SCP to connected impervious area ratio, roof depression storage	saturated hydraulic conductivity, average capillary suction head, ponded depth, the initial soil water deficit	—	—	—	soil layer dimensionless water content, the limiting hydraulic conductivity
HEC-HMS	Mechanism	interception and surface depressions	The deficit and constant loss model; The exponential loss model; The Green and Ampt loss model; The initial and constant loss model; The SCS curve number loss model; The Smith Parlange loss model; The soil moisture accounting (SMA) loss model	The relationship between storage and other variables, i.e., Elevation-Storage-Discharge, Storage-Discharge, Elevation-Area, and Elevation-Storage (identified by routing method)	—	Transport potential functions	Outflow Curve, Specified release, and Outflow Structures
	Input variables	empirical value	The deficit and constant loss model: maximum deficit, percolation rate, and initial deficit; Green and Ampt Loss Model: initial loss, hydraulic conductivity, wetting front suction, volume moisture deficit; Initial and Constant Loss Model: loss rates; SCS Curve Number: soil cover, land use, and antecedent moisture; SMA model: the maximum infiltration rate, evapotranspiration (ET), volume of soil storage	—	—	the specific gravity of the sediment grains, the density of dry clay sediment	—
GIF Mod	Mechanism	—	—	head-storage relationship: Van Genuchten-Mualem equation	—	transport of solid particles and dissolved and Solid-Associated water quality constituents governing equation	head-flow equations: Van Genuchten-Mualem equation, Manning equation, and Darcy equation
	Input variables	—	—	—	—	bottom area, initial water depth, depth, saturated moisture content, initial particle concentration	external flux, inflow time series
StormTac	Mechanism	An equation quantifying acceptable recipient loads considers retention; different SCP have different equations to calculate retention volume	Losses such as evaporation, ET and infiltration are considered in water balance calculations	—	—	The total pollutant concentration is calculated as a flow-weighted average of stormwater and baseflow concentrations	—
	Input variables	—	—	—	—	the catchment area	—

(Continued on following page)

TABLE 1 | (*Continued*) Comparison of the mechanisms and input variables of hydrological models in terms of the six mandated processes in sponge city design.

Model name	Types	Retention	Infiltration	Storage	Utilization	Purification	Discharge
SWAT	Mechanism	2 methods: vary with soil profile water content or accumulated plant ET	Green-Ampt method				Manning's equation
	Input variables	Water content, ET					
P8	Mechanism		SCS curve method			Particle concentrations in runoff are calculated using an empirical equation	Manning's equation
	Input variables						
L-THIA-LID	Mechanism	The initial abstraction, which describes all losses of precipitation (interception, infiltration, surface storage, and evaporation), is a function of the CN (SCS method)				NPS pollutant masses are computed by multiplying runoff depth for a land use by the area of that land use and the appropriate EMC value and converting units	
	Input variables	Soil properties				Land use properties	
Hydrus-1D	Mechanism	—	soil hydraulic function	—	—	—	deep drainage from the soil profile function
	Input variables	—	scaled unsaturated soil hydraulic conductivity, pressure head, scaling factor for the water content, scaling factor for the hydraulic conductivity, scaling factor for the pressure head, scaled volumetric water content, residual soil water content, scaled residual soil water content	—	—	—	empirical parameter in the deep drainage function, empirical parameter in the deep drainage function, the reference position of the groundwater level, pressure head
MUSIC	Mechanism	a process related to the ground conditions	the infiltration rate is defined as an exponential function of the soil moisture storage	impervious storage, pervious storage: soil moisture storage, and groundwater storage		Transfer functions; The graphical relationship between the inflow and outflow concentration	—
	Input variables	sub-catchment properties, impervious store capacity	soil moisture store capacity, maximum infiltration loss, infiltration loss exponent, soil moisture, field capacity, groundwater data	catchment properties		pollutant concentration information	rainfall and ET
LIDRA	Mechanism	the rainfall interception from tree canopy is related to rainfall	The soil infiltration rate is a function of soil type	—	—	—	—
	Input variables	Rainfall depth	Soil type, hydraulic conductivity	—	—	—	—

balance model. RECARGA, L-THIA LID and P8 use the SCS curve method and SWAT uses the Green-Ampt method.

