Prospects of eco-hydrological model for sponge city construction

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ABSTRACT

Introduction: Understanding complex urban eco-hydrological processes through models is an important approach in sponge city construction. However, the research on this has not kept pace with the urgent need for sustainable development of urban water resources, which makes the current construction efficiencies unsatisfactory.

Outcomes: This review highlights the importance of establishing a multi-scale urban distributed eco-hydrological model by analyzing the connotations of sponge city construction. Hydrological models that can be configured for sponge city construction were selected. Traditional models have limitations in coupling ecological and hydrological processes, multi-scale and landscape-based simulations, refined simulations, and computational efficiency. By contrast, cellular automaton has a discrete data structure in space, time, and states, is capable of bottom-up computing, and provides a new conceptual framework for simulating complex urban eco-hydrological processes.

Discussion and Conclusion: Future model development may focus on the conduction of multi-scale simulation systems, the simulation of coupled urban eco-hydrological processes, the quantification of eco-hydrological responses to land cover composition, spatial configuration and low impact development practices, and improving simulation accuracy.

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processes but also the ecological processes. Also, an urban landscape is intrinsically an ecological system, and thus ecological processes are essential to reveal the responses of water fluxes to landscape patterns. Therefore, it is very important to involve more ecological processes in hydrological models for sponge city construction. However, most studies used storm water models that neglect or greatly simplify ecological processes (Deng et al. 2018), and in some models the ecological processes are considered only for LID facilities (Li et al. 2020). Some studies applied land surface models to urban water management by estimating the eco-hydrological effects of different land covers (Xie et al. 2020). Although some models have been developed to simulate energy and water budget in the urban environment by describing plant physiological and biophysical characteristics (Meili et al. 2020), there is still a great gap in understanding urban eco-hydrological processes and applying eco-hydrological models for sponge city construction.

This review explores the problems that might be ignored in hydrological models and analyzes the connotations of sponge city construction. Then, the special requirements for the eco-hydrological model for sponge city construction are identified and usable models are determined. Finally, the future development of urban eco-hydrological models for sponge city construction is summarized and analyzed.

**Modeling requirements for sponge city construction**

Hydrological models that can assist in sponge city construction have special requirements for simulating and processing. For the final objective of developing an eco-hydrological model, it is essential to establish a strategy of multi-scale simulation of eco-hydrological processes based on refinement consideration (Figure 1).

**Figure 1.** Modeling requirements for sponge city construction.
Eco-hydrological model

The direct goal of sponge city construction is to effectively reduce the impact of rainstorms (especially flash floods) on a city by constructing LID facilities and ensuring effective urban storm water management. In contrast to the previous approach of “rapid removal and end concentration,” the approach of “slow discharge and release and dispersed sources” is adopted in sponge city construction, in which a comprehensive application of seepage, retention, storage, drainage, and utilization approaches is adopted (Figure 1). Moreover, many studies have shown that the changes resulting from urbanization in canopy interception, evapotranspiration (Grimmond and Oke 1991; Salvador, Bronders, and Batelaan 2015), infiltration (Zhou et al. 2010; Jacobson 2011; Wang et al. 2011), and depression (Tholin and Keifer 1960; Marsalek et al. 2007) have substantial impacts on surface runoff and pipe network runoff (Berthier et al. 2006; Rodriguez, Andrieu, and Morena 2008). Therefore, in addition to drainage and depression-related hydrological processes, it is also necessary to simulate eco-hydrological processes such as canopy interception, evapotranspiration, and infiltration (Figure 1), which are more closely related to seepage, retention, and storage. All these processes directly affect the design, implementation, and evaluation of the corresponding construction measures.

The long-term goal of sponge city construction is that a city can “adapt flexibly” to environmental changes and natural disasters (Qiu 2015). This means that sponge city construction should develop or improve urban ecosystem services and ensure the sustainable management of water resources. Understanding the complexity and long-term nature of the water cycle and coupling the long-term and continuous eco-hydrological processes in urban areas is the scientific basis for achieving this goal (Figure 1).

In summary, to complete both the direct and long-term goals of sponge city construction, a renewed interdisciplinary approach is required to understand the way urban ecosystems operate and to develop coupled urban eco-hydrological models describing both transient runoff processes and continuous water cycle budgets (Figure 1).

Multi-scale and landscape-based model

Sponge city construction creates a multi-scale and landscape-based water ecological infrastructure (Qiu, 2015; Che et al. 2015; He et al. 2019). Eco-hydrological processes can shape landscape patterns, which in turn can affect water movement and storage and produce different hydrological responses (Ferguson 1992; Gao et al. 2018). This pattern-process relationship is scale-dependent (Salvadore, Bronders, and Batelaan 2015). An important strategy to reveal pattern-process-scale relationships requires identifying the multi-scale patterns of an urban landscape (for example, from points to locals to sub-catchments or catchments to landscapes), establishing a multi-level hierarchical simulation system of eco-hydrological processes, and ultimately exploring the mutual feedback between these processes and landscape patterns within and among different hierarchical levels (Figure 1).

