Prioritizing Sponge City Sites in Rapidly Urbanizing Watersheds Using Multi-Criteria Decision Model

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Prioritizing Sponge City sites in rapidly urbanizing watersheds using multi-criteria decision model

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Abstract: Spatial planning is crucial for Sponge City (SC) construction; however, prioritizing SC sites at the watershed scale has not been fully explored. In this study, a multi-criteria decision model, considering demand and suitability of SC construction, was established by monitoring, model simulation and index calculation. This new model was then tested in a rapidly urbanizing watershed, Beijing, China and the priority of SC construction at both grid scale (1km×1km) and subwatershed scale was ranked. The results showed that the highest priority was found in emerging regions where urbanization is ongoing, and followed by urban core areas. In addition, six indexes were identified by clustering heatmaps as key factors affecting the priority of SC planning, including topographic index, water pollution index, pollution rate based on the state standard of surface water environment quality, urbanization planning, urban levels, and vegetation index, which could guide SC planning in data-lacking regions. The approach and findings in this study can not only provide helpful references for watershed managers and urban planners but also can be easily used in other regions.

Keywords: Sponge City planning; Priority index; Macro scale; Multi-criteria model; Urbanizing watershed; AHP method

1. Introduction

Concerns about sustainable development of cities have increased globally due to rapid urbanization, which has changed the land use and land cover (LULC) considerably (Chatzimentor et al. 2020, Luan et al. 2019, Nguyen et al. 2020). As a result, natural hydrologic and ecological process have been impacted significantly by urbanization, followed by a variety of problems (i.e., urban flooding, stream degradation and ecological risk) (Lee et al. 2012, Liu et al. 2015, Zhang et al. 2017). Conventional urban construction, where independent infrastructures are constructed, ignores the resilient response capability, especially in terms of climate change and environmental risk (Rauch et al. 2017). Despite this, it is possible to implement practices for reducing urban problems and promoting a natural environment (Mustafa et al. 2018), such as Low Impact Development (LID), Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDs) and Sponge City (SC) practices.

An extensive adoption of green infrastructure to supplement conventional urban development is required. The application of green infrastructure reflects the mainstream narrative aiming to reconcile conflicting goals by integrating environmental concerns in decision-making processes of urban development (Apostolopoulou et al. 2014). Sponge city, which has been implementing in China since 2013, is regarded as an effective practice to improve urban resilience with respect to water and environmental system management. The focus of SC construction has shifted from the efficiency of individual facilities to systematic planning in recent years (Martin-Mikle et al. 2015). Optimal spatial layout planning can achieve comprehensive benefits, such as reducing runoff/pollutant loads by 3.9-7.7 times and placement costs by 4.2-14.5 times (Liu et al. 2016). Besides, hydrologically sensitive areas (HSAs) were employed to identify priority sites for LID implementation in a watershed with a geographic information system (GIS)-based framework and indicated 16% and 17% reductions in nutrient and sediment loads into receiving waters (Martin-Mikle et al. 2015). Scholars have also explored the optimal spatial scheme for facilities based on multi-objective models, including information on facility efficiency and cost (Hou et al. 2020a, Leng et al. 2020). The location of those facilities implemented within a watershed can be the most important factor in determining the effectiveness of SC construction (Jia et al. 2017). Although it is widely accepted that the construction of such strategies needs to consider ecological sensitivity and field suitability (Chan et al. 2018, Ishaq et al. 2019), systematic research on region selection at the macro scale is still in its infancy, which can easily lead to fragmentation of SC construction during urban planning.

However, the tools currently available to implement LID on a large scale are complex models (e.g., SUSTAIN, SWMM models), which require large amounts of data, such as monitoring data and detailed subsurface properties (Baek et al. 2020). The implementation of this process is especially difficult over a large scale in a city. In recent years, SC implementation has analyzed regional demands, including water issues and management, and regional suitability, such as location sites (Thu Thuy et al. 2020). This process is a multi-criteria and multi-objective decision-making process involving environmental, social, and economic issues. Therefore, a suitable model for decision-making is available to consider different weights to quantify qualitative criteria and compare different processes for multidimensional issues. The analytic hierarchy process (AHP) is one of the useful tools for multi-criteria analysis (Saaty 1980), and this tool has been applied to flood risk assessment with multiple criteria systems (Pantelidis et al. 2018). However, the AHP has not yet been systematically applied to SC construction, especially on a large scale, such as the urban scale or watershed scale.

In this study, a typical urbanized watershed with a drainage area greater than 4000 km^2 was set as a case study. The primary goal was to extend our knowledge of SC planning on a large scale. The objectives of this study were to 1) build a macro-scale and multi-criteria priority index (PI) model to quantify SC planning; 2) identify priority management units at the raster scale or regional scale for SC construction within a watershed; and 3) identify key factors affecting SC planning.

2. Methodology

2.1 Study area

The Beiyun watershed, the largest water system in Beijing, is a typically urbanizing watershed. Fig. 1 shows that the study area extends from the centre of Beijing to the northwest and southeast, with a total area of 4348 km^2 and a total river length of 89.4 km. Most of the watershed is relatively flat (elevation of 20~40 m), except for the northern forest area (elevation of 1000-1265 m). Within a warm temperate semi-humid continental monsoon climate, the average temperature is 11~13°C. The annual precipitation is 500-600 mm, with 80% received from June to August. The Beiyun watershed receives 90% of flood discharge, the water quality of which is related to water environmental security, human health and safety in Beijing.

However, the water quality has been greatly affected by rapid urbanization.

The primary land uses in the study area in 2017 were recorded as urban (impervious surface accounted for 39.77%) and agricultural land (accounting for 33.37%). The urban areas are mainly located in the middle of the watershed with an impervious cover of over 70%. Moreover, Fig. 2 shows that urbanization in the Beiyun watershed involves the transformation from agricultural land to impervious surfaces. Significantly, grassland (including grassland and wetland) and forest (including forest and shrubland) recovered in 2015, which may be a benefit from the implementation of SC construction since 2013. However, urbanization is continuously developed, and the adjacent areas of the city dominated by agricultural land use are awaiting transformation to meet the demands of urbanization. Urgently, how to integrate SC construction into urban development planning is a problem to be solved. The Beiyun watershed is a representative watershed that is experiencing rapid urbanization. As SC construction is indispensable to eliminate urban environmental problems, the Beiyun watershed is a reasonable study area for this issue.

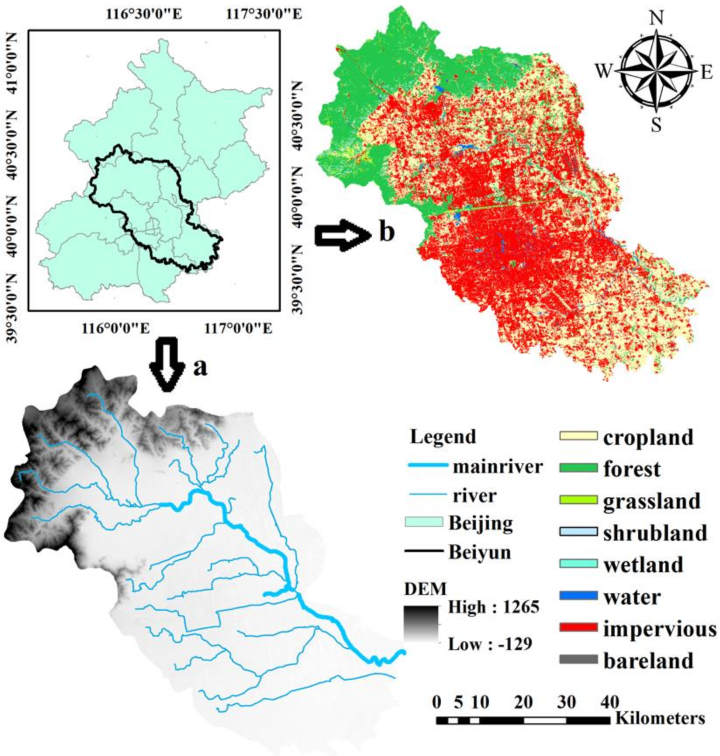

Fig. 1 Land use and elevation in the Beiyun watershed

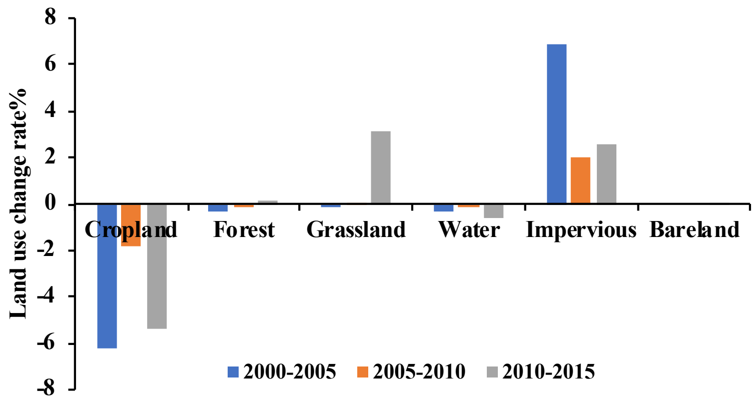

Fig. 2 Land use change in the study area

2.2 Priority index model

Performing large-scale priority site assessments of SC in China and other countries is of great significance, as the assessments provide guidance for government officials and stakeholders to develop sustainable cities and improve regional management and planning efficiency. To comprehensively evaluate priority sites for SC construction at the watershed scale, a multi-criteria priority index model was constructed. To compute index weights in the model, the IAHP method was introduced to balance the comprehensive weights, which combined subjective weights from expert interviews and objective weights from the CRiteria Importance Through Intercriteria Correlation (CRITIC) method (Diakoulaki et al. 1995). After data normalization, the results were calculated with GIS-based weighted summation.

Combined with the aforementioned methodology, the research framework can be seen in Fig. 3.

