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An Evaluation Model for Sponge Cities Based on the Ecosystem Services Concept

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Abstract: Existing technical standards and research achievements related to sponge cities are largely concentrated on construction practices, while studies on evaluation mechanisms and systems for sponge cities remain extremely scarce. In order to construct a comprehensive evaluation system for sponge cities, this paper starts from a top-level design perspective and proposes a sponge city evaluation framework based on the ecosystem services concept. Water ecology, water environment, water resources, water security, institutional development and implementation, and visibility are adopted as first-level evaluation indicators. On this basis, feasible second-level evaluation indicators are extracted through an in-depth analysis of low-impact development (LID) stormwater systems. The analytic hierarchy process (AHP) and fuzzy comprehensive evaluation are introduced as systematic tools to establish a practical evaluation model, which is then applied to the assessment of the Yuelai Sponge City project in Chongqing.

Keywords: Sponge city; ecosystem services; evaluation model

1. Introduction

In current engineering practice, there is a strong tendency to address complex problems through single-objective engineering measures by constructing "gray" infrastructure. With regard to evaluation mechanisms or evaluation theories for sponge cities, Chinese scholars have conducted some exploratory attempts and theoretical constructions [1]. Some studies have established sponge city control indicator systems based on indicators such as stormwater control volume per unit area, permeable pavement ratio, sunken green space ratio, and green roof ratio; other studies have selected indicators including urban green coverage rate, the ratio of water resource consumption to supply, comprehensive water quality compliance rate, urban water reuse rate, and rainwater resource utilization rate, and have constructed comprehensive evaluation calculation models based on the weighted average method. The release of the Evaluation Standard for Sponge City Construction (Exposure Draft) has provided a reference direction for evaluation. How to effectively evaluate sponge city construction has become an urgent task and should also be a key focus for scholars and relevant departments.

2. Sponge City Evaluation System

2.1 Basis for Construction

The essence of sponge city development lies in promoting coordinated and harmonious urbanization with resource and environmental protection. The core focus is on establishing low-impact development (LID) stormwater systems, which mitigate urban waterlogging and river pollution by controlling stormwater quantity and quality. From the perspective of ecosystem services, the cross-scale construction of water ecological infrastructure is a fundamental requirement for achieving the overall development objectives and represents the core concept of the "sponge city."

The construction of an evaluation system depends on in-depth research into stormwater drainage patterns, through which feasible evaluation indicators can be identified and extracted. The construction process of an LID stormwater system is shown in **Figure 1**.

2.2 Principles for the Selection of Evaluation Indicators

To meet the overall planning and construction objectives, the principles for selecting control indicators for sponge cities are defined from the following four aspects:

(1) Comprehensiveness principle. Sponge city construction involves multiple dimensions, including urban water systems, green space drainage systems, urban drainage and flood control, and road transportation. Therefore, social, economic, and environmental factors should be fully considered, and comprehensive analysis and evaluation should be conducted [2].

(2) Manageability principle. Based on construction project planning and the *Measures for Performance Evaluation and Assessment of Sponge City Construction (Trial)*, the indicator system should be aligned with existing regulatory planning management systems to ensure simplicity, accuracy, and completeness.

(3) Quantifiability principle. Through hydrological and hydraulic calculations and simulations, indicators should be quantitatively assessed to determine whether they meet the control requirements of sponge city construction.

(4) Implementability principle. Indicators related to runoff reduction, runoff pollution control, and rainwater resource utilization should be selected as guiding indicators to reflect the actual effectiveness of sponge city construction.