In SWMM and SUSTAIN, infiltration can be calculated using the Horton infiltration equation, the Green-Ampt method or the

SCS curve method. Users can choose a specific method according to their research needs and data availability. For example, the Horton infiltration equation is applicable when exploring a small watershed or when soil data is inadequate; however, a limitation is

that it does not consider the conditions of the saturated and unsaturated zones (Wang and Chu, 2020; Yang et al., 2020). The Green-Ampt method has strict data requirements i.e., requires comprehensive soil data (Huo et al., 2020; Salifu et al., 2021). The SCS curve method is applicable to large watersheds, but a limitation is that it does not reflect the influence of rainfall intensity and rainfall processes on runoff (Nile et al., 2018; Lian et al., 2020).

HEC-HMS calculates infiltration based on loss models, e.g., the exponential loss model, Green and Ampt loss model or the Smith Parlange loss model (Zema et al., 2017). Different models corresponded to various parameters, and users can choose the appropriate model according to research needs or data availability.

The algorithm to calculate infiltration in MIKE-URBAN is incorporated in the four surface runoff models, which are Time-Area Method, Kinematic Wave Method, Linear Reservoir Method, Unit Hydrograph Method (UHM), and one continuous hydrological model called MOUSE Rainfall Dependent Infiltration (RDI) (DHI, 2017). In the Time-Area method, infiltration is included as runoff loss, and it is not defined separately (Akram et al., 2014; Fariborzi et al., 2019). Both the Kinematic Wave and Linear Reservoir methods apply the Horton infiltration equation to calculate the infiltration (Yin et al., 2020). For UHM, the SCS Curve method is used to estimate the infiltration (Kocsis et al., 2020; Strapazan et al., 2021). In RDI, there are two methods for simulating the infiltration process: Fast Response Component (FRC) and Slow Response Component (SRC) (Zhang S et al., 2018). If the soils' previous hydrological conditions are considered, users can choose the SRC method (Ohlin Saletti, 2021).

L-THIA LID cannot calculate infiltration based on independent methods. The infiltration coefficient in StormTac can be estimated from its relationship with runoff. LIDRA estimates soil infiltration rate from the hydraulic conductivity of different soil types (Rawls et al., 1982). In MUSIC, the infiltration rate of the soil can be calculated from an exponential function of soil moisture storage (https://wiki.ewater.org.au/display/MD6). When the soil water reserve is empty, the infiltration rate reaches its maximum value, and when the soil water reserve is full the infiltration rate gradually decreases to its minimum value. Hydrus-1D uses a soil hydraulic function which can more precisely simulate infiltration compared with the above-mentioned models, however it requires more input variables than other models (Feitosa and Wilkinson, 2016; Hilten et al., 2008; Jiang et al., 2010; Tu et al., 2021).

3.1.3 Storage
The calculation of storage is mainly based on two methods. Some models (e.g., SWMM) directly calculate storage by detecting its relationship with other parameters (e.g., catchment area and depth) (Rossman et al., 2015). Some other models (e.g., MUSIC) divide storage into different parts and calculate each part based on various corresponding methods (https://wiki.ewater.org.au/display/MD6), as shown below.

The storage curve is used in SWMM and SUSTAIN to calculate storage based on the relationship between storage and water depth (Yazdi et al., 2019; Tu et al., 2020). The former uses a linear equation to calculate storage area, while the latter applies a tabulated method (Liu et al., 2018; Deitch and Feirer, 2019); both require water depth or volume as input variables.

GIF Mod applies the Van Genuchten-Mualem equation to estimate catchment wide storage, which identifies catchment storage based on the relationship between storage and water head (Onoja et al., 2019; Weber et al., 2020). In HEC-HMS storage is computed by various equations revealing the relationship between storage and other variables such as catchment area, elevation and discharge (https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm).