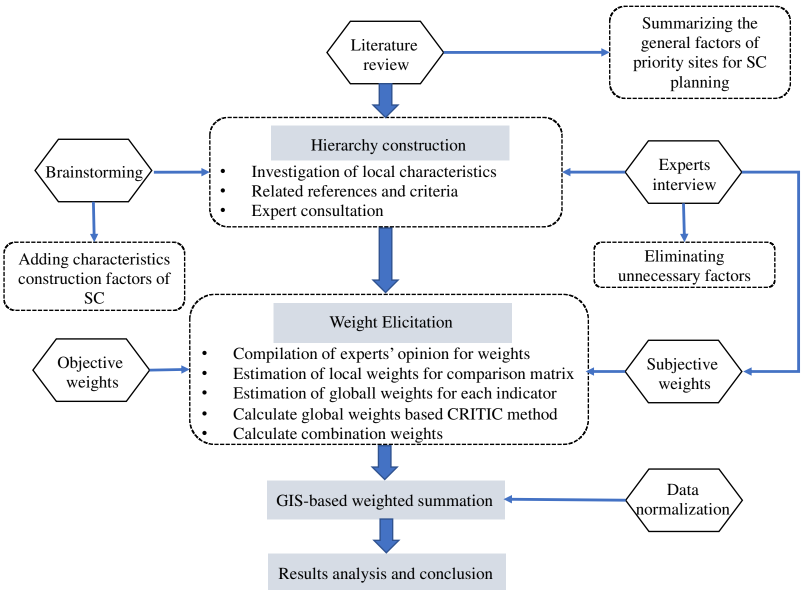

Fig. 3 Framework of this study

2.2.1 Literature review

Sustainable urban development has been popularizing globally to cope with environmental issues caused by rapid urbanization, which originated from urban stormwater management in developed countries in the 1970s (Pauleit et al. 2005). Sponge city was officially proposed in 2013 by Chinese government to solve the environmental problems with regional characteristics, which has been proved to have positive influences on urban water environmental, water ecology and water security

(Chan et al. 2018). However, regional rationality assessment is needed to integrate SC construction into urban planning, based on the experiences during pilot period since 2015. To identify reasonable criteria for SC construction at a macro scale, various researches relating to site selection were collected and reviewed, as summarized in Table 1. Detailed information is provided in the *supplementary materials*. Five categories were concluded from the related literature, including climatic conditions, demand for urban flood control, demand for urban pollution management, site suitability and support from social development.

Table 1 Framework of criteria to evaluate site priorities of SC construction

Criteria	indexes	Definition	Reference
Climatic conditions	Precipitation Temperature Evaporation	Affect the selection of SC facilities	(Hou et al. 2020b, Qin et al. 2013)
Urban flood control	Elevation	Important topographic factors affecting runoff generation	(Martin-Mikle et al. 2015)
	Slope		(Martin-Mikle et al. 2015)
	Soil permeability	Important factors to mitigate runoff	(Ahiablame et al. 2012)
	Impervious cover	Main factors of runoff generation	(Martin-Mikle et al. 2015)
Surface water pollution	Water pollution index	General pollution status of rivers	(Charlesworth et al. 2016, Han et al. 2020)
	Urban NPS contribution	Contribution ratio of NPS to river pollution	(Ma et al., 2018)
Site suitability	River buffer	River shoreline	(Shen et al. 2015)
	Land use	Site suitability of SC construction	(Charlesworth et al. 2016, Jia et al. 2013)
	Vegetation index	Characterizing regional ecological sensitivity	(MOHURD, 2019)
	Urban levels	Construction space of SC	(Jia et al. 2013)
Social development	Population density	Human activity intensity and potential disaster risk	(Nguyen et al. 2020)
	GDP	Financial support for SC construction	(Hou et al. 2020a, Jia et al. 2013)

Criteria	indexes	Definition	Reference
	urbanization planning	Urban future development planning	(Charlesworth et al. 2016, Nguyen et al. 2020)
	Public opinion	Public acceptance of SC	(Brown et al. 2016)

2.2.2 Construction of index system

The brainstorming method provides unique chance for researchers to discuss their opinions freely and positively (Osborn 1957). To initially assess and adjust the evaluating indicators for priority site selection of SC construction at macro-watershed scale, brainstorming method was introduced in this study to improve the reliability of the hierarchical structure considering the suitability and demand of SC construction. Afterward, expert interview method was employed twice to construct the final hierarchical framework (using NetMeeting and Email) and determine the weights (using questionnaire survey), respectively (Zhang et al. 2019). Consulting qualified experts is vital to establish credibility. Therefore, 42 experts were included, who came from universities, research institutions, the China Academy of Urban Planning and Design, and the government. The arithmetic mean was used to aggregate the experts' opinions. The findings are presented in *Section 3*.

2.2.3 Calculation of weight

The AHP method, as one of the most useful multi-criteria approaches, determines index weights based on the subjective attributes (Saaty 1980). Comparatively, the CRITIC method can estimate the objective importance by incorporating both contrast intensity and conflict of a decision structure (Diakoulaki et al. 1995). Accordingly, we introduced IAHP method by combining the subjective weights generated by AHP and objective weights generated by CRITIC to comprehensively determine index weights.

Specifically, three steps were involved, as shown below:

(1) Subjective weights generated by AHP method

The AHP method decomposes goals or problems into several hierarchies, and the index weights in each hierarchy were determined by experts' judgement. The pairwise comparison matrix was constructed according to the collected judgments made by experts, as shown below:

$$\boldsymbol{A} = \left(M_{ij}\right)_{n\times n} = \begin{bmatrix} M_{11} & M_{12} & \cdots & M_{1n} \\ M_{21} & M_{22} & \cdots & M_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ M_{n1} & M_{n2} & \cdots & M_{nn} \end{bmatrix} \tag{1}$$

where M_{ij} is the relative importance of factor i to factor j, computed by pairwise comparison with nine-quantity measurements (Table S1).

Thereafter, the relative importance of each criterion could be obtained using Eq. (2), where the normalized values of matrix $\boldsymbol{A}$ were determined by Eq. (3).

$$W_i^* = \sum_{j=1}^{n} M_{ij}^* \qquad \forall i = 1, 2, \cdots, n \tag{2}$$

$$M_{ij}^* = \frac{M_{ij}}{\sum_{j=1}^{n} M_{ij}} \qquad \forall i \& j = 1, 2, \cdots, n \tag{3}$$

The index weight vector was calculated using Eq. (4):

$$W_i' = \frac{W_i^*}{\sum_{i=1}^{n} W_i^*} \qquad \forall i = 1, 2, \cdots, n \tag{4}$$

The consistency of index relative importance in each hierarchy should be examined to determine the reliability of index weights. Therefore, the consistency rates have to be calculated by Eq. (5). These indexes are considered to pass the consistency test with CR less than 0.1.

$$CR = \frac{CI}{RI} \tag{5}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(mw)_i}{w_i'} \tag{7}$$

where RI is a random index, given in Table S2; CI is the consistency index; and λ_{max} is the eigenvalue maximum.

(2) Objective weights generated by CRITIC method

In the CRITIC method, each criterion C_i contains a certain amount of information, which can be quantified by Eq. (8). A higher C_i value indicates larger amount of information, showing higher importance in the decision-making process.

$$C_i = \sigma_i \cdot \sum_{k=1}^{m}(1 - r_{ik}) \qquad \forall i = 1, 2, \cdots, n \tag{8}$$

where σ_i is the standard deviation of i; and r_{ik} is the correlation degree between the vectors X_i and X_k.

These values were normalized to uniform objective weights according to Eq. (9).

$$W_i'' = \frac{C_i}{\sum_{k=1}^{m} C_k} \qquad \forall i = 1, 2, \cdots, n \tag{9}$$

(3) Comprehensive weights generated by IAHP method

To balance the subjective intention and objective impartiality of AHP method and CRITIC method, the mean values of the two methods were taken as the comprehensive weights. Comprehensive weights W_i were computed by Eq. (10).

$$W_i = \frac{W_i' + W_i''}{2} \qquad \forall i = 1, 2, \cdots, n \tag{10}$$

where W_i' denotes the subjective weight determined by the AHP method.

2.2.4 Priority index (PI)

To compare and weight data with different units or orders of magnitude, data normalization was employed to transform data sources into dimensionless scores ranging from 0.00 to 1.00. Data normalization was computed through the fuzzy membership tool in ArcGIS software.

After weighted and scored, GIS-based weighted summation was performed using Eq. (11):

$$PI = \sum_{i=1}^{n} W_i \times S_i \tag{11}$$

where W_i is the comprehensive weight; S_i is the index score; and *n* is index quantity. Afterwards, the spatially-detailed time sequence of SC construction can be quantified according to the *PI* model.

2.3 Data acquisition and pre-process

2.3.1 Runoff control indexes

Runoff is mainly affected by topography and landscape, including elevation, slope, soil permeability and impervious cover. Soil conductivity and soil depth are from the Soil Science Database. Soil data and impervious surface cover in 2017 are available at the Department of Earth System Science, Tsinghua University. A 30-m digital elevation model (DEM) from Resource and Environment Data Cloud Platform was processed using the ArcGIS hydrology toolset to develop slope and elevation.

However, we did not determine weights for the four indexes by AHP. The topographic index has been identified as evidence for generating runoff that can alter stream hydrology and potentially transport pollutants to streams (Beven &Kirkby 1979). Thus, we built an improved topographic index, which can cover this information perfectly based on the wetness index. The wetness index λ calculated by Eq. (12) is unitless, used to model surface runoff contribution area.

$$\lambda = \ln(\frac{\alpha}{\tan\beta}) \tag{12}$$

where α represents the surface runoff contribution area of 1-meter contour length; and β is the slope in radians ($\beta > 0$).