Refined simulation

The sponge city construction focuses on the land cover composition and spatial configuration of local areas. Urban areas are characterized by complex and fragmented land covers, small catchment sizes, inconspicuous boundaries of adjacent catchments, and varied micro-topographic changes (Xu and Zhao, 2016; Liu et al. 2017). All these characteristics make a refined simulation become an essential basis (Figure 1). This specialized simulation can be considered from two perspectives. The first concerns the refinement of the topography and land cover information. During a rainstorm process, even if both given surfaces are pervious or impervious, their temporal variations in surface runoff may differ considerably (Wan and Yang 2007). Thus, simply distinguishing pervious from impervious surfaces is not sufficient, and classifying more refined land cover types is suggested. The second perspective regards the fine division of basic hydrological response units (HRUs). Traditional distributed or semi-distributed hydrological models usually use catchments as basic HRUs; however, these are not sufficient for refined simulation (Arnold and Fohrer 2005). In contrast, grid-based units can thoroughly describe the spatial heterogeneity of urban land cover and should meet the requirements for fine division (Rodriguez, Andrieu, and Morena 2008; Jacobson 2011).

Hydrological models for sponge city construction

Traditional hydrological models

Based on the above requirement analysis, we found multiple hydrological models that may assist sponge city construction from those currently widely used or having local validations. These suitable models can be categorized into storm water management models and eco-hydrological models according to the simulated processes (Figure 2).

Storm water management models

Storm water management models are mainly used to simulate regional rainfall runoff, and the simulated results can be used as the basis for storm water management (Table 1).
The storm water management model (SWMM) is the most extensively studied and widely used urban storm water management model (Tsihrintzis and Hamid 2015). It classifies land cover types into pervious and impervious surfaces and simulates the surface runoff within catchments as well as the one-dimensional flow movement in pipe networks (Rossman and Huber 2016). SWMM also includes LID and runoff water quality modules. SWMM has been widely used to simulate the water accumulation and drainage effect under different rainstorms and runoff processes under different rainfall characteristics and land covers in China, and its accuracy and reliability have been verified (Liu et al. 2006; Cong et al. 2006; Zhao et al. 2008; Chen, Zhang, and Wu 2014; Luo et al. 2020). However, SWMM neglects some critical ecological processes (such as canopy interception) that may greatly influence surface runoff during rains, and simplifies (even neglects at many situations) the simulation of evapotranspiration that may greatly influence surface runoff after rains. It uses catchments as the basic simulation units and ignores the spatial heterogeneity of land surface within the catchments that may influence water flows. It considers the impact of change of land cover composition (such as pervious area ratio) on surface runoff, while the impact of land cover configuration is not fully explored.

Both InfoWorks ICM (integrated catchment management) and MIKE FLOOD are comprehensive simulation systems commonly used in urban storm water management. They construct a hydraulic model for urban drainage to simulate the interaction between the drainage network and rivers; based on this simulation, a risk assessment of urban waterlogging disasters and a further assessment of the drainage and storage capacity of drainage networks may be made (Sun et al. 2006; Tan 2007; Patro et al. 2009; Li 2014). Like SWMM, these systems also use catchments as the basic HRUs and simply classify the land cover types according to their permeability or storm water management measures (e.g., LID and BMPs (best management practices)).

WMS (watershed modeling system) is a type of watershed-oriented comprehensive simulation system that included the grid-based continuous hydrological model HEC-1 (hydraulic engineering center hydrologic modeling system) and distributed hydrological model GSSHA (gridded surface subsurface hydrologic analysis). It differs in multiple land cover types and simulates surface runoff based on grids. WMS is also widely used in watershed planning and runoff forecasting (Downer and Ogden 2004; Cline, Molinas, and Julien 2010; Han, Jianming, and

Figure 2. Traditional hydrological models that may assist sponge city construction.
Shuigen 2014). However, it does not consider pipe flow and storm water management measures (such as LID), which are important for sponge city construction.

In addition to the aforementioned international software programs, China has independently developed a series of hydrological and hydraulic coupling models for storm water management. The storm pipeline simulation calculation model (SSCM) is the first complete model for rainfall-runoff calculation and design in China and is mainly used in urban storm water control and storm water pollution prevention (Cen, Zhan, and Hong 1993). SSCM includes modules for rainstorms, surface runoff generation and routing, flow in pipe networks, and drainage network design. A storm water model for plain cities (especially in China) is established, including four modules: runoff generation, overland flow, flow in pipe networks, and river routing. The simulation of runoff generation considers land cover and hydraulic conditions and thus has a relatively higher accuracy (Xu 1998). The integrated urban flood modeling system (IFMS), a domestic flood analysis software, was specially developed for urban flood disasters by integrating a 1D drainage network model and a 2D surface hydraulic model (Yu et al. 2018). The Wenyuhe River distributed hydrological model (WDHM), a distributed hydrological model considering different land cover types, describes eco-hydrological processes such as vegetation interception, soil infiltration, surface runoff, and river routing (Tang et al. 2005). However, it was initially established for the Wenyu River basin in Beijing; thus, WDHM must be calibrated and validated before being applied to other basins (Tang and Peng, 2009). These self-developed models can simulate urban storm runoff, and some may be run on grids. However, all these models do not include storm water management measures and their effects on runoff processes.

### Coupled eco-hydrological models

The water cycle is an extremely complex and continuous process. Eco-hydrological models, based on the water cycle and water-energy balance of the “soil-plant-atmosphere continuum” (SPAC) system, can explain and describe this complex process to a certain extent (Philip and Forecasting 1969). This is essential information in guiding sponge city construction.