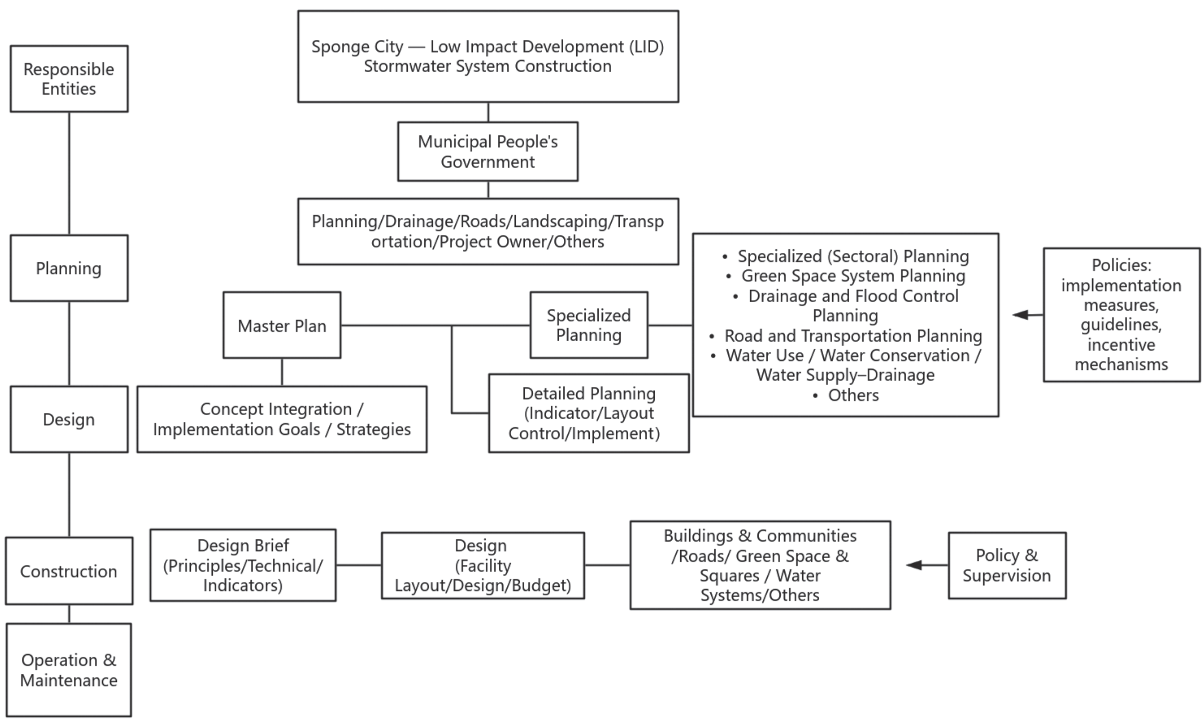

Figure 1. Schematic diagram of the construction of a low-impact development rainwater system

2.3 Hierarchical Evaluation Framework

The *Measures for Performance Evaluation and Assessment of Sponge City Construction (Trial)* propose that implementation effectiveness should be evaluated from six aspects based on the actual performance of specific projects. These include water ecology, water environment, water resources, water security, institutional development and implementation, and visibility.

Research indicates that within the low-impact development (LID) process of sponge cities and the corresponding supporting facilities, as well as among the various parameters involved in sponge city construction, there exists a pronounced hierarchical structure. Moreover, both the relationships among indicators and the relationships between individual indicators and the overall construction objectives exhibit a certain degree of "fuzzy correlation."

Based on these characteristics, this study establishes a hierarchical structure for the sponge city evaluation system, as shown in **Figure 2**.

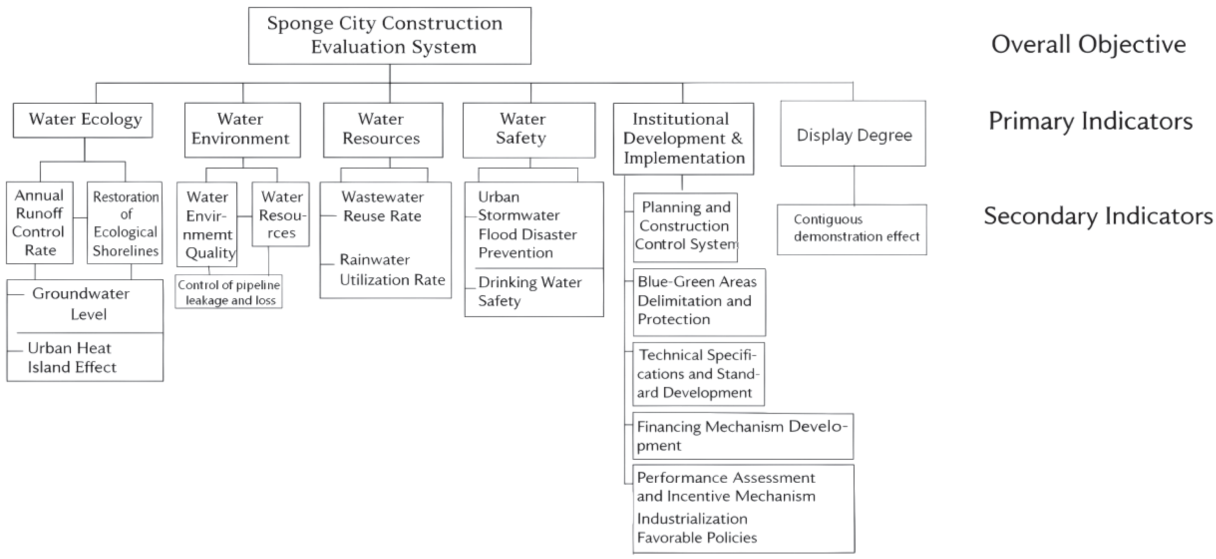

Figure 2. Hierarchical Structure of the Sponge City Construction Evaluation System