However, this index masks the soil water storage capacity. Besides, the impervious surfaces in urban regions deprive the soil water storage capacity. So, we improved a modified topographic index (TPI) to extend the usability of topographic index in urbanized areas, as shown in Eq. (13)-(14).

$$\ln(K_s D)^* = \ln(K_s D) \times \begin{cases} 1, & pervious\ \ surface \\ 0, & impervious\ \ surface \end{cases} \tag{13}$$

$$TPI = \ln\left(\frac{\alpha}{\tan\beta}\right) - \ln(K_s D)^* \tag{14}$$

where K_s is the soil hydraulic conductivity (m/day); and D refers to soil depth of restrictive layer (cm) with a maximum value of 200 cm.

2.3.2 Surface water quality indexes

Surface water quality indexes were obtained from river monitoring and the SPARROW model simulation. YPL and U-NPS of each subwatershed, as well as the pollutant concentration of each river section could be obtained from the calibrated model. Detailed information about the SPARROW model and simulation results were shown in Fig. S1-S4.

PR was calculated by the ratio of the monitoring concentration to the regional Environmental Quality Standards for Surface Water (EQSSW). Sample sites and collection were shown in our previous study (Zhang et al. 2020).

$$\mathrm{PR} = \frac{n}{N} \times 100\% \tag{15}$$

where n is the quantity of collected samples in a sampling site that are beneath the water quality standards based on the required EQSSW; and N is the total number of collected water samples in a sampling site.

The water pollution index (WPI) reflects the river pollution status, which was computed by Eq. (16).

$$\mathrm{WPI} = \sum_{i=1}^{n} W_i \times C_i \tag{16}$$

where n is the total number of water quality indicators (NH_3-N, TP, COD, FC, SS); W_i is the weight of the ith indicator; and C_i is the normalized concentration of the ith indicator. Remarkably, indicator weights were determined by the pollution levels of each indicator, which were obtained according to percentage of river sections exceeding standard Class V of surface water quality. The percentages were normalized to be the weights (Table S3).

Although PR and WPI reflect the water quality of river sections, they were transformed into raster data for GIS weighted summation with other data. This method is understandable, because river water quality represents the regional surface water environment.

2.3.3 Site suitability indexes

Land use and vegetation index data are available at the Resource and Environment Data Cloud Platform. We defined whether each type of land use permitted LID implementation according to previous studies (Charlesworth et al. 2016), and the suitability of five levels and scores are shown in Table S4. Besides, MOHURD (2019) claimed that the SC construction should protect ecologically sensitive areas, so the development of areas with high ecological sensitivity should be restricted. The vegetation index is a simple, effective and empirical measure of vegetation status and can thus be used as an alternative indicator of ecological sensitivity. The urban level was quantified by the impervious surface ratio, which represented the SC construction space; the higher the urban level, the smaller the construction space, resulting in lower priority. However, the urban level with less than 30% impervious cover was set to the lowest priority because SC construction aims to solve water problems in urban areas. Moreover, the river buffer is the distance to the river, which was calculated in ArcGIS using Spatial Analyst tools. Previous study indicates that landscape patterns have different influences on water quality at diverse buffer zone scales (Shen et al. 2015). Thus, the river buffer was divided into five levels: 0-100 m, 100-500 m, 500-1000 m, 1000-1500 m, and >1500 m, with standardized scores of 100, 80, 60, 40 and 20.

2.3.4 Social development indexes

Population density and GDP data are available at the Resource and Environment Data Cloud Platform. Urbanization planning (UP) was characterized by the growth rate of impervious surfaces (Eq. (17)). A higher UP value indicates that a region is in the process of urbanization, where it is considered a priority site to integrate into sponge city planning.

$$\mathrm{UP} = \frac{IM_{2015} - IM_{2010}}{IM_{2010}} \tag{17}$$

where IM_{2015} and IM_{2010} are the impervious surface ratios in 2015 and 2010.

2.4 Priority site assessment and verification

To find priority areas at either the raster scale or regional scale within a watershed, cluster analysis was introduced in this study. The iterative self-organizing (ISO) cluster and maximum likelihood classification were combined for priority site clustering analysis. The ISO cluster is most often used in the preparation of partitioning, unsupervised and iterative clustering algorithms, which uses a process where each iteration computes the minimum Euclidean distance when assigning each candidate cell to a cluster. Most classification objects are improbable to appear during the initial stage of cognition or classification. More detailed information relating to ISO cluster can be found in previous studies (Ball &Hall 1965, Richards 1986). Thereafter, the resulting signature file from the ISO cluster algorithm was put into the maximum likelihood classification, during which classification parameters can be designed accordingly. All the processes were completed using ArcGIS techniques, enabling priority sites for SC planning to be obtained for scientific analysis.

To verify the effectiveness of the method that was produced to prioritize SC sites at the watershed scale, we selected 3 sites stochastically to validate the effectiveness through filed visits, because changes may occur after data collection (e.g. construction), or space becomes limited owing to coarse-resolution land use data. Spatial heterogeneity of LULC characterizes urban patterns (Luo et al. 2020). The suitability was determined based on the feasibility of facilities implementation at a specific site. The GIS-based remote sensing possesses advantages to prioritize potential SC sites, outperforming the expensive and time-consuming approach to access all potential sites across watersheds.

2.5 Statistical analysis

To identify the underlying causes affecting the priority distribution, the SC priorities were explored at the subwatershed scale, where regional characteristics could be characterized more easily. We calculated the mean values of the indexes in each subwatershed in ArcGIS using Spatial Analyst tools and prioritized the subwatersheds using the ISO-maximum likelihood method. The normalized index values of each subwatershed of different priority levels were calculated in SPSS software. The inherent diversity and complexity of regional characteristics requires statistical descriptions to better understand how the evaluation index may influence the priority of SC planning. Hierarchical clustering provides unsupervised classification of all selected factors to identify characteristic factors. Thus, heatmaps of indexes in different priority regions were drawn by the *pheatmap* package within R. The distribution characteristics of index values were visualized.

3. Results

3.1 The construction of priority index model

Four criteria, including fifteen indexes, were recognized through brainstorming and expert interviews (Fig. 4). More specifically, in addition to the general factors, another two priority factors were added (“yield of pollution load” and “pollution rate based on EQSSW”) owing to pollution characteristics of complex watersheds. After that, the initial priority list was further subjected to modification in the next expert interview. The same opinions were proposed that four factors (“precipitation”, “temperature”, “evaporation” and “public opinion”) were excluded in this hierarchy structure, because of little spatial heterogenicity in the Beiyun watershed.

Based on the detailed description in *Section 2.2.3*, the index weights were calculated. The pairwise comparison matrix of the criterion layer and index layer according to experts' suggestions of AHP were shown in Tables S5-S8. The value of CR was within acceptable limits (<0.1), so the suggestions from experts were reasonable. Table 2 illustrates the weights of each index. The results of W-C showed that surface water quality was the most important indicator with a weight of 0.3784, followed by runoff control indicator with a weight of 0.3441. This result could be explained by the fact that urban water management, integrating water pollution and runoff floods, is the priority target of SC construction (Li et al. 2019, Lin et al. 2020), between which water pollution is the first priority (Leng et al. 2020). The next most important indicator was site suitability with a weight of 0.1477, which determines the effectiveness of SC facilities. In recent years, site suitability indicators have been emphasized and developed deeply by urban and landscape planners, as well as specialists and scholars in SC construction (Martin-Mikle et al. 2015). Social factors were considered less important for SC planning. In most studies, urban future planning has always been ignored (Hou et al. 2020a). However, these factors are indispensable; for example, financial conditions provide a foundation for SC construction but largely depend on investment from government at present (Zhang et al. 2019).

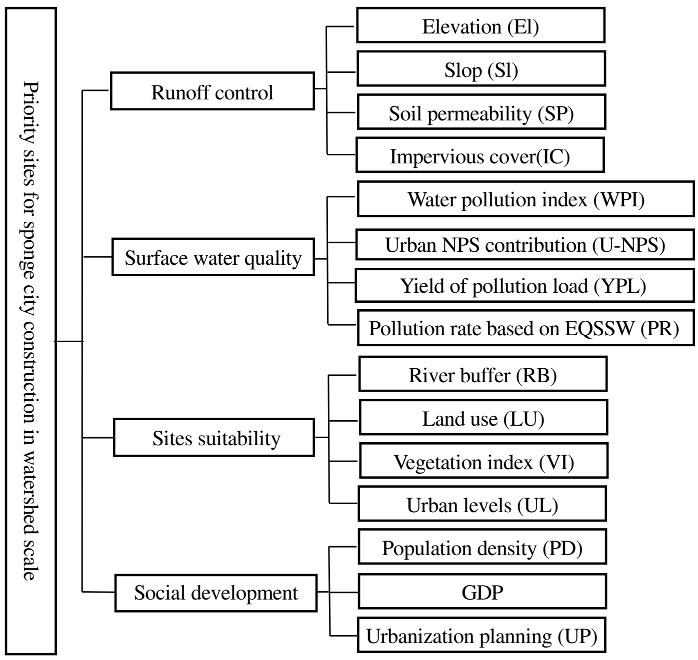

Fig.4 Hierarchical structure of SC planning in the Beiyun watershed

Table 2 Weights of the SC planning index

Criterion	W'_G-C [a]	Index	W'_L [b]	W'_G-I [c]	W'' [d]	W-C [e]	W-I [f]
Runoff control	0.38	El	(TPI)	0.38	0.1143	0.3441	0.3441
		Sl			0.0136		
		SP			0.1682		
		IC			0.0122		
Surface water quality	0.37	WPI	0.29	0.1073	0.1679	0.3784	0.1376
		PR	0.32	0.1184	0.1047		0.1115
		YPL	0.21	0.0777	0.0678		0.0728
		U-NPS	0.18	0.0666	0.0465		0.0565
Sites suitability	0.15	RB	0.39	0.0585	0.0927	0.1477	0.0755
		LU	0.27	0.0405	0.0136		0.0271
		VI	0.20	0.0300	0.0203		0.0252
		UL	0.14	0.0210	0.0188		0.0199
Social development	0.10	PD	0.41	0.0410	0.0585	0.1298	0.0498
		GDP	0.26	0.0260	0.0466		0.0363
		UP	0.33	0.0330	0.0543		0.0437

[a] W'_G-C: Global weights of AHP for criterion; [b] W'_L: Local weights of AHP for index; [c] W'_G-I: Global weights of AHP for index; [d] W'': Objective weights; [e] W-C: Combination weights for criterion; [f] W-I: Combination weights for index.