In MIKE-URBAN storage is calculated using the Kinematic Wave method, which considers the surface storage as three parts: snow surface, unsaturated zone ("root zone") and ground water in RDI (Hernes et al., 2020; Thrysøe et al., 2021). The input variables are height, porosity, conductivity and clogging factor.

In MUSIC, storage is divided into impervious storage and pervious storage. Impervious storage is a user defined constant, and pervious storage consists of soil moisture storage and groundwater storage. The specific equations are however not publicly available (https://wiki.ewater.org.au/display/MD6).

3.1.4 Purification
The number of pollutants that can be removed from stormwater by SCP is difficult to accurately simulate. Amongst the models we reviewed only MUSIC and L-THIA LID are able to simulate purification performance by different types of SCP. However, most models (such as SWMM, SUSTAIN, HEC-HMS, GIF Mod, L-THIA LID, StormTac, and P8) can calculate the concentration of sedimentation or pollutants.

For pollutant accumulation models such as SWMM and SUSTAIN, pollutant accumulation and wash-off are simulated based on the accumulation and wash-off functions (Johannessen et al., 2019). However, both functions only estimate the pollutant reduction within the runoff flow volume (Rossman et al., 2015). SUSTAIN uses the Vegetative Filter Strip Model algorithms for sediment interception, which is more accurate than SWMM (Shoemaker et al., 2009). The input variables in each process are pollutant initial buildup, street sweeping interval, street sweeping availability, and last swept. In StormTac, the total pollutant concentration is calculated as a flow-weighted average of stormwater and baseflow concentrations (Lindgren, 2019; Wu J et al., 2021). In P8, particle concentrations in runoff are calculated using an empirical equation (Walker, 1990). For pollutant transporting models, GIF Mod uses a governing equation to calculate the transport of solid particles and other water quality constituents (Massoudieh et al., 2017). HEC-HMS calculates pollutant transport with potential functions (MacAsieb et al., 2021).

In L-THIA LID, NPS pollutant concentration masses can be calculated by the runoff depth, multiplying the area and the appropriate Event Mean Concentration (EMC) value (Engel and Harbor, 2017). The treated pollutants by SCP was estimated by

the treatment node in MUSIC, using the transfer functions (Gavrić et al., 2019). These transfer functions calculate the effluent concentration of stormwater based on the simple graphical relationship between inflow and outflow concentrations. Therefore, compared with other models, MUSIC can simulate stormwater quality more accurately.

Hydrus-1D and LIDRA do not include algorithms to simulate water quality.

3.1.5 Utilization

Here, it should be noted that the collection function of SCP, such as rainwater collected by rainwater harvesting tanks or cisterns, is regarded as a function of "utilization" in the context of China's sponge cities. Therefore, only models with rainwater harvesting simulation capability (e.g., SWMM, SUSTAIN and MIKE-URBAN) were investigated in this category. These models have specific SCP modules, and users can define the collecting capacity by relevant input variables such as storage layer parameters. For example, Campisano et al. (2017) estimated rainwater harvesting and evaluated the performance of rain tanks based on SWMM. They found that SWMM overestimated this value, especially for rain tanks smaller than 2 m^3. Li et al. (2021) simulated rainwater harvesting and reuse of rain barrels in Brentwood watershed (Texas, United States) and designed the optimizing parameters of rain barrels for efficient stormwater management, based on SWAT.

However, utilization functionality is still in development and there are different interpretations of it. Some researchers found stormwater utilization is associated with stormwater storage capacity, domestic water demand and current technologies (Hamdan, 2009; Nnadi et al., 2015). For example, the capability of stormwater storage is related to the size of rain tank or reservoir (Vargas et al., 2019; Kim et al., 2021). Domestic water demand can be affected the public policies and local population and industries (Takagi et al., 2018; Fernandes et al., 2020). Sustainable stormwater management can alleviate the water scarcity with some degree (Morales-Torres et al., 2016). Additionally, the development of advanced purification technologies and the new materials can also influence the stormwater utilization (Kolavani and Kolavani, 2020; Awang Ali et al., 2021).