2.4 Quantification of Evaluation Indicators

2.4.1 Quantification and Normalization of Quantitative Indicators

Quantitative indicators can be divided into two categories: cost-type indicators and benefit-type indicators. As their calculation methods and units differ, it is necessary to normalize the quantitative indicators to make them dimensionless. The dimensionless normalization functions are as follows:

① Normalization of cost-type indicators

$$y_{ij}=\begin{cases}0 & x_{ij}\geq B_{ij}\\ \dfrac{x_{ij}-A_{ij}}{B_{ij}-A_{ij}} & x_{ij}\in(A_{ij},B_{ij})\\ 1 & x_{ij}\leq A_{ij}\end{cases}\qquad(1)$$

② Normalization of benefit-type indicators

$$y_{ij}=\begin{cases}1 & x_{ij}\geq B_{ij}\\ \dfrac{x_{ij}-A_{ij}}{B_{ij}-A_{ij}} & x_{ij}\in(A_{ij},B_{ij})\\ 0 & x_{ij}\leq A_{ij}\end{cases}\qquad(2)$$

where x_{ij} denotes the evaluation indicator;$x_{ij}\in[A_{ij},B_{ij}]$, $B_{ij}>A_{ij}>0$, y_{ij} denotes the normalized (dimensionless) result; $y_{ij}\in[0,1]$.

2.4.2 Quantification of Qualitative Indicators

For qualitative indicators, in order to obtain intuitive evaluation results, qualitative indicators should be quantified by establishing grading standards and determining corresponding score ranges. The specific score of each indicator is then derived according to the grade to which the indicator belongs. Based on the hierarchical structure of the constructed evaluation system, in combination with existing research on sponge city evaluation and the *Measures for Performance Evaluation and Assessment of Sponge City Construction (Trial)*, this study classifies qualitative evaluation indicators into five levels. The corresponding grading standards and score ranges are shown in **Table 1**.

Table 1. Grading Standards for Qualitative Indicators

Grade	1	2	3	4	5
Grading standard	Excellent	Good	Moderate	Poor	Very poor
Score range	[90, 100]	[80, 90)	[70, 80)	[60, 70)	[0, 60)

3. Evaluation Model

Considering the multi-level correlations and fuzzy characteristics between the indicator layers and the target layer of sponge city construction, the fuzzy comprehensive evaluation method is employed to construct the evaluation model.

3.1 Determination of the Factor Set and the Evaluation Set

The factor set is denoted as

$$U=\{u_1,u_2,\cdots,u_m\}$$

where u_i represents the i-th first-level indicator. Each u_i contains n second-level indicators, i.e.,

$$u_i=\{u_{i1},u_{i2},\cdots,u_{in}\}$$

where u_{ij} denotes the j-th second-level indicator under the i-th first-level indicator, $i=1,2,\cdots,m$; $j=1,2,\cdots,n$.

The evaluation set is expressed as

$$V=\{v_1,v_2,\cdots,v_w\}$$

where w is the number of evaluation grades, that is, the set of evaluation criteria for the indicators.

3.2 Determination of Indicator Weights

Methods such as the Delphi method, analytic hierarchy process (AHP), entropy method, and rank correlation analysis can be used to determine indicator weights. In this study, elements at each level of the hierarchical structure are compared pairwise with respect to the relevant elements in the upper level to establish a judgment matrix.