3.2 Prioritized SC sites

The raster-scale priority areas were developed using GIS techniques. Fig. 5a shows the result of the priority index result of SC planning, which ranged from 0.049-0.764 and exhibited a near normal distribution (Fig. 5c). Priority areas on the raster scale (1 km×1 km) corresponding to the priority index were generated based on the ISO-maximum likelihood clustering algorithm, according to which five levels were compared. Fig. 5b describes the spatial distribution of priority areas, where low priority areas (priority 1 and priority 2) accounted for 49.07% and the highest priority areas accounted for 15.03% (Fig. 5d).

In the Beiyun watershed, the areas of priority 5 were more prominent in the middle of the main stream, as well as the middle and lower reaches of the watershed where emerging urban areas are rising rapidly. These areas were identified primarily due to serious surface water pollution that results from rapid urbanization and weak infrastructure (Dou &Kuang 2020, Ishaq et al. 2019). The WPI in these areas was over 85, which is far more serious than that in the Baiyangdian Lake located in the prime core area of the Beijing-Tianjin-Hebei region, where the highest index was below 80% (Han et al. 2020). Besides, these areas have ample space for sponge facilities with an impervious cover of less than 60%. According to Dou and Kuang (2020), this is not yet developed urban areas. However, these areas have developed rapidly in the past decade accompanied by a growth rate of more than 20% compared with related reports (Sulemana et al. 2019).

Furthermore, Fig. 5b shows that the center of the watershed, which was the core area of Beijing city, was classified as priority 4. As demonstrated in Fig. S5, these areas generally exhibit good surface water quality, which supports the conclusions from previous studies that urban surface water quality has been improved over the past decade (Han et al. 2020). However, despite the limited space, these areas were selected as priority 4 due primarily to low infiltration capacity that results from large impervious surface areas of this region (over 60% impervious cover) with a topographic index of over 8. Martin-Mikle et al. (2015) also considered areas with a topographic index above 8.79 as hydrologically sensitive areas, based on which priority sites for LID implementation were identified. Additionally, if a flash flood occurs in these areas, there will be a large number of casualties and property losses due to the dense populations and high property concentration, which was consistent with what was widely reported by previous individual studies (Lin et al. 2020). Therefore, the SC construction in urban built-up areas should focus on flood management.

The areas with priority 3 surrounded the urban core areas (priority 4) and were in the middle and upper reaches of the watershed. Thus, if the resources are sufficient, including funds, government support, and human resources, etc., then SC planning and construction can be carried out in these areas. At present, SC construction is not recommended in priority 1 and 2 areas that are located upstream and downstream of the watershed, where forestland and agricultural land account for large proportions (over 40% and 50%, respectively). In theory, numerous suitable sites can be identified. However, social, economic and environmental benefits may decline as high-priority sites give way to low priority sites (Lin et al. 2020). We focused on the priority areas for SC planning to demonstrate where, along a continuum of benefits, the greatest return would be realized.

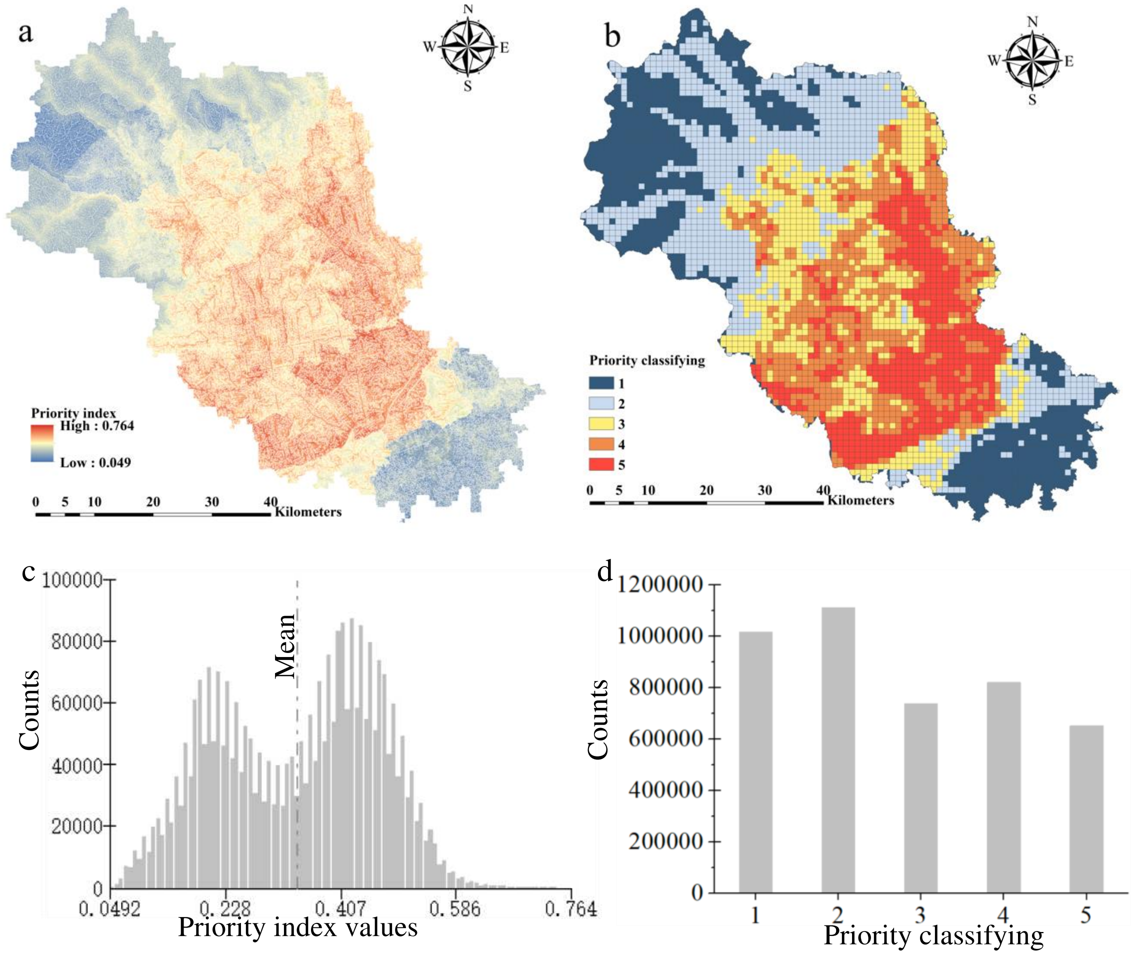

Fig. 5 Spatial distribution of priority sites for SC construction in the Beiyun watershed

3.3 Verification

Land use and elevation of the study area (Fig. 1) show that the northern part of the watershed is mountain areas and country parks where there is a low residential density. Besides, although the lower watershed is plain, which is conducive to the construction and implementation of LIDs, there are almost no residential areas or commercial areas in this area. Both of the areas mentioned above are consistent with the low priority in our study. The areas surrounding the center of the watershed are newly built-up areas, which is the best time for SC integration, supporting the highest priority for LID construction in these areas. The center of the watershed (core areas and downtown areas) is still a high density of residential and commercial areas accompanied by a high risk of casualties and property losses when facing disasters (Lin et al. 2020), requiring a higher priority of SC construction. So, the spatial distribution of priority sites, shown in Fig. 5, is reasonable.

The suitability of the three selected validation sites were verified through field survey (Fig. 6). There was a considerable area of bare land and under construction land that will provide enough space to facilitate bioretention ponds, which would be possible to manage runoff and pollutants from adjacent areas. The riparian buffer was the ideal site for LID implementation (such as riparian buffer) to slow and filter runoff. Besides, the validation sites contained buildings and roads with different densities where green roofs, rain barrels and porous pavement could be suitable facilities for treating runoff volume and quality. Briefly, the priority is reasonable, as the verification sites not only demonstrate the suitability of land use but also suggest that there is sufficient space in these areas to construct sponge facilities.

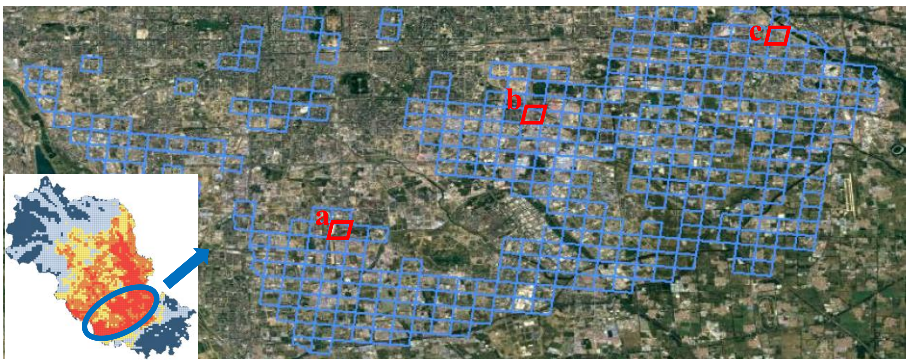

Fig. 6 Sites validation of the priority for LID implementation

4. Discussion

4.1 Advantages of the PI model

Sponge City planning has been demonstrated to be a multi-criteria and multi-objective decision-making process involving environmental, social, and economic issues (Thu Thuy et al. 2020). The present study reveals that 15 priority factors were included in watershbed-scale SC planning. The PI model is shown below, according to which the time sequence of SC construction at the raster scale or subwatershed scale can be quantified.

$$PI = \sum_{i=1}^{n} W_i \times S_i$$

$$= 0.3441 \times \text{"}runoff\ \ control\text{"} + 0.3784 \times \text{"}surface\ \ water\ \ quality\text{"} + 0.1477 \times \text{"}sites\ \ suitability\text{"} + 0.1298 \times \text{"}social\ \ development\text{"}$$

$$= 0.3441TPI + 0.1376WPI + 0.1115PR + 0.0565U\text{-}NPS + 0.0728YPL + 0.0755RB + 0.0271LU + 0.0252VI + 0.0199UL + 0.0498PD + 0.0363GDP + 0.0437UP$$

Although there has been generous research on coupling multi-objective decision support systems and mechanism models (e.g., SUSTAIN, SWMM) to optimize LID sites and combinations (Leng et al. 2020), most of these studies focused on the community scale and catchment scale, which has pushed SC planning to fragmentation (Ishaq et al. 2019). Determining spatial planning on a large scale is a challenging task owing to complicated contexts. Notwithstanding that SC planning and implementation are subject to substantial variabilities across influence factors and scenarios (Zhang et al. 2019), Martin-Mikle et al. (2015) identified priority sites for LID in a mixed-use watershed through hydrologically sensitive areas by calculating the topographic index. We admit that this is an important basis; however, more factors should be considered. Thus, the PI model in this study integrated micro-scale multi-objectives into macro-scale planning, which provides intelligible theory for the PI model in this study and will bridge the gap between macro-scale master planning and micro-scale facility layout.