3.1.6 Discharge

Discharge describes the movement of stormwater through drainage pipes, and models calculate this using various hydraulic equations (Chang et al., 2015; Cao et al., 2021). SWMM and SUSTAIN calculate the runoff routing in the pipeline based on the St. Venant flow equations for the dynamic wave and kinematic wave. Regarding the steady flow, the joint solution of Manning and continuous equation is used to calculate the flow rate (Rossman, 2015). SWAT uses the Manning equation to model stormwater movement in drainage systems, while P8 applies the curve number method to simulate runoff from pervious and indirectly connected with imperious surface (Minnesota Stormwater Manual). RECARGA and GIF Mod use the van Genuchten equation. The MIKE-URBAN module features an advanced Real-Time Control (RTC) simulation capability for urban drainage and sewer systems in the form of overflow pipes, weirs, orifices, etc. The stormwater between two nodes can be calculated with Muskingum Cunge method in MUSIC. The outflow hydrograph and pollutograph can be estimated by the continuity of mass equation (Peters, 2012). Hydrus-1D and LIDRA do not consider stormwater discharge in the urban drainage system. The processes of retention, infiltration, storage, and discharge are well simulated in SWMM, SUSTAIN, MIKE-URBAN, and MUSIC. The algorithms adopted in SWMM and SUSTAIN to simulate the above processes are similar, such that the required input parameters are the same. MIKE-URBAN can more accurately simulate the movement of stormwater in the drainage system given that it adapts five hydraulic methods depending on the process in question. The purification process, which corresponds to the improvement of water quality and the removal of pollutants, was fully simulated by MUSIC, i.e., it simulates the entire removal of various pollutants. SWMM and SUSTAIN only model the reduction in runoff mass load caused by the reduced runoff flow volume (Rossman et al., 2015; Shoemaker et al., 2009). None of these models can simulate the process of stormwater utilization and this is an area requiring further research.

3.2 The Performance of Stormwater Management Models in Decision Support and Policy Making

Amongst the 10 selected DSTs there were two free online tools, one free GIS-based tool, two commercially available software programs, two free software programs, and three free MS Excel-based tools. Specially MUSIC, WinSLAMM, UrbanBEATS and E^2 STORMED DST, as stand-alone software, have more complex operating processes than the online and spreadsheet tools. The environmental, economic and social benefits evaluated by the 10 DSTs are summarized in **Table 2**.

3.2.1 Environmental Benefits

The environmental benefits of SCP include improved hydrological performance (Dagenais et al., 2017; Spahr et al., 2020) such as stormwater quality improvement, flood mitigation, runoff reduction and groundwater recharge, as well as indirect benefits related to ecosystem services (Andersson et al., 2015; Dietrich and Rahul Yarlagadda, 2016; Gallo et al., 2020). Improved ecosystem services include adjustment to the local microclimate, carbon sequestration and storage, biodiversity conservation and restoration, and air pollution (Gómez-Baggethun and Barton, 2013; Ando and Netusil, 2018; Kazak et al., 2018).

Most models containing DST capability only address the hydrological aspects of environmental benefits, for example the reduction of water quantity and the improvement of water quality. LIDRA, for example, evaluates the benefits related to runoff reduction in various SCP scenarios. SWMM, SUSTAIN, MUSIC, winSLAMM, WMOST, and UrbanBEATS can evaluate

TABLE 2 | Comparison of DSTs.

Model name	Free or not	User interface	Simulated benefit		
			Economic	Social	Environmental
E² STORMED DST	√	Software	√		√
GI Valuation toolkit	√	Excel-internal tool	√	√	√
GVC	√	Online tool	√		
LIDRA	√	Online tool	√		√
L-THIA LID	√	Online tool	√		
MUSIC	×	Software	√		√
SUSTAIN	√	GIS-based tool	√		√
UrbanBEATS	√	Software		√	√
winSLAMM	×	Software	√		√
WMOST	√	Excel-internal tool	√		√

the benefits associated with runoff reduction and water-pollutant removal by various SCP.