According to the coupled mechanism, eco-hydrological models can be divided into three categories. The first is a hydrological model that is coupled with ecological processes. For example, the variable infiltration capacity (VIC) model compensates for traditional hydrological models in describing the energy fluxes and estimating the momentum exchanges of water, heat, and carbon dioxide in an SPAC system (Rodriguez and Tomasella 2015). However, it cannot simulate plant growth processes in detail. In contrast, the soil and water assessment tool (SWAT) can simulate plant growth processes, although it only utilizes

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**Table 1. Storm water management models.**

| Model         | Developer          | Simulation mechanism | Basic hydrological response units | Land cover type                        | Simulation of process in drainage network | Simulations of effect of storm water management measures | Simulated hydrological or ecological process | Simulation dimension |
|---------------|--------------------|----------------------|-----------------------------------|---------------------------------------|------------------------------------------|-----------------------------------------------------|---------------------------------------------|----------------------------|
| SWMM          | USEPA              | Integration          | Catchment                         | Pervious and impervious covers        | Yes                                      | LID                                                 | Hydrological process                       | 1D                         |
| InfoWorks ICM | Walling Ford       | Integration          | Catchment                         | Pervious and impervious covers        | Yes                                      | LID/BMPs                                           | Hydrological process                       | 1D-2D                      |
| MIKE FLOOD WMS | DHI                | Integration          | Catchment                         | Support multiple land covers          | Yes                                      | LID/BMPs                                           | Hydrological process                       | 1D-2D                      |
|               | EMRL and USACE     |                     | Catchment/grid                    | Multiple land covers                  | Yes                                      | No                                                  | Hydrological process and simplified ecological process | 1D-2D                      |
| SSCM          | Cen Guoping et al. | Hydrology and hydraulics | Catchment                        | Pervious and impervious covers        | Yes                                      | No                                                  | Hydrological process                       | 1D                         |
| Storm water model for plain cities | Xu Xiangyang | Hydrology and hydraulics | Catchment                        | Pervious (with or without vegetation) and impervious covers | Yes                                      | No                                                  | Hydrological process                       | 1D                         |
| IFMS          | IWHR et al.        | Hydrology and hydraulics | Grid                            | Multiple land covers                  | Yes                                      | No                                                  | Hydrological process and simplified ecological process | 1D-2D                      |
| WDHM          | Tang Lihua et al.  | Hydrology and hydraulics | Catchment/grid                   | Pervious (differing vegetation types) and impervious covers | No                                      | No                                                  | Hydrological process                       | 1D                         |

Notes: USEPA, United States Environmental Protection Agency; DHI, Danish Hydraulic Institute; EMRL, Environmental Modeling Research Laboratory (Brigham Young University); USACE, U.S. Army Corps of Engineers; IWHR, China Institute of Water Resources and Hydropower Research.
a fixed plant growth model (Jia and Wen 2005). The second approach includes ecological models that are coupled with hydrological processes. For example, the Regional Hydro-ecological Simulation System (RHESSys) is based on carbon flux and water flux; however, it cannot fully reflect the impact of ecological processes on hydrological processes (Morán-Tejeda et al. 2014). The third method is the biphasic coupling model. An example is the vegetation interface processes (VIP) model, which is based on energy balance and the water, carbon, and nitrogen cycles (Mo, Liu, and Lin 2012).

Clearly, current eco-hydrological model research is still in the exploratory stage. The main barrier to its development is the inconsistency of the scale between ecological processes and hydrological processes. Generally, reparameterization or lumping approaches are adopted to upscale fine ecological processes, but these are accompanied by losses or unsolicited modifications of information. Moreover, most eco-hydrological models are for natural watersheds that do not fully account for human activities, which is a critical requirement for analyzing urban areas (Lei 2011; He and Frank 2018).

In summary, the aforementioned traditional models have strengths and weaknesses in sponge city construction. First, most models are run at one scale (such as catchment or grid). The lack of multi-scale simulation makes it impossible to derive the relationships between eco-hydrological processes and landscape patterns across different scales, which is one of the scientific bases for sponge city construction. Next, storm water management models focus on the hydraulic processes of drainage and weaken the flow generation processes, and few consider the interactions between ecological and hydrological processes. Eco-hydrological models do account for these interactions; however, their coupling mechanisms are deficient and upscaling remains difficult. Moreover, these eco-hydrological models are mostly oriented to natural watersheds, which have considerably different characteristics from urban catchments or watersheds. Additionally, catchments or sub-catchments are often used as basic HRUs in both models. In storm water management models, land cover types are mostly simplified into pervious and impervious surfaces. Simulations for these artificially homogenized land surfaces cannot reflect the internal flow connectivity, which is closely associated with the fine composition and configuration of land covers. Finally, given the biophysically based nonlinear eco-hydrological mechanisms and numerical simulations inherent in these models, it is difficult to improve the computational efficiency. Thus, the contradiction between the simulation accuracy and computational efficiency is highly prominent, especially when the study area is broad and the spatial or temporal grain is fine. These shortcomings of the traditional hydrological models have limited their application to sponge city construction.