The PI model will provide a unique chance to quantify the effect of SC on surface water bodies more easily in a watershed. Besides, fewer strategical construction allows for more affordable and consistently manageable SC projects. Additionally, from the perspective of mechanism, the method and systematic framework in this study should perform well in any region, although specific model parameters and coefficients may need to be recalibrated to more accurately plan SC construction on a large scale.

4.2 Management implications

It is clear that any policy or initiative aimed at maximizing the sponge effect must consider the priority of SC planning, given that it is a spatial multi-criteria and multi-objective decision-making process. The varying PI in our study highlights the urgent and important opportunities to implement SC in emerging regions where large area of buildings and infrastructures have yet to be constructed, which tracks with other research showing that emerging regions are optimal areas to mitigate carbon emissions owning to sufficient construction space (Cao et al. 2020). To avoid environmental problems during urbanization development, emerging regions should avoid replicating the patterns of urban planning from developed regions and instead pursue a LID strategy to achieve sustainable cities (Chatzimentor et al. 2020, Hou et al. 2020a).

Fig. 7 shows the subwatershed-scale priority of SC planning. The total area of subwatersheds with the highest priority accounted for 18.70%, followed by 26.45%, 12.22% and 42.63% (priority 2 and priority 1). The spatial distribution of priority is similar to that in Fig. 5b (see detailed discussion in *Section 3.2*). Fig. 8 shows the clustering results of the index at different priority levels. The high-priority regions generally exhibit higher WPI, PR and TPI, which is in line with the goals of SC construction. These findings are consistent with other research showing that SC is effective in managing surface water quality and urban flooding (Leng et al. 2020, Martin-Mikle et al. 2015). Besides, higher UP and lower UL provide sufficient construction space and unique opportunity for SC planning. Cao et al. (2020) also highlighted the priority of emerging regions to mitigate carbon emissions. Thus, SC is projected to become much more limited as the urban level rises. Fig. 8b shows that higher UL and lower UP reduced the priority compared to that in Fig. 8a. Moreover, a higher VI pushed SC planning to its lowest priority, as shown in Fig. 8c and 8d. The development of ecologically sensitive areas is restricted; thus, urban planning is not allowed, and some non-structural measures may suit these regions (Lintern et al. 2020).

Briefly, our analysis revealed that TPI, WPI, PR, UP, UL and VI are key factors affecting the regional priority for SC planning on a macro scale, which suggests that these six factors can be used as an alternative index for evaluating the priority of SC construction when a sufficient evaluation index is lacking. These insights in this study should be consistently included in SC planning toward facilitating the long-term mitigation of environmental problems during global urbanization.

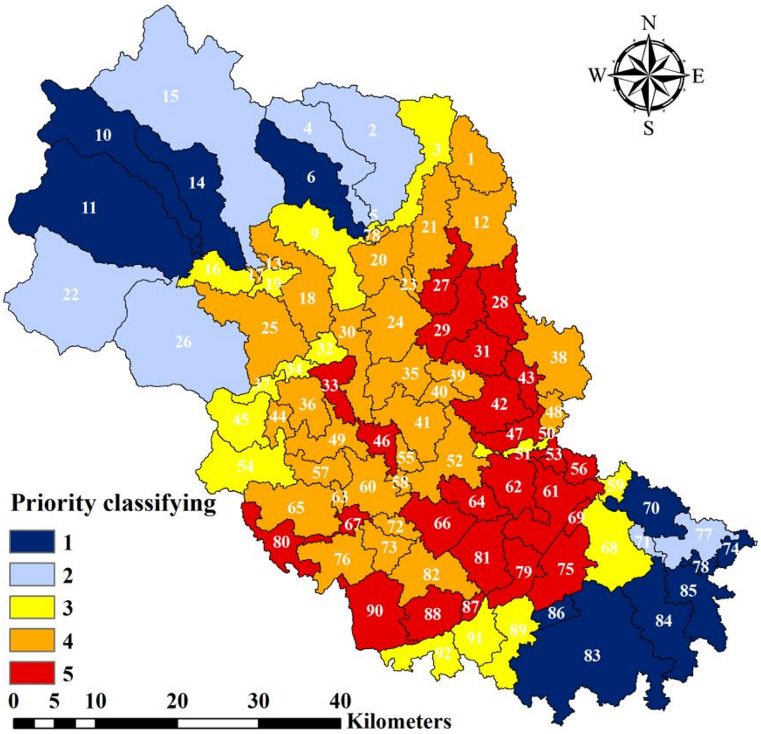

Fig. 7 Priority of SC planning in subwatershed scale

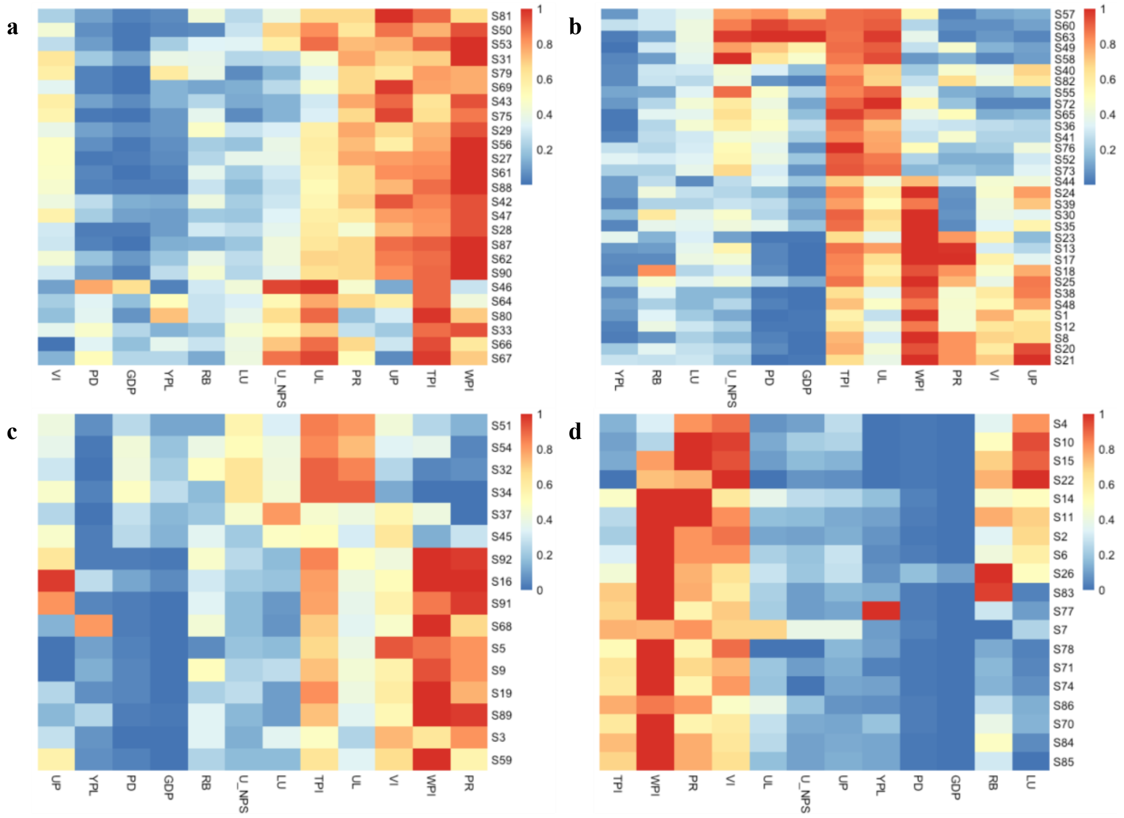

Fig. 8 Normalized index values of the assessment indices of the subwatersheds in different priorities (a: subwatersheds of priority 5; b: subwatersheds of priority 4; c:

subwatersheds of priority 3; d: subwatersheds of priority 2 and priority 1)

4.3 Limitation

There may be some uncertainties due to the accuracy of the publicly-available data that we obtained. Therefore, high-resolution data and accurate drainage network datasets are still needed to improve the prioritization approach. However, simulating underground drainage networks remains challengeable in urban areas. In addition, it is also advised to add extra assessment index when expanding this approach to other regions based on regional characteristics (i.e., SC facility applicability and decision maker preferences). Consequently, the SC can be constructed to prevent and solve site-specific and watershed-specific problems. Finally, to compute the overall priority index, the weights calculated by the AHP and CRITIC methods are equal, but some adjustments may be needed in the future studies.

5. Conclusion

The PI model was built based on multi-criteria in this study to prioritize SC planning at both the raster scale and regional scale to bridge the gap of opportunistic and empirical planning at the macro scale. The parameters were categorized into 4 criteria and 15 indexes through a literature review, brainstorming and expert interviews. Model coefficients were determined by the IAHP method.