The benefits associated with ecosystem services may also be assessed. For example, the E² STORMED DST can evaluate CO_2 reduction and energy benefits resulting from SCP. Additionally, the GI valuation toolkit can incorporate climate change adaptation and mitigation, as well as the biodiversity conservation related to SCP.

3.2.2 Economic Benefits

There are three main methods for evaluating the economic benefits of SCP. The first method calculates the life cycle cost of various SCP configurations. E² STORMED DST, GI Valuation Toolkit, LIDRA and MUSIC utilize this method. The second method generates a cost-benefit curve or report to help with decision making, and is used by SUSTAIN, WinSLAMM and WMOST. SUSTAIN has an optimization module to generate the most cost-effective scenarios based on the scatter search method and the non-dominated sorting genetic algorithm II method. Regardless of the cost related to improving water quantity, WinSLAMM provides the most cost-effective solutions for urban stormwater quality requirements (Pitt et al., 2002). In WMOST, a Pareto Frontier or trade-off curve can be generated by setting control experiments. The third method is associated with net present value (NPV), which is a widely used method to assess financial viability. This method incorporates the time value of money into decision making based on discounted cash flow techniques (Ye and Tiong, 2000). In the GVC this method is adopted to evaluate economic benefits.

In terms of life cycle costs MUSIC can calculate more types of cost compared with E² STORMED, LIDRA and L-THIA LID. More specifically, the life cycle cost of MUSIC includes the total acquisition cost, annual establishment cost, typical annual maintenance cost, renewal/adaptation cost, decommissioning cost and nominal cost. The types of cost in other models are mainly limited to construction costs and maintenance costs, for example LIDRA and L-THIA LID.

3.2.3 Social benefits

The social benefits related to SCP involve the improvement of aesthetics, public health, human welfare, public acceptability
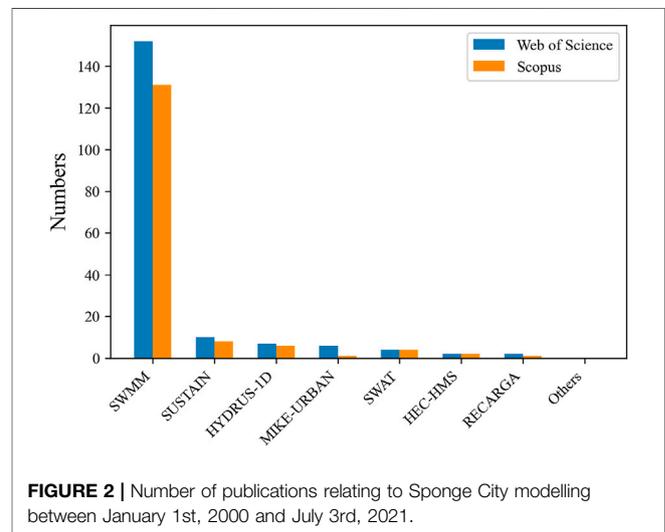
FIGURE 2 | Number of publications relating to Sponge City modelling between January 1st, 2000 and July 3rd, 2021.

and city sustainability, noise reduction and entertainment (Keeley et al., 2013; Chini et al., 2017; BenDor et al., 2018; Bell et al., 2019). Only two tools amongst the reviewed models were found to be able to evaluate social benefits: UrbanBEATS and GI Valuation Toolkit. UrbanBEATS is a spatial planning tool with advanced visual outputs; it considers the influence of urban population density and the urban drainage system to help stakeholders make better decisions. The GI Valuation Toolkit can evaluate the improvements in community performance, health and wellbeing, tourism and recreation, and leisure related to SCP.

