From sponge city to sponge watershed: addressing comprehensive water issues through an innovative framework

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Abstract. This paper advocates a shift for Sponge City construction from urban scale towards the watershed scale through strengthening the ecosystem services at a holistic perspective. An innovative framework has been established to address integrated solutions for comprehensive water issues. It enclosed with water resilience pattern, water resource pattern, water treatment pattern, water ecology pattern, waterscape pattern, and LID (low-impact-development) transportation pattern. Specifically, water resilience pattern and water resource pattern deal with the livelihood issues of urban population; water treatment pattern and water ecology pattern provide a sustainable basis through ecological and technical approaches in the context of urban agglomeration. Besides, the waterscape pattern and LID transportation pattern correlated grey infrastructure with green infrastructure, which helps to optimize the quality of urban development and minimize the intervention on the watershed ecosystem. The analyses and discourses from this study identify significant methodological implications to shift the sponge city practice from the urban context towards nature context. The prominent contribution is to optimize the regulation and support service of the watershed ecosystem and promote a healthier environment for people and wildlife living in the watershed.

1. Introduction
After 40 years of urban development and socio-economic growth, more than 59% of Chinese population flocked into cities [1], leading to serious concerns about the degradation of aquatic ecosystems, reduction of water conservation forests, continuous deterioration of water quality, and decline in water storage capacity [2, 3]. Urban agglomeration becomes a significant indicator of the population growth and the process of urbanization in China, which led to profound interrelations with regional economic development and national policy-making [4]. In 2015, the State Council of the People's Republic of China released the national strategy for the Sponge City construction, which aimed to tackle the issues of stormwater management and ecological civilization [5].

Previous studies have drawn close attention to the national strategy of sponge city. Yu et al. [6] interpret the origin, process, content and methodologies of the sponge city conception, which attempt to provide an integrated solution to the significant water predicament in urban and rural China. Qiu [7] introduces the primary connotation, implements the approach, and makes a prospect for strengthening the new technology of sponge city construction. Wang [8] identifies the core issue of sponge city should correspond with the comprehensive urban development, including urban planning, flood control, water resources protection, water pollution prevention, water ecological restoration, and...
multi-departmental collaboration. Zhang et al. [9] identified that the urban water system is the core issue in the construction of the sponge city and an overall program on the watershed and city scale. However, the current development of the sponge city mainly focuses on the urban built-up area in the administrative unit in terms of municipal facilities, building standards, urban green space, and urban water system. It separates the natural ecological attributes of the watershed water system and affects the effectiveness of sponge city construction and management [10].

The construction of sponge city should be implemented under the scale of the watershed and coupled green infrastructure with grey infrastructure to deal with the comprehensive water issues [3, 8, 11].

2. Methodology

2.1. Study context
Cities and towns are typically distributed along with the network of the water system, i.e. the Yangzi River, the Pearl River, and the Yellow River. The urban spatial pattern at national scale from the perspective of social-economic development has made remarkable progress. In contrast, the correlation between urban spatial design and the natural ecological system has not been given enough concern [12]. Under the circumstance of urban agglomerations, the municipal water system is indispensable to sustain the water circulation in the catchment unit [9]. In a watershed area, the central cities, urban agglomerations, and rural settlements are connected by the mainstream and tributaries, upstream and downstream, left and right banks, which composed the watershed ecosystem with the natural elements of mountain, forest, lake, river, field, etc. [13]. The holistic watershed ecosystem model involves the abiotic variables and biologic variables, which significantly correlated with the water resources conservation, tourism and leisure, sediment and material transport, climate regulation, aesthetic functions, natural systems maintenance, biodiversity and other values [14].

However, the rapid urbanization in recent decades has a significant impact on the watershed ecosystem. Specifically, the rapid expansion of urban built-up area leads to a sharp decline in the agricultural field and water space, which degrade the ecosystem function and debase the value of ecological services [15, 16]. Yao et al. [17] explored the spatial correlation between urbanization and ecosystem service value, which identified that population urbanization has the most significant negative correlation with ecosystem service value, followed by spatial urbanization and then living urbanization. Wang et al. [18] suggested that the government should prohibit the disorderly expansion of urban construction and restore ecological space by converting the urban renewal area and brownfield into natural landscapes. From the perspective of urban flood-waterlogged security, strengthening the comprehensive service functions of a river watershed could help against extreme hydrological events and alleviate the disquiet of climate change [19]. From the perspective of water pollution control, the sponge city construction should involve the watershed-scale instead of the urban built-up areas, which covers the rural areas of the non-point source pollution control [20].