The model was applied to the Beiyun watershed as a case study, and some findings were drawn. High-priority areas for SC construction were recognized in the emerging regions where large area of buildings and infrastructures have yet to be constructed, followed by developed areas with the highest urban level where the construction of SC should focus on flood control. Ecological protection areas and agricultural areas were considered as the lowest priority. Concurrently, these insights verified the rationality of the method. Additionally, clustering heatmaps showed that TPI, WPI, PR, UP, UL and VI were identified as key factors affecting the priority of SC planning. As such, the method and findings in this study will provide a reference for SC planning in other regions, even in the case of insufficient data.

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Authors' contributions Methodology, writing-Original draft preparation and software: Xiaoyue Zhang. Conceptualization, supervision and writing-Original draft preparation: Lei Chen. Investigation and software: Meng Zhang. Methodology, writing-Reviewing and editing: Zhenyao Shen.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Compliance with ethical standards

Competing interests The authors have no financial or proprietary interests in any material discussed in this article.

Ethical approval Not applicable

Consent to participate Not applicable

Consent to publish Not applicable

Supplementary Information

Details information about the SPARROW model, river water quality, source apportionment, results of the pairwise comparison matrix of AHP method can be seen in supplementary information.

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Figures

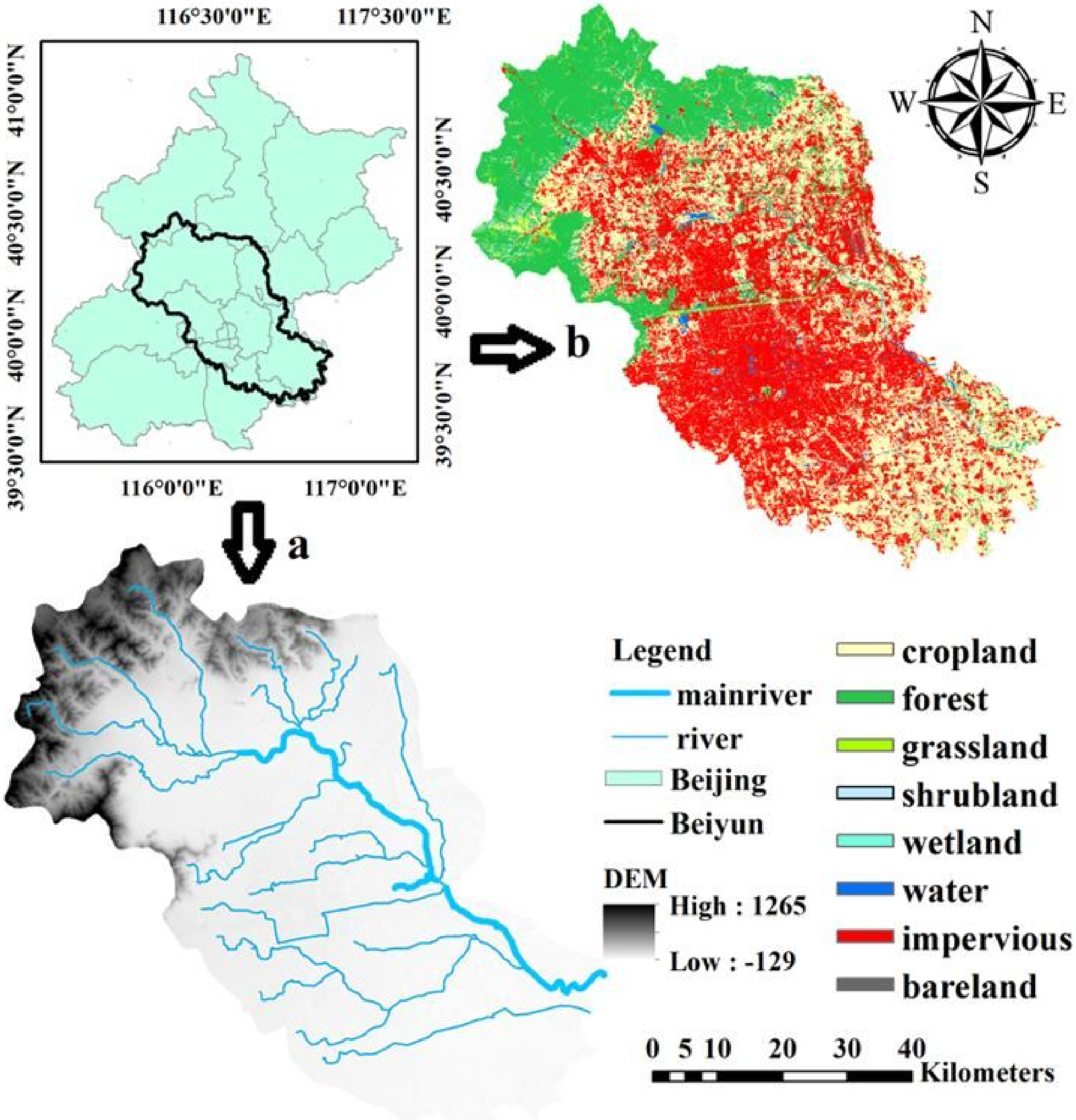

Figure 1

Land use and elevation in the Beiyun watershed Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