In conclusion, with the exception of UrbanBEATS, all other tools were found to be able to evaluate the economic benefits of SCP by calculating the NPV of the sponge system or by identifying the cost of SCP under various scenarios. Amongst the reviewed models only the GI Valuation Toolkit and UrbanBEATS can evaluate social benefits. At present, the methods used to evaluate the social benefits of SCP are mainly indicator based screening and quantification (Dagenais et al., 2017; He et al., 2019; Li H et al., 2019). Because the original purpose of SCP is to reduce urban runoff and remove pollutants, all models except GVC can evaluate environmental benefits (Steffen et al., 2013; Berland et al., 2017).

FIGURE 3 | Breakdown of the six hydrological processes included in Sponge City case studies in China.
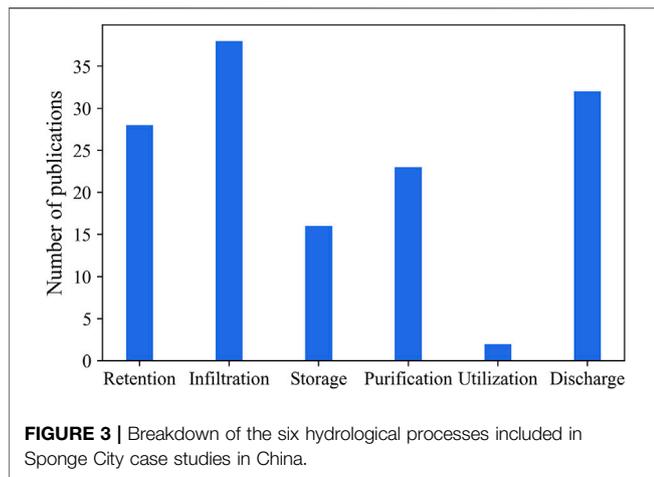
4 CASE STUDIES IN CHINA

Among the filtered 199 studies, 146 cases with a defined municipal study area were selected. Specially, 66 of the 146 cases are in northern China, while the remainder are in southern China. Only 5 studies were published before 2010, which reflects the increased application of stormwater modeling over the last decade. Moreover, we found that most of studies were based on experiments at community or neighborhood scales. The results were mainly based on monitoring and simulations for single or multiple rainfall events, rather than long-term monitoring or simulations.

Amongst the articles we reviewed there were only seven models applied in China (**Figure 2**), of which SWMM was the most widely used. SWMM was capable of not only addressing the hydrological performance of SCP but, when coupled with other land use planning software, achieving real-time stormwater management and comprehensive performance evaluation (Li C et al., 2019; Zeng et al., 2021). Hydrus-1D was used to simulate infiltration-based SCP such as green roofs, permeable pavements, and bioretention (Qin et al., 2016; Fu et al., 2020; Li et al., 2020). MIKE-URBAN was useful for simulating urban stormwater drainage system performance, such as urban waterlogging (Luan et al., 2018). SUSTAIN was applied in both SCP hydrological performance assessment and assisting in the planning of SCP (Gao et al., 2015; Zhang et al., 2021). RECARGA was used to simulate the influence of bioretention on the water balance in an expressway service area in China and the appropriate parameters for bioretention was identified (Gao et al., 2018). HEC-HMS was applied to compare and analyze comprehensive regulation effects of three different storm water management scenarios (Liu et al., 2020). SWAT performed the cost-benefit analysis of SCP in Xiangxi River, China (Liu et al., 2014).

Early studies focused on the simulation of water quality and water quantity, as well as evaluation of the environmental benefits of SCP in terms of runoff and pollution control (Meng et al., 2014; Li et al., 2016). Outcomes identified optimal scheme choice and spatial layout amongst different configurations of SCP (Liao et al.,

2015; Xu et al., 2017). Amongst the literature investigated, Guo et al. (2008) conducted the first stormwater modeling application study in Beijing with SWMM, and analyzed the different rainfall-runoff characteristics of various rainfall densities. Recently, studies related to improving the accuracy, efficiency, and robustness of hydrological models have been highlighted (Pang et al., 2020; Yin et al., 2020; Tang et al., 2021). Moreover, these stormwater management models are increasingly coupled with other platforms or models to achieve more comprehensive functions or to run simulations at larger spatial scales (Duan and Gao, 2019; Liang et al., 2020; Xu et al., 2021). Hydrological models were also integrated with remote sensing techniques, and neural networks have become more popular (Wang et al., 2021; Wu Z et al., 2021).