2.2. Research trends
The emerging tendency in research and practice that supporting urban water management (UWM) is represented by various terms, including sustainable urban drainage systems (SUDS) [21, 22], low impact development (LID) [23-25], best management practices (BMP) [26, 27], water sensitive urban design (WSUD) [28, 29], and green infrastructure (GI) [30, 31]. Although many diversities are between these terminologies, the sharing philosophy underneath refers to transforming the linear character of the conventional UWM into a recyclable approach via the employment of the landscape within the watershed for the sake of mitigating flooding risk, reducing non-point source pollution, recharging groundwater, and supplementing environmental flows [32, 33]. The research trends of the recent years have shifted from small-scale LID/BMP designs to large-scale SUDS, GI and WSUD implementation [3, 33].
Therefore, sponge city construction should transfer from the urban scale to the watershed scale, which creates integrated solutions for the watershed water issue [11]. The research scope of the sponge watershed is based on the natural hydrological unit, including the upstream water source conservation area, the midstream plain water network area, and the downstream estuarine wetland area. Depending on the original local water system, the essential of sponge watershed demonstrates an innovative planning strategy for the sponge city construction, which aims to optimize the regulation and support service of the watershed ecosystem and promote the environmental quality from the urban scale towards watershed scale.

3. Results

The significant asset of a sponge city is to maintain the urban ecosystem health and safety [6, 15], which cover the issues of water security, water environment, water ecology, water resources, and system management, etc. [5, 34, 35]. The conceptual framework of sponge watershed is enclosed with water resilience pattern, water resource pattern, water treatment pattern, water ecology pattern, waterscape pattern, and LID (low-impact-development) transportation pattern [11]. Specifically, water resilience pattern and water resource pattern deal with the livelihood issues of urban population; water treatment pattern and water ecology pattern provide a sustainable basis through ecological and technical approaches in the context of urban agglomeration. Besides, the last two items correlated grey infrastructure with green infrastructure, which helps to optimize the quality of urban development and minimize the intervention on the watershed ecosystem. Each pattern is illustrated as follows (Figure 1).

3.1. Water resilience pattern

First, the primary issue of the water resilience pattern is to address the disasters and challenges of climate change and extreme weather. As an essential principle, the sponge watershed system should respect the local landscape and keep a balance between development and conservation. Specifically, reserving the existing rivers, lakes, wetlands, pit ponds and ditches and maintain the natural hydrological characteristics before urban development as much as possible [36]. According to the various function of infiltration, stagnation, regulation, the sponge watershed system is available to alleviate the risks of high-intensity rainfall and extreme flood, promote the utilization of rainwater management and purify the non-point source pollution of primary rain [37, 38]. Meanwhile, it is necessary to integrate the urban renewal with conduit reopening, which relieves the waterlogging and restore the natural water system. Due to the land resource is limited, and the continuous urbanization is expansive, it is significant to optimize the efficiency of land use and promote the model of vertical development [39].

3.2. Water resource pattern

Second, the research objective of the water resource pattern is to establish an innovative perspective of water resources planning and allocation. There is a transition from the traditional view that concerns production and domestic water only towards the new concept of production, domestic and ecological water integration [40]. Dealing with the dual pressure of the current scarcity of water resources and the massive demand in the future, the water resources innovation will adapt the water allocation from "demand-based supply" towards "demand-constrained supply". From the perspective of sponge watershed, ecological water will be adequately hydrated into the local water system through the components of the mountains, forests, farmlands, rivers, lakes, etc. [41]. A multi-purpose water source allocation network should be established with the coupled water quality model and water quality model, which tackle the issue of scalability and versatility of the water resource systems.

3.3. Water treatment pattern

Third, the water treatment pattern is requested to find a proper solution for the stock sewage water while dealing with the incremental pollution brought by the future population sustainably. An innovative model block-water-clean (BWC) system is established that transformed the concept of
comprehensive utilization of urban sewage treatment from the emphasis on concentration to the perspective of relatively dispersed at the block scale [11]. BWC system comprises the modules of stormwater management, sewage treatment, water quality and quantity monitoring, and operating warning, which help to promote the reuse of greywater, relieve waterlogging, acquire real-time data and remote control in low-cost operating. In the future, there is a severe limitation of sewage treatment capacity and sewage pipe network coverage, as well as the irregular facilities utilization and unbalanced resource distribution. Therefore, the new pattern of water treatment proposes integrated strategies, including self-digestion in central areas, efficient transformation, balancing resources, and distributed processing in the block drainage system [42].

3.4. Water ecology pattern
Fourth, the water ecology pattern aims to optimize the distribution of urban ecological infrastructure for water and soil sensitive areas. According to the national policy in environmental conservation, the survey, investigation and restoration concentrate on the water source protection areas, which helps to strengthen the rigid constraints on urban runoff source reduction and the non-point source pollution control in the context of the watershed unit [43]. A three-dimensional ecological network system is demonstrated with the artificial treatment and the natural approach to endorse the safety and health of the human settlements surrounded by the environmental conservation zone. Besides, sludge from the bay and estuary will be reclaimed and implemented in urban development and construction through the comprehensive technology of soil remediation and sediment dredging. Specifically, the dehydrated sea sand is a suitable material for the land reclamation, and the treated sludge from the riverbed, for another example, could transform into the greening construction soil or landscaping fertilizer for the riparian zone after bio-safety disposal [44].