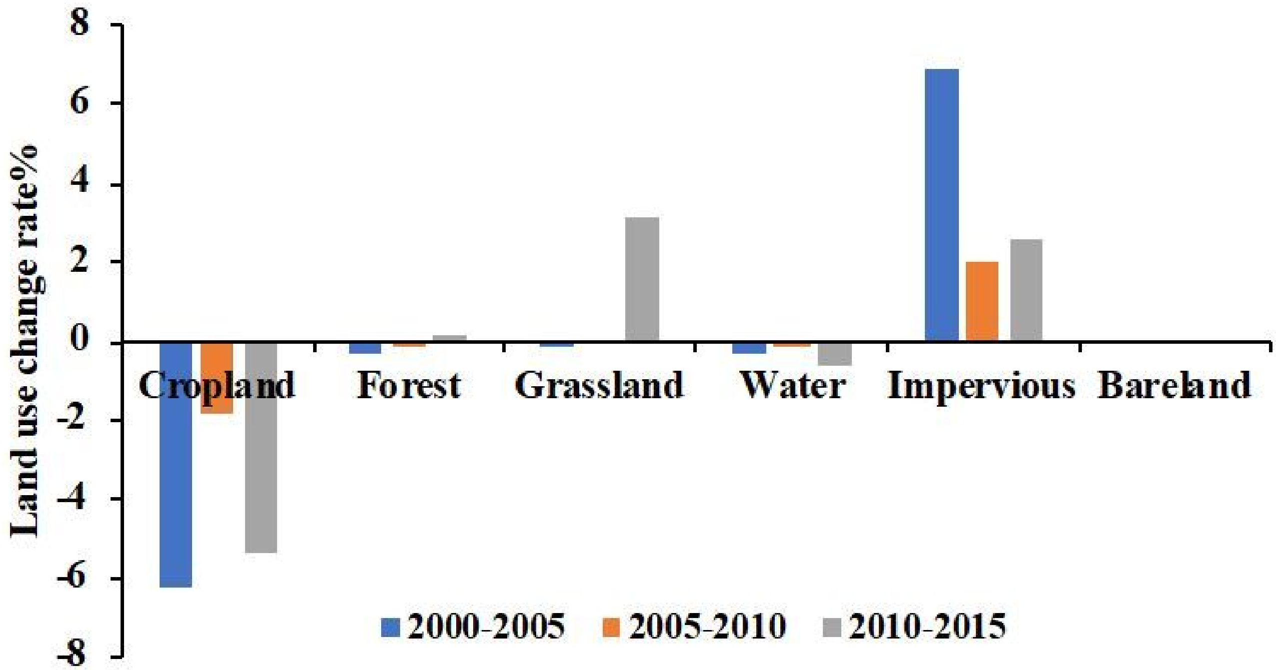

Figure 2

Land use change in the study area

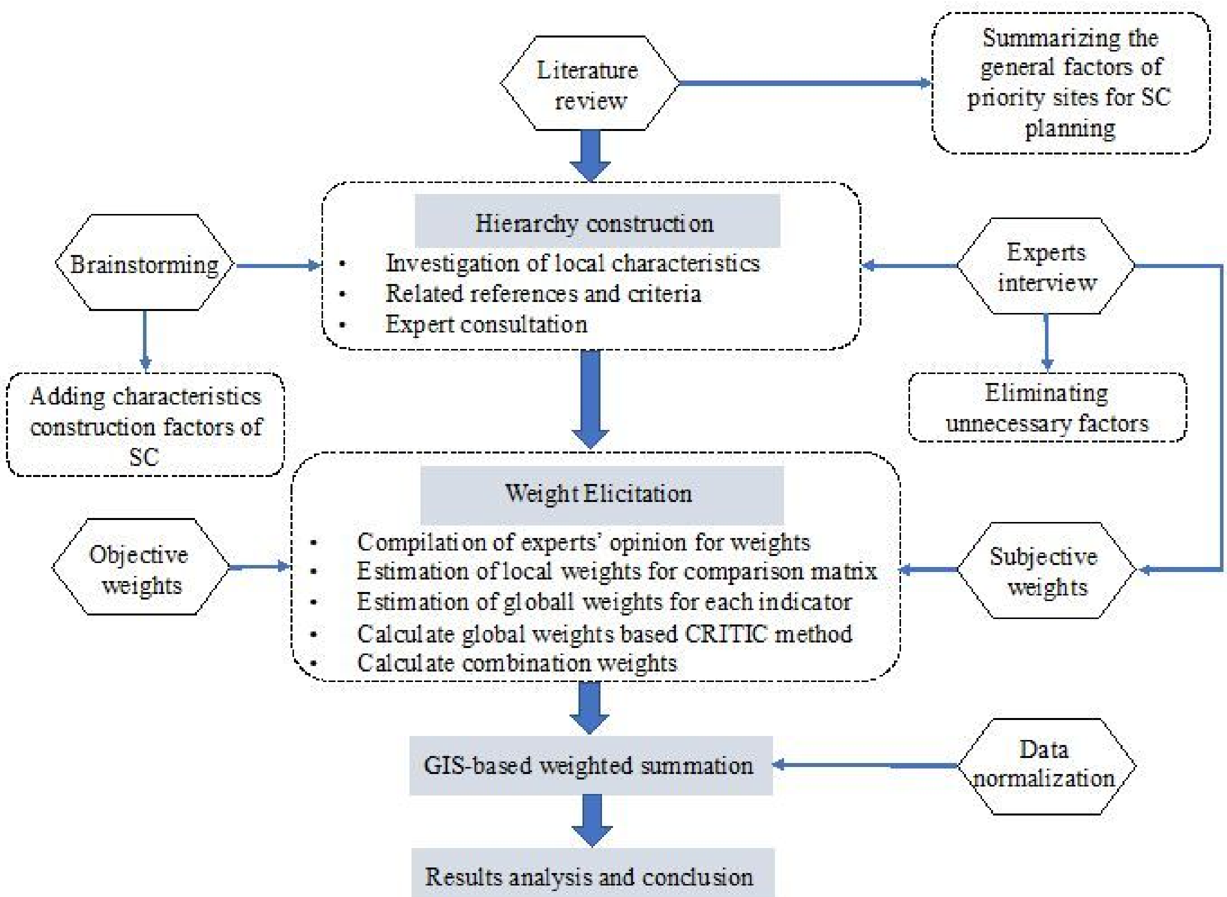

Figure 3

Framework of this study

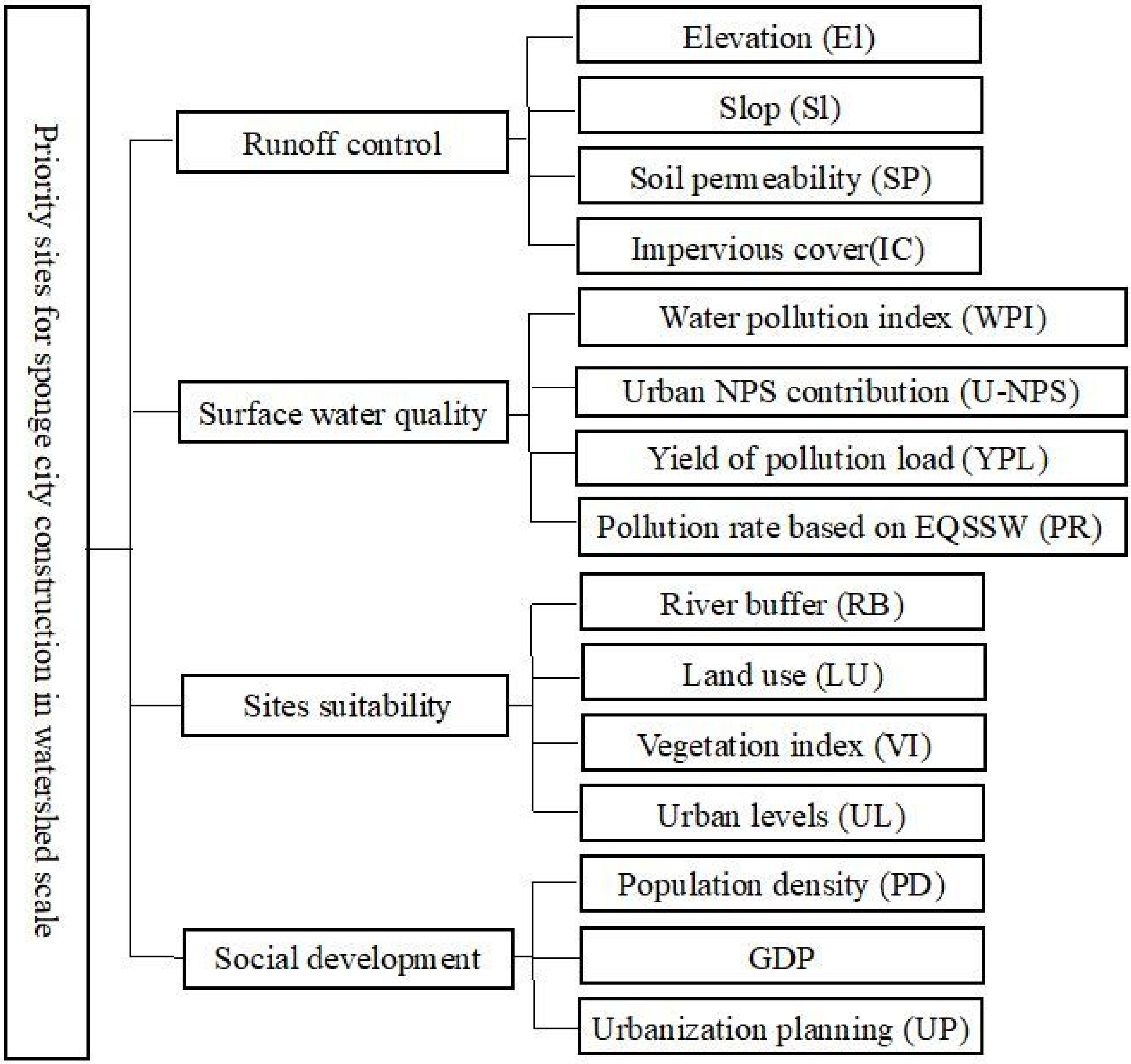

Figure 4

Hierarchical structure of SC planning in the Beiyun watershed

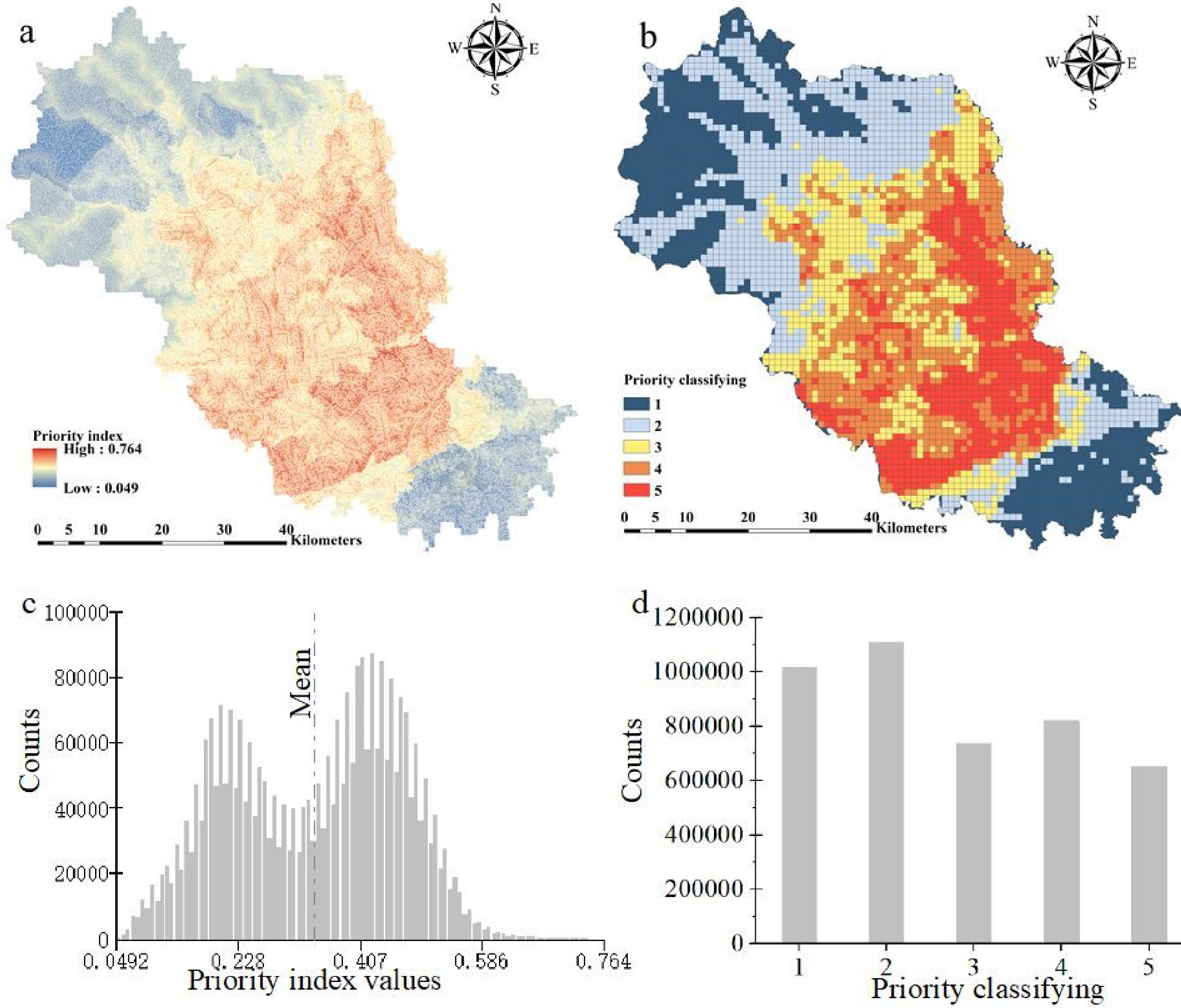

Figure 5

Spatial distribution of priority sites for SC construction in the Beiyun watershed Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