Hydrological models based on cellular automaton

Cellular automaton (CA) can provide a simulation framework that establishes simple local transition rules and adopts them in each local area so that the complex dynamical evolution process over an entire system can be simulated. These rules may depend on the states of a cell and its neighbors and their local interactions at the previous time step. CA has been introduced to hydrology field to improve the structures and ideas of traditional models, and it may represent a valid alternative to classic biophysically based methods and empirical approaches (Chase 1992; Favis-Mortlock 1998; Rinaldi et al. 2007; Ma, Zhou, and Guo 2009). The bottom-up simulation approach of CA provides a useful framework for developing multi-scale and landscape-based models. Based on fine cell units, CA has a discrete data structure in time and space, which makes it efficient in refining simulations. Finally, CA provides a parallel computing approach, which is more efficient than classic differential equation methods for modeling complex hydrological and hydraulic processes (Wolfram 1984; Mendicino, Pedace, and Senatore 2015).

However, some issues must be concerned when using CA for real landscapes with specific environments and requirements. The selection of flow direction is one of the issues. The simplest single-flow-direction (SFD) algorithms, such as D8 (O’Callaghan and Mark 1984) and p8 (Fairfield and Leymarie 1991), assume that all the flow within a cell is transferred to one downstream adjacent cell. Since SFD only considers the elevation difference and ignores the water volume within the cell, it cannot reflect the flow interaction between cells and cannot capture the dynamic variation in runoff (Shao et al. 2015). In contrast, the multiple-flow-direction (MFD) algorithm considers multiple possible downstream adjacent cells and performs more accurately than SFD, especially for small-scale watersheds (Zhan, Qin, and Zhu 2012). Notably, whichever algorithm is selected, the definition of the cell neighborhood (such as 4 or 8 neighborhoods) may greatly affect the simulated values, and thus, a comparative study is also needed to determine the most suitable neighborhood in a real landscape (Erskine et al. 2006).

Another issue regards the selection of time step. Given that the CA model is usually run at a high spatial resolution, it is especially critical to adapt the time step so as to simultaneously achieve a high simulation accuracy and high computational efficiency (Mendicino, Pedace,
and Senatore 2015). As the cell size decreases, the corresponding water surface slope may become larger, so the simulated discharges will be overestimated when not considering the inertial effect of fluxes that may reduce the water fluxes between cells in gradually varying shallow water flows (Guidolin et al. 2016). This problem can be alleviated by reducing the time step. However, reducing the time step may cause an exponential reduction in computational efficiency (Hunter et al. 2006). For this problem, modifying formulations for the water flux in the CA model may be a solution. For example, Bates et al. (2010) introduced the inertial term in the De Saint Venant equations into a 2D flood inundation model, which maintains the overall accuracy of the results, while reducing the run time by the use of a great and stable time step. Dottori and Todini (2011) implemented the local adaptive time step algorithm within the CA model to make the time step contain locally given values that are significantly smaller than those in the rest of the computational area, which can increase the computational efficiency by 25%–70% without a loss in accuracy compared with global adaptive time step methods.

Most importantly, to process complex phenomena or real landscapes, it is often necessary to expand classic CA models to allow more complicated cell space structures and real transitions rules. CA models used for constructing a sponge city require necessary expansion or integration and the structure of CA makes it susceptible to expansion and integration. There are some examples of these adaptations. First, the classic CA models use uniform cells as basic units. By contrast, in the expanded models, polygonal grids with irregular sizes and shapes that represent actual micro spatial entities (such as land cover patches or geographical units) can be used as basic units. Next, the classic CA rules are mostly characterized by local interactions, from which the entire system is directly scaled up without any intermediate level(s). However, in a real landscape, the states of a cell are also affected by factors or processes at scales broader than the neighborhood. These effects are usually limited within a patch or geographical unit with a homogeneous land cover, landform, or LID practice. Hence, multi-layer neighborhoods and a CA-based multi-scale simulation system is required to exhibit eco-hydrological processes at multiple scales and their gradually upscaling relationships from cells and neighborhoods to a patch or geographical unit and a subsequent sub-catchment. Moreover, the classic CA assumes that the transition rules are homogeneous for all cells. For a large region, unique rules may be set for different sub-landscapes owing to, for example, unique driving factors, especially landscape patterns and land-use policies closely associated with human activities. Lastly, CA has the property of self-organization, which suggests that it can provide an efficient approach to develop an agent-based CA (Arai and Basuki 2012). Cell water moves like an agent growing in biological behavior with interactions among neighboring cell waters and interactions between cell water and the surrounding environment.

Prospects of urban eco-hydrological models

Under the simulation framework that CA models provide, the critical concerns include what processes and what pattern-process relationships are adopted at certain spatial scales for sponge city construction (Figure 3).

Multi-scale simulation

Considering the multi-scale nature of sponge city construction, it is necessary to construct a multi-scale spatial hierarchical structure from cells or locals to patches (such as different land covers, LIDs, and depressions) to sub-catchments or catchments to landscapes (Figure 3). Based on this hierarchical structure, a multi-scale eco-hydrological simulation system may be constructed to simulate discrete eco-hydrological processes at different scales and the mutual feedback between the eco-hydrological processes and spatial patterns at corresponding scales. Pattern-process relationships across different scales may also be explored. This simulation system may effectively address scale inconsistency by linking fine-scale ecological processes (such as rainfall interception of tree canopy) with board-scale hydrological processes (such as surface runoff). It is conducive to naturally upscaling eco-hydrological processes when building connections among cells, patches, or sub-catchments. For example, the surface flow among cells exactly reflects the hydrological process at the patch scale; the flow among patches exactly reflects the process at the catchment scale.