3.5. Waterscape pattern
Fifth, the prominent goal of waterscape pattern is to create a comprehensive water corridor with multifunctions, including linking the urban water system from the mountain to the seaside, coordinating sensitive areas and habitats with human settlements, establishing a continuous recreation network, encouraging slow traffic, as well as protecting cultural heritage [13, 45, 46]. In the future, a three-level water corridor system will be demonstrated at the regional, city, and block levels. The regional-level corridor connects to the Pearl River Delta greenway network, which links the green resources of forest parks, nature reserves, scenic spots, country parks, waterfront parks and historical and cultural sites in the Greater Bay Area. The city-level corridor is divided into the river corridor, lake & reservoir corridor, and coastal corridor with diverse themes and characteristics. All the natural elements, including mountain, forest, lake, river, field, are integrated into the major river watersheds and merge the city into nature. The street-level corridors take care of the natural topography and promote green lifestyle through cooperating with leisure cultural resources, urban road systems, green sponge facilities and other elements in diverse spatial forms.

3.6. LID transportation pattern
Last, the LID transportation pattern seeks innovation that fundamentally adjusts the barbaric destruction and rough separation of natural ecosystems by the construction mode of urban highways and expressways. Diverse solutions are proposed to address the variant status of transportation construction [23, 47]. For those main road networks at the planning phase, viaduct form is suggested to cross the ecologically sensitive area that pledges the maximum protection of the biological substrate with the low-impact construction mode. For the case that the trunk road network has been completed already, it is recommended to transform the highway into an under-drainage tunnel at important ecological nodes. If the elevation condition is limited, it is suggested to increase the upper-span ecological corridor to ensure the migration and conservation of inter-regional fauna groups. Also, the LID transportation pattern should be integrated with the exchange hub of the urban public transport system and the slow traffic system in the central city. Through the integration of TOD (transport-
oriented development) model, a high-density LID transportation network is well established, which links a variety of services and public open space along with the riverside and waterfront areas. The three-dimensional pedestrian crossing facilities are requested for excellent walking and cycling experience.

In sum, the conceptual framework of sponge watershed contributes to reinforce the resilient ability of flood control, optimize the water resource efficiency, maximize the capacity of water pollution treatment, strengthen the water ecological services, promote the multi-functions of the waterscape, and minimize the negative influence of the urban transportation system. The ultimate goal is to achieve the health and stability of the urban ecosystem and the sustainable development of the city.

Figure 1. The innovative framework of sponge watershed construction.
4. Discussion
According to reviewing the development of sponge city construction, there are barriers and challenges in the current circumstance that can risk the achievement of the sponge city performance and implementation [9]. Previous studies identified that the current fragmented governance and responsibilities in urban catchment management inhibit integrated strategies to urban water cycle management [3, 48]. To optimize the performance of stormwater technologies and the implementation of administrative efficiency, the research scope of sponge city should shift from the urban built environment towards a broader vision of watershed scales in terms of health and well-being of the urban ecosystem [14, 49]. Specifically, the sponge watershed should base on the natural hydrological unit, which includes the water source conservation of the upstream region, the plain water network of the midstream region, and the estuarine wetland of the downstream area. It is urgent to propose an innovative approach that addresses not only urban water problems but also concerns the ecological sustainability and climate risks [3].

This paper argues for shifting sponge city construction from the urban scale to watershed scale to demonstrate integrated solutions for the watershed water issues. Depending on the original local water system, the essential of sponge basin proposes an innovative planning strategy for the sponge city construction, which aims to optimize the regulation and support service of the basin ecosystem and promote a healthier environment for people and wildlife living in the watershed. An innovative framework is established that enclosed with water resilience pattern, water resource pattern, water treatment pattern, water ecology pattern, waterscape pattern, and LID (low-impact-development) transportation pattern.

5. Conclusion
The intention of this study contributes to reinforce the resilient ability of flood control, optimize the water resource efficiency, maximize the capacity of water pollution treatment, strengthen the water ecological services, promote the multi-functions of the waterscape, and minimize the negative influence of the urban transportation system. This framework bridges the gap between stormwater management and water resource allocation, sewage pollution treatment and non-point source pollution control, water corridor connectivity and public transportation construction. The analyses and discourses from this study identify significant methodological implications to shift the sponge city practice from the urban context towards nature context. The ultimate goal is to achieve the livelihood security, ecosystem sustainability, and development symbiosis between human and nature.

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