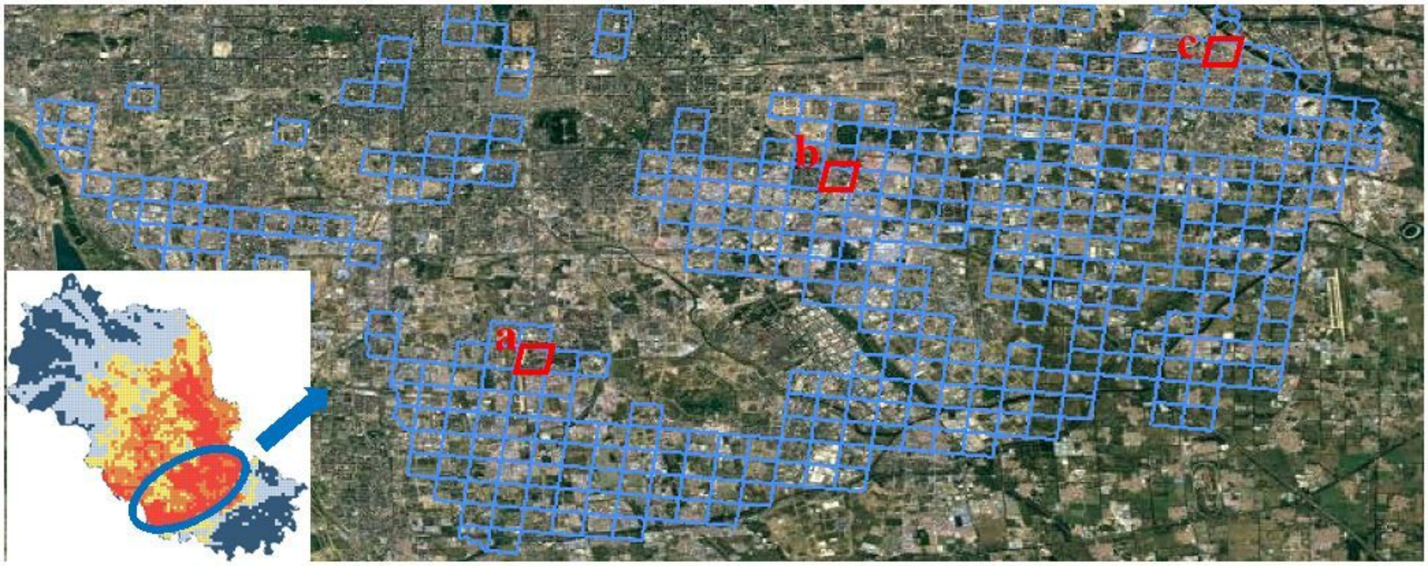

Figure 6

Sites validation of the priority for LID implementation Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

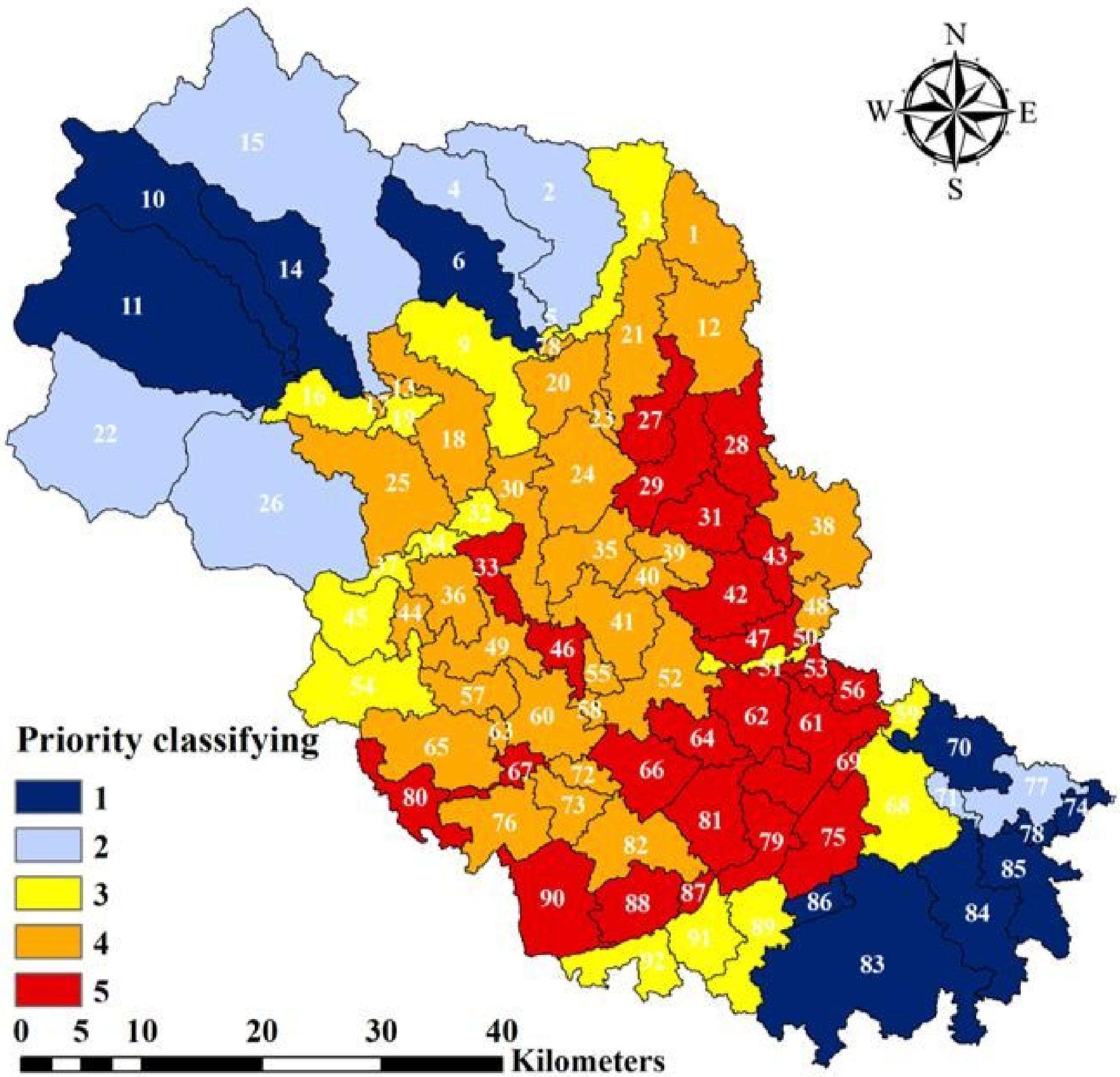

Figure 7

Priority of SC planning in subwatershed scale Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

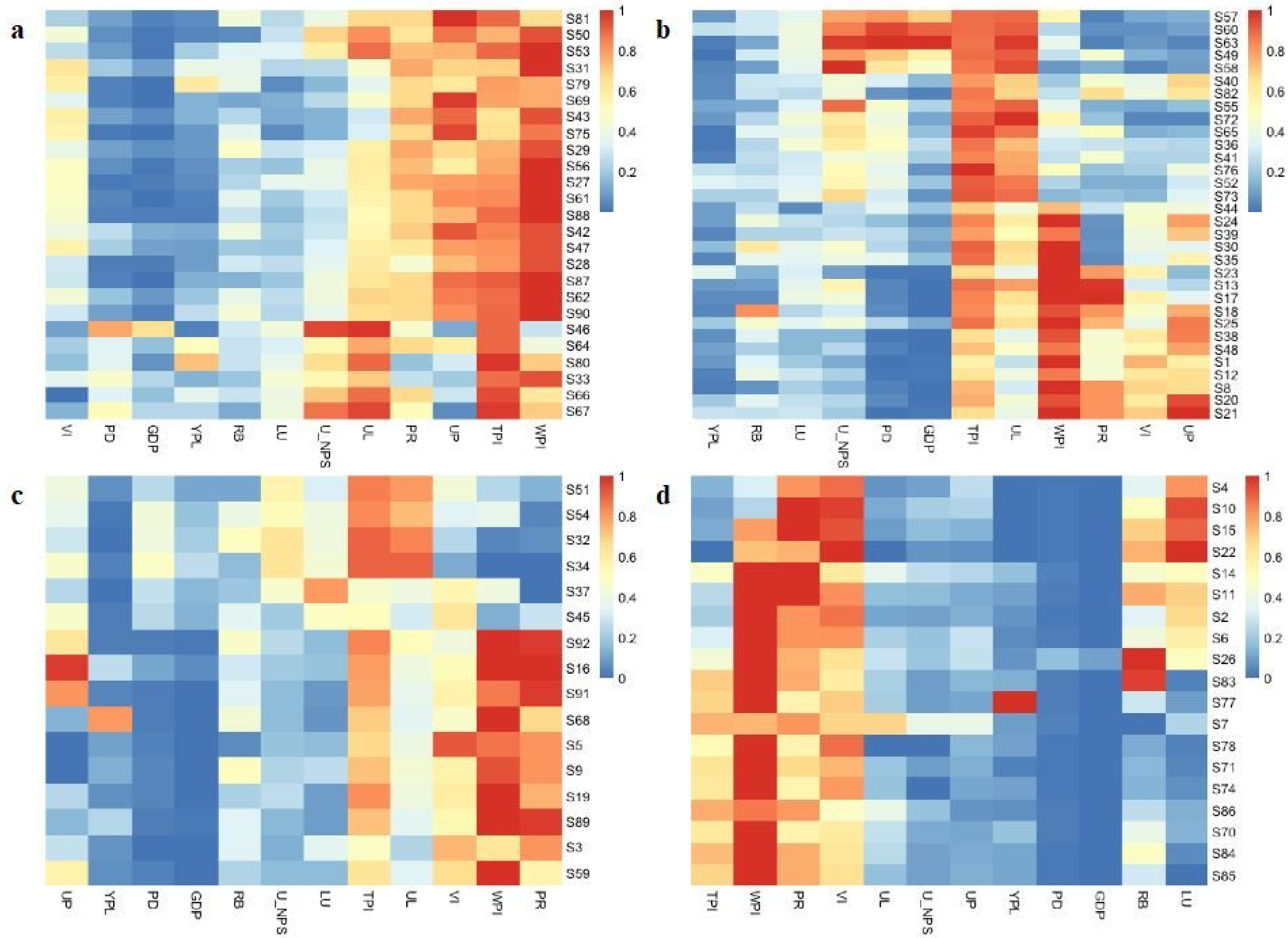

Figure 8

Normalized index values of the assessment indices of the subwatersheds in different priorities (a: subwatersheds of priority 5; b: subwatersheds of priority 4; c: subwatersheds of priority 3; d: subwatersheds of priority 2 and priority 1)

Supplementary Files

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