However, relevant multi-scale studies are not yet sufficiently thorough. The most common studies are to partition a large watershed into multiple catchments and then further multiple sub-catchments, and simulate the eco-hydrological processes at different hierarchical levels (Shao et al. 2019; Li and Zhao, 2017). Noh et al. (2019) summarized and captured the runoff process at different scales based on the basic high-resolution simulation results from a high-resolution hydrodynamic model. Sidle et al. (2017) developed a multi-scale nested simulation approach, in which eco-hydrological processes at different scales (such as canopy interception and infiltration at a site and evapotranspiration at a plot) are firstly monitored, and then are simulated at their respective optimal scales, further they are linked by upscaling and downscaling. Although there are just
a few examples of multi-scale studies, they provide critical heuristics to the future development of eco-hydrological simulation.

When constructing a grid-based multi-scale simulation system, an appropriate grid size (spatial grain) and time step (temporal grain) must be selected (Figure 3). If the grid size or the time step is too small, the simulation efficiency is low; if they are too large, the error from the analytical solution of the kinematic wave equation describing flow movement is substantial. Generally, the broader the grid, the more the micro-topography information is masked and the flatter the terrain is, resulting in a reduction in the simulated flow rate, total runoff, and peak discharge (Fread 1985; Chow, Maidment, and Mays 1988; Hessel 2005; Vivoni et al. 2005). The larger the time step, the more the instantaneous dynamic information of rainfall is masked and the rainfall intensity is averaged, thereby resulting in a decrease in peak discharge; however, this may have a minimal effect on the total runoff. Studies have shown that there may be a threshold for the effect of the time step on the runoff process. When this threshold is exceeded, both the peak discharge and total discharge decrease, and the simulation error increases accordingly (Hessel 2005).

The determination of the optimal spatial scale to simulate the relationship between certain ecological or hydrological processes and spatial patterns is also a key issue. The pattern-process relationship can only be correctly revealed at an appropriate scale (Allen and Starr 1982; O’Neil, 1986; Wu 2004). Determining the spatial scale(s) with significant correlation after analyzing the relationships between ecological or hydrological processes and spatial patterns at each

Figure 3. Framework of eco-hydrological model for sponge city construction.
scale is an effective means. Peng et al. (2020) proposed a single-scale coherence rate index and analyzed the priority scale using a multi-factor attribution analysis for urban land surface temperature. This method is also applicable to eco-hydrological research. Before doing this, the critical characteristic scales (or intrinsic scales) at which the phenomena of spatial patterns or ecological or hydrological processes occur are supposed to be identified first. Multi-scale analysis methods in landscape ecology can provide such an approach, including wavelet analysis and scale variance analysis (Moellinger and Tobler 1972; Wu 2007; Zhang and Zhang 2011) for an eco-hydrological process and landscape metric scalograms (Zhang and Li 2013) for land cover patches or LiD facilities.

**Simulation of urban eco-hydrological processes**

The key to the urban eco-hydrological model is to address the coupling of hydrological processes and vegetation growth and the impact of land-use/cover change (LUCC) on hydrological processes (Figure 3). Hydrological processes are closely related to the ecological processes of vegetation (Mcclain et al. 2014; Sela, Svoray, and Assouline 2015). However, vegetation is generally regarded as a static influencing factor in a hydrological model, as either empirical parameters are used to generalize the effect or remote sensing products are utilized to exhibit the spatial variation in vegetation density (e.g., normalized difference vegetative index and leaf area index) at certain times. Most temperate vegetation growth and soil properties have obvious seasonal variations and thus produce seasonal effects on eco-hydrological processes, such as the interception of tree canopy and land surface litter, soil water flow, and soil-surface-atmosphere fluxes. Vegetation growth, in turn, responds to dynamic soil water availability, which is the outcome of the hydrological cycle. This suggests a renewed understanding of the mutual relationships between hydrological processes and vegetation dynamics.

LUCC is the most direct embodiment of human activities. Through changing land surface conditions, LUCC has become the most direct human driving factor affecting urban eco-hydrological processes. However, characteristics of the impacts of LUCC are generally based on the assumption that the land surface conditions are fixed within a certain simulation period (Maheepala, Takyi and Perera 2001; Li and Ye, 2007). This assumption is a compromise regarding the lack of dynamic land cover information. The time interval of the current land cover data is mostly 5 or 10 years, which therefore cannot reflect the LUCC within a certain 5 or 10 years. When using this data, it is nearly impossible to improve the simulation accuracy, especially for local flash floods. The usual solution is to obtain land cover data with a temporal resolution higher than the general 5 or 10 years. However, the optimal resolution is not equal to the high resolution. The optimal temporal resolution depends on the temporal extent of study associated with the study objective (Zhang 2006). The inconsistency between temporal resolution and extent can significantly reduce simulation accuracy. For example, in the temperate areas, if the temporal extent covers the entire flooding period (e.g., from June to August) or certain flooding period when most plants are in their growing peak with relatively stable growing dynamics and thus relatively stable absorbing water and transpiration dynamics, land cover data for any period during the growing season may meet the requirement for simulation accuracy (Jin and Jin, 2018). If the temporal extent goes through one year from spring to winter, land cover data during both the growing and non-growing seasons is needed because land covers (especially deciduous vegetation) have great differences in different seasons (Rudorf, Melack, and Bates 2014). If the temporal extent goes across multiple years, land cover data during the growing seasons within each year may be needed to exhibit the possible great interannual variation in vegetation types and growing conditions (Cuo et al. 2008). Only if the temporal extent goes across decades, land cover data over the years (e.g., 5 or 10 years) may be used to exhibit the possible great variation in land covers from urban planning or vegetation succession (Omer et al. 2017). The long-term sponge city construction inevitably accompanies with continuous urban development. To formulate construction schemes that can coincide with future urban development, it is usually necessary to couple LUCC prediction models with hydrological models.