We further summarized the simulations of the six physical processes involved in the 199 case studies (**Figure 3**). Only 2 cases refer to utilization, and both of these used the SWAT model. Most studies focused on infiltration (38 no.) and discharge (32 no.). Thus, these two physical processes are well simulated in current models, whereas other processes such as storage and utilization were relatively uncommon.

Amongst the 199 case studies, 146 cases focused on specific study areas. We extracted these and further summarized model applications to climatic zones in China. The climate classification map is based on data retrieved from the Resource and Environment Science and Data Center (**Figure 4**, https://www. resdc.cn/data.aspx?DATAID=243). It may be seen that these cases are mainly distributed in eastern China where precipitation is higher and sponge city pilot projects are mostly located. The cases were spread amongst 57 cities, in which Beijing has the largest portion, corresponding to stormwater-resource management demands (Zhang D et al., 2018).

We further analyzed these cases and found that in northern China hydrological model use tends to focus on simulation of infiltration processes of SCP (Luan et al., 2017; Li et al., 2018). Precipitation in northern China is low, and unsaturated zones can reach hundreds of meters. As a result, rainfall exhibits low

FIGURE 4 | Spatial distribution of case studies, retrieved from Web of Science and Scopus between January 1st, 2000 and July 3rd, 2021.
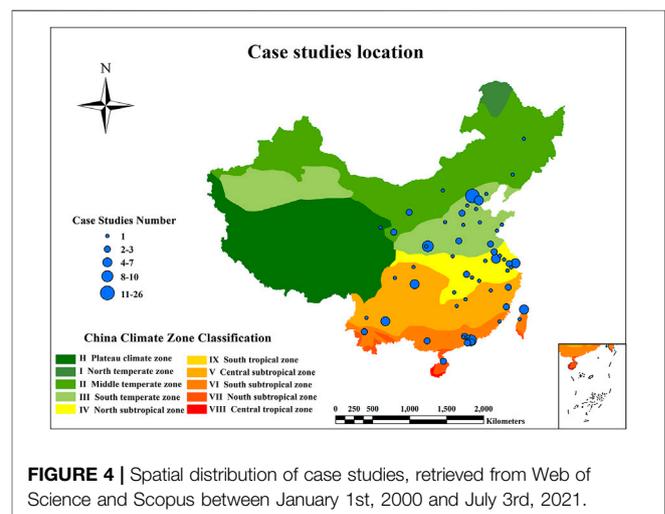
infiltration and field capacity is rarely reached (Han and Banin, 1999; Li H et al., 2019). Improving soil infiltration capacity is an effective way of reducing runoff, recharging groundwater and reducing surface water flooding (Li Z et al., 2017). In the southeast coastal area, application of hydrological models focused on simulating the storage of SCP (Qin et al., 2016; Mao et al., 2017). Because rainfall is more abundant and groundwater levels are high, soil moisture content is also high in the early stages. It is vital therefore to increase stormwater storage capacity through SCP in order to reduce flood risk.

DST functionality has not yet been widely applied in China. At present, sponge city planning mainly relies on a combination of hydrological models and other decision-support methods, such as multi-objective decision making (MODM), analytic hierarchy process (AHP), and a multi-objective evolutionary algorithm (MOEA) (Jia et al., 2015; Xu et al., 2017; Zhu et al., 2021). There are no systematic social and environmental evaluation criteria for sustainable stormwater management in China.

5 DISCUSSION AND CONCLUSION

This research reviewed 19 stormwater models, of which 13 models can perform hydrological simulations and 10 can function as decision support tools. We primarily analyzed the hydrological models for six key processes, as mandated by the Chinese government for sponge city construction. We also compared various DSTs in evaluating the economic, social, and environmental benefits of SCP. Finally, we collected case studies of model applications in China and analyzed the spatial variability and simulation advantages in various climatic zones.