**Eco-hydrological responses to composition and spatial configuration change of urban land cover**

Composition of land cover refers to various land cover types and the areal proportion of each type. Spatial configuration of land cover refers to the spatial distribution characteristics of patches composed of adjacent units with the same land cover type. Land cover composition and spatial configuration determine the storage, exchange, and movement of water flow (Baldwin et al. 2004; Kearns et al. 2005; Shi, Lei, and Li et al. 2013). Some ecologists and landscape planners believe that land cover composition has a significant impact on surface runoff processes (DeFries and Eshleman 2004; Glavan, Pintar, and Volk 2013), whereas others believe that land cover configuration is more important for improving the hydrological service function of a catchment (Ziegler et al. 2007; Shi
et al. 2013). Given the lack of quantification of how and to what extent the land cover composition and configuration affect eco-hydrological processes, this information cannot be used to provide scientific advice and formulate effective evaluations of sponge city construction and management (Zhou, Wu, and Peng 2012; Wang, Liu, and Zhao 2014; Su et al. 2014; Elledge and Thornton 2017).

Eco-hydrological responses to composition change of land cover

Urban eco-hydrological processes are highly sensitive to changes in the permeability of land surfaces, regardless of rainfall characteristics (Endreny and Thomas 2009). In many models, urban land surfaces are often classified as pervious and impervious types, and the eco-hydrological responses of land covers with different permeabilities are estimated (Kang, Park, and Singh 1998; Tucci 2001; Tao and Jiang, 2019). However, this division usually cannot be used to distinguish the eco-hydrological processes for different land covers, and thus, the results cannot be accurately applied to construction practices. Some models classify land cover types as green spaces, construction land, roads, and water bodies (Zhu 2007; Feng, Fu, and Li 2015); however, this is far from sufficient. For example, woodlands, grasslands, and shrubs have substantial differences in many eco-hydrological processes such as canopy interception, root water absorption, transpiration, and evaporation; common asphalt roads and brick roads have highly different infiltration capacities and flow resistances (Axel, Daniel, and Gerd 2002). The different eco-hydrological responses caused by different land covers are a particularly critical basis for sponge city construction (Figure 3).

Previous studies have been mostly concerned with the impact of urbanization (i.e., the transition from less to more impervious covers) on eco-hydrological processes; they have focused mostly on impervious covers and their hydrological responses, with much less attention paid to pervious covers and their responses (Law, Cappiella, and Novotney 2009). In contrast, sponge city construction concentrates on ecological restoration (i.e., the transition from less to more pervious covers). The minimum percent pervious cover (PPC) that should be retained or restored to effectively alleviate urban storm floods must be quantitatively determined (Figure 3). The minimum PPC is a critical threshold that varies with rainfall levels and landscape patterns; thus, it must be determined separately under different conditions. When the PPC is lower than this threshold, the increase in pervious area has a significant impact on hydrological processes such as surface runoff, while when PPC is higher than this threshold, the hydrological response of pervious area change is not as obvious. Zhang et al. (2018) conducted a study in a high-density urban area surrounding the North Moat in Beijing, China, and found that 30%–40% may have been the critical threshold for PPC to affect the surface runoff of some sub-catchments. When PPC was less than 30%–40%, surface runoff decreased more rapidly with an increase in PPC. Given that PPC reaching a minimum threshold may be one of the most efficient measures to control storm flooding in highly urbanized and constrained areas, this metric deserves considerable attention in a model.

Eco-hydrological responses to spatial configuration change of land cover

Except for PPC or percent impervious cover (PIC) and their thresholds, the spatial configurations of different land cover patches also have an important impact on the eco-hydrological processes in urban areas (Figure 3). When reflecting the relationship between urbanization and hydrological changes, certain non-spatial indicators are usually used to quantify urbanization, such as population density, road density, urban land-use area, and green space area (Jacobson 2011). In the past decade, some studies have addressed the spatial configuration of pervious or impervious patches, among which landscape metrics are often used. Except for area-related metrics such as the mean patch size of impervious patches and the largest patch index of green patches (Alberti et al. 2007; Zhang et al. 2015, 2018), the metrics associated with connectivity, fragmentation, aggregation or dispersion of pervious or impervious patches are also often used (Hattermann et al. 2004; Mejia and Moglen 2009, Mejia and Moglen 2010 LinkManagerBM_REF_1ehVskT; Luo, Zhang, and Yan 2011; Zhang et al. 2015, 2018). Some studies have shown that these metrics can significantly affect the urban eco-hydrological processes. Increasing the area of pervious patches in a catchment as well as their aggregation, connectivity, or proximity, or reducing their dispersion, can significantly weaken surface runoff. Conversely, performing these actions to impervious patches can significantly enhance rain (especially rainstorm) runoff. However, all these findings have resulted from the correlation analysis between the modeled processes and metrics estimated separately; the future research should determine how to involve landscape metrics and their effects in an eco-hydrological model (Figure 3).

In addition to landscape metrics, some spatial statistical methods can also be used to identify other spatial configuration characteristics of patches. For example, lacunarity analysis and fractal analysis can be used to identify the spatial distribution of different patch types, such as randomness, clustering, regularity, or fractal structures; join count analysis can be used to analyze the positive or negative spatial association of a certain patch type. Although there are explicit spatial configuration indicators, their effects on urban eco-hydrological processes are still implicit. In addition,
similar to landscape metrics, including these indicators and their effects in an eco-hydrological model is also a challenge.

Shuster et al. (2005) and Roy and Shuster (2010) defined effective impervious areas (EIAs) as the area of impervious cover that is hydraulically (directly) connected to the drainage system. A large EIA can drastically increase runoff volume, flow rate, peak flow, and flood frequency. Spatial organizations of overland flow routings may differ between pervious or impervious surfaces and outlets (Figure 3). For example, Zhang et al. (2018) defined four flow routings based on those in the SWMM. For the direct flows from a pervious surface to an outlet (PERV) or the flows from an impervious surface over a pervious surface to an outlet (IMPERV-PERV), the flow connectivity is low, whereas for the direct flows from an impervious surface to an outlet (IMPERV) or the flows from a pervious surface over an impervious surface to an outlet (PERV-IMPERV), the flow connectivity is high. Studies have shown that when the PPC is small, the runoff of most rainfall (except for extraordinary rainstorms) can be substantially reduced if the overland flow routing changes from IMPERV or PERV-IMPERV to IMPERV-PERV. This means that it is feasible to ensure that a catchment can stringently control floods by changing overland flow routings, even if the pervious area is small. As it is affected by the spatial heterogeneity of micro-topography and land cover, the overland flow routing within a catchment may be complex and varied. A key issue is how to extract these flow routings’ commonness and distinguish their differences to ensure appropriate classifications in the modeling process. The classification depends on the permutation and combination of types of micro-topography and land cover and their spatial arrangements. There might be quite a few flow routings based on the number of pervious and impervious patches and their arrangements on a continuously declining slope, let alone on a rugged slope. In addition, the discretization of sub-catchments as limited by terrain and land cover type data will also affect the determination of flow routings and the estimations of their effects on hydrological processes.

Eco-hydrological responses to low impact development practice

LID practice is the most practical measure for sponge city construction. According to different regulation purposes, there are different LID types, including water storage measures (e.g., rain barrels, green roofs and pervious pavements) and water collection measures (e.g., rain gardens, sunken green spaces, and bio-retention cells) (Figure 1). Appropriate LIDs can only be selected under different construction conditions after the runoff reduction effects of different LID types and their spatial arrangements are quantified.

The method of scenario simulation is often used to analyze the runoff reduction effects of different LID types, a single LID type using different materials, and combinations of different LIDs (Hakimdavar et al. 2014; Hu, Ren, and Pei 2015; Huang, Wang, and Zhang 2017; Peng et al. 2018). However, relevant analyses are still limited. We therefore must quantify the runoff reduction effects of different LIDs (including individuals and combinations) in all scenarios, systematically summarize the control indicators and thresholds that may affect eco-hydrological processes (Figure 3), and build a complete technology and theoretical system for the corresponding modeling (Sun 2011).

Some models (e.g., SWMM) have addressed the runoff reduction effects of different LID types and the impact of rainfall characteristics (such as rainfall, rainfall duration, and rainfall peak) on LID practices, whereas less attention has been provided to the spatial arrangement of LIDs (Qin, Li, and Fu 2013; Li et al. 2018). The area of a single LID is limited (0–40 hm²), and thus multiple single or combined LIDs are often utilized (Shen, Zhang, and Xu 2018). This requires setting scenarios with different spatial arrangements to analyze the runoff reduction effects of the spatial locations and spatial distribution of multiple single LIDs and the spatial organization and flow routing of combined LIDs. However, the related research and models on this subject are deficient.

Different land cover types may have unique eco-hydrological processes, and thus the LIDs that can be applied to certain land covers may differ (Tang, Li, and Qin 2010; Wang, Liu, and Zhao 2014). The crux is to correlate LIDs with land cover in the early stage of planning and construction with the aid of models. An effective approach is to decompose the urban area into land parcels according to land-use characteristics (e.g., construction land, roads, and green spaces) or functional characteristics (e.g., residential areas, commercial areas, roads, and squares), and then select suitable LIDs based on these parcels through scenario simulation. For example, LID types (such as sunken green spaces, bio-retention cells, and pervious pavements) may surround the construction land and road to ensure local absorption of rainwater and effective reduction of runoff from the impervious surface. LID types (such as infiltration trenches, vegetative swales, and rain gardens) may also be considered in a green space to more effectively ensure the detention, storage, and infiltration of rainwater (Hu, Ren, and Pei 2015; Shen, Zhang, and Xu 2018). For complex land parcels with multiple land covers (such as residential areas), the runoff processes of typical catchments with different land cover combinations may be compared, as the LID type that is planned will depend on both the functional characteristics and land cover composition in these combinations (Li 2020). Therefore, an important model development is
to add the corresponding parcels-LID analysis module to provide decision-makers with an overall viewpoint of infrastructure construction (Figure 3).