This study reveals some deficiencies in the current simulation for SCP. First, the changes in the nature of SCP over time, such as change in plant coverage and/or the volume of water storage facilities, were not longitudinally studied. In the context of climate change and more intense and frequent rainfall, greater pressure is being placed on the urban ecosystem. Hence, the related hydrological impacts have not been validated by stormwater management models. Observations for vegetation and hydrologic changes need to be recorded to enable improved performance of stormwater management models.

Second, models are known to perform well in different regions of the world, but need further refinement for more meaningful application in sponge city construction in China. For example, the construction standards of rain gardens in China are different to those in other countries, so the parameters related to the capacity of stormwater treatment are also different (Wang et al., 2009). Moreover, these hydrological models cannot fully simulate the entire circulation of stormwater in the context of a sponge city. Case studies in China have mainly focused on reducing stormwater runoff and mitigating stormwater pollution; there is no coherent analysis of how stormwater replenishes groundwater, thus requires further research. Additionally, how stormwater is utilized, such as toilet flushing and irrigation of public green spaces, is still unknown. The model algorithms for understanding how SCP affect the six processes also need to be further optimized.

Third, it should be noted that rainwater harvesting by rainwater tanks or cisterns is classified as "utilization" in the context of China's sponge cities (Peng J et al., 2018; Peng S et al., 2018; Wei et al., 2019). How the collected water is then used (e.g., toilet flushing and urban irrigation) cannot be simulated by current stormwater management models, to our best knowledge. In the "utilization" category, we've clarified how to assign collected rainwater or treated stormwater (Takagi et al., 2018; Fernandes et al., 2020; Hajani and Rahman, 2014).

Finally, current DSTs only focus on evaluating the positive benefits of SCP and ignore the negative effects of SCP. Many studies have shown that SCP can also have negative effects. For example, rain gardens may accidentally increase the phosphorus content in stormwater (Hatt et al., 2009), and wetlands may cause eutrophication of water bodies (Heal et al., 2006). Reservoirs may act as a sink for pollution, endangering health in wildlife and humans (Paus et al., 2014). Data on economic costs in DSTs are lacking in China and require further study. Another limitation of DSTs is the lack of social-benefit assessment modules. Modules that evaluate the social benefits of SCP would assist in the long-term implementation of more SCP in communities. In addition, combining increased stakeholder participation with DSTs is becoming a crucial aspect of sponge city construction (Cousins, 2017; Qiao et al., 2018); DSTs are still not fully used in policy and decision-making.

Overall, for Chinese sponge cities, most models are capable of simulating the hydrological performance of SCP, however the application of DSTs is relatively poor and ineffective in China. Decision-making involves many social, economic, and political factors which may be different from the countries in which the DSTs were developed. Therefore, developing models that can adapt to China's sponge city conditions is crucial. Our review of case studies application in China show that stormwater models use is mainly distributed to central and eastern China. In northern China, studies tend to focus on simulating infiltration, whilst in southern China studies focus on the storage functions of SCP. This finding is significant in terms of selecting an appropriate model according to climatic zone and simulation functions. In summary, in this study, we have evaluated and compared the physical mechanisms embedded in stormwater models based on water retention, infiltration, storage, utilization, purification, and discharge; these factors are important in sponge city construction in China. Additionally, our study explored the social, environmental, and economic benefits of sponge city practices, which can be simulated by current decision-support tools. Furthermore, the application of these tools was also investigated in various climatic zones in China. The study not only improves the understanding of processes involved in the construction of a sponge city, but also provides insight into the development of future stormwater models.

AUTHOR CONTRIBUTIONS

QL wrote the manuscript, built the method, acquired data, and conducted data processing and analysis. WC conceived the study,

built the method, and wrote the manuscript together. JL conceived the study, acquired the funding, and contributed to the manuscript writing. MT, YT and ZT contributed to the manuscript editing.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.816093/full#supplementary-material

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