**Accurate simulation**

Three improvements are suggested to improve simulation accuracy: refine model inputs, evaluate modeling performance, and improve the computational efficiency of the model (Figure 3).

First, refining inputs, such as rainfall, terrain, land cover, and catchment data, is a necessary condition for accurate simulations (Figure 3). It is also critical to match the resolution of the input data with the simulation spatiotemporal scale, although it is easily ignored (Xu 2010). However, data in urban areas are relatively scarce, and it is difficult to obtain input data with a high precision and corresponding resolution. Remote sensing technology, especially high-resolution remote sensing, hyperspectral remote sensing, and lidar technology, as well as certain algorithms can provide highly detailed land cover and morphology information that might meet certain data requirements (Wu and Liu, 2002).

Second, the aim of model development is to achieve accurate and reliable modeled values. Accurate and reliable results are not equal to deterministic results; in contrast, most are uncertain with a probability distribution. It is very important to perform an uncertainty analysis of the modeled values. However, related research is still lacking in the hydrological field (Pappenberger and Beven 2006). The input data from different sources, such as field measurements, remote sensing inversions, and simulations will inevitably have errors and uncertainties (Coon and Reddy 2008). Identifying and evaluating error sources and formulating uncertainty assessments of input data are important aspects of uncertainty analyses (Figure 3).

Except for the input data, the rationality of the assumptions and the authenticity of the simulated processes have the greatest impact on the credibility of the results (Figure 3). The assumptions of a model can simplify the presentation of a complex urban system and its internal processes, but the premise is the suitability of the assumptions. On the other hand, to ensure that the simulated processes are increasingly realistic, certain assumptions may be replaced with real cases, although this will obviously increase the complexity and reduce the universality of a model. In other words, the authenticity and universality of a model can be adjusted by changing the assumptions. However, related uncertainty analyses are still rare in studies on hydrological or eco-hydrological models (Park 2012).

Understanding the biophysical mechanisms of the SPAC system in an urban environment is the basis for determining the authenticity of the simulated processes (Figure 3). However, limited understanding limits the development of urban eco-hydrological models (Xu 2010). It is indispensable to constantly integrate the latest mechanistic findings for future model development.

Finally, the computational efficiency is greatly reduced when refining the input data and complicating the simulated processes to increase simulation accuracy (Figure 3). Generally, the computational efficiency can be improved by simplifying the calculation processes, such as through enlarging the computational grids (Yu and Lane, 2006; Liu et al. 2013), replacing the Saint-Venant equation with the motion wave or diffusion wave equations (Zou et al. 2015; Li, 1998), and estimating the flooded area while ignoring the flow simulation (Li and Ye 2007; Chen, Hill, and Urbano 2009; Krupka 2009; Zhang, Wang, and Zhao 2014). Nevertheless, these approaches usually reduce the simulation reliability and may cause partial losses of valid information. Developing models based on the CA framework and parallel computing technology represent an effective approach.

**Conclusions**

Developing urban eco-hydrological models is an indispensable method to understand complex urban eco-hydrological processes. Understanding these processes may provide an essential scientific basis for ensuring the sustainable development of urban water resources through sponge city construction. To develop an urban eco-hydrological model and apply it to sponge city planning, construction, and management, four crucial issues that must be addressed are summed as follows. The first is the scale issue, including conducting a multi-scale simulation system, identifying the most suitable simulation grain, and determining the spatial scale with a significant correlation between ecological or hydrological processes and spatial patterns. The second is the coupling of ecological processes (especially vegetation growth dynamics and LUC) and hydrological processes. The third is the relationship between eco-hydrological processes and composition and spatial configuration of land covers. For land cover composition, we suggest subdividing the land cover according to permeability and underlying characteristics and utilizing PPC and its eco-hydrological effects in the model. We also suggest developing additional methods to quantify various spatial configurations of patches, involving spatial configuration indicators and their effects in an eco-hydrological model, distinguishing spatial organization of overland flow routings, and further exploring the combined effects of overland flow routings and PPC on eco-hydrological processes. Furthermore, we suggest systematically simulating the effects of different LIDs, exploring the effects stemming from different spatial
arrangements of multiple single LIDs or combined LIDs, and adding the parcels-LID module to correlate the LIDs with their surrounding or internal land-use types or functional areas. The fourth is ensuring an accurate simulation; this is related to refining the input data, addressing the uncertainty of the input data, detailing the assumptions used for simulated processes, updating our understanding of water cycle mechanisms, and improving the computational efficiency.

The improved models should estimate hydrological processes, predict peak discharges of rainstorms, and control flood hazards and thereby assist in sponge city construction. Moreover, they also provide warnings needed to ensure the long-term sustainable management of urban water resources under future climate and land-use changes.

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