(1) Construction of the judgment matrix

Let the set of evaluation objects be $M=(M_1, M_2, \cdots, M_m)$ and the indicator set be $N=(N_1,N_2,\cdots,N_n)$. According to the evaluation objects M_i, the relative importance of indicator N_i to indicator N_j is denoted by $x_{ij}=(i,j=1,2,\cdots,n)$. The judgment matrix A is constructed as follows:

$$A=\begin{bmatrix} M_i & N_1 & \cdots & N_n \\ N_1 & x_{11} & \cdots & x_{1n} \\ \vdots & \vdots & & \vdots \\ N_n & x_{n1} & \cdots & x_{nn} \end{bmatrix} \tag{3}$$

(2) Normalization of each column of the judgment matrix

$$\overline{x}_{ij}=\frac{x_{ij}}{\sum_{k=1}^{n}x_{kj}}\left(i=1,2,\cdots,n\right) \tag{4}$$

(3) Row summation of the normalized judgment matrix

$$\overline{W}_i=\sum_{j=1}^{n}\overline{x}_{ij}\left(i=1,2,\cdots,n\right) \tag{5}$$

(4) Normalization of the vector $\overline{W}_i=\left[\overline{W}_1,\overline{W}_2,\cdots,\overline{W}_n\right]^T$

$$W_i=\frac{\overline{W}_i}{\sum_{i=1}^{n}\overline{W}_i}\left(i=1,2,\cdots,n\right) \tag{6}$$

$W_i=\left[W_1,W_2,\cdots,W_n\right]^T$ is the eigenvector of the judgment matrix.

(5) Consistency test

The maximum eigenvalue is calculated as

$$\lambda_{\max}=\sum_{i=1}^{n}\frac{(AW)_i}{nW_i} \tag{7}$$

The consistency index (CI) of the overall hierarchical ranking is

$$CI=\frac{\lambda_{\max}-n}{n-1} \tag{8}$$

The random consistency ratio (CR) of the overall hierarchical ranking is

$$CR=\frac{CI}{RI} \tag{9}$$

In Eqs. (7)–(9), $\lambda_{\max}$ denotes the maximum eigenvalue of the judgment matrix A; n is the number of indicators. RI represents the average random consistency index of the same order as CI, and its value is obtained by consulting **Table 2**. When $CR < 0.1$, the judgment matrix is considered to have satisfactory consistency.

(6) Determination of comprehensive weights.

The comprehensive weight of U_{ij} with respect to U is obtained by multiplying the weight of U_{ij} with respect to U_i by the weight of U_i with respect to U.

Order	RI	Order	RI	Order	RI	Order	RI	Order	RI	Order	RI
1	0.00	3	0.58	5	1.12	7	1.32	9	1.45	11	1.52
2	0.00	4	0.90	6	1.24	8	1.41	10	1.49	12	1.54

3.3 Construction of the Fuzzy Evaluation Matrix

The membership degree of indicator U_{ij} to evaluation grade $v_t\left(t=1,2,\cdots,w\right)$ is denoted as r_{ij}. The judgment (evaluation) set of U_{ij} is expressed as

$r_{ij} = \left(r_{ij1}, r_{ij2}, \cdots, r_{ijw}\right)$, where $i = 1, 2, \cdots, m; j =, 2, \cdots, n$. Accordingly, the fuzzy evaluation matrix R_{ij} for the m second-level indicators can be obtained:

$$R_i = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1w} \\ r_{i21} & r_{i22} & \cdots & r_{i2w} \\ \vdots & \vdots & & \vdots \\ r_{in_i1} & r_{in_i1} & \cdots & r_{in_iw} \end{bmatrix} \quad (10)$$

3.4 Fuzzy Comprehensive Evaluation

Let the secondary-level evaluation weight vector of the *i-th* first-level indicator be $W_{2i}\left(i = 1, 2, \cdots, m\right)$. The fuzzy comprehensive evaluation vector of the *i-th* first-level indicator is given by

$$H_i = W_{2i} \bullet R_i \quad (11)$$

Let the comprehensive weight vector of the first-level indicators be W_1. Then, the final comprehensive evaluation result vector is

$$Y = W_1 \bullet H = W_1 \bullet W_2 \bullet R = \left(y_1, y_2, \cdots, y_w\right) \quad (12)$$

4. Application of the Model

Yuelai New City in Liangjiang New Area, Chongqing, has successfully been approved as a pilot city for sponge city construction. The implementation plan for its construction is shown in **Table 3**.

Table 3. Implementation Plan for Sponge City Construction in Yuelai, Chongqing

No.	Component	Key Implementation Points
1	Urban Status	Regional conditions, topography and landform, hydrological and climatic conditions, rainfall characteristics, flood characteristics, water resource conditions, water environment and aquatic ecosystem status; existing urban planning, administrative zoning, land-use structure, urban drainage system status; urban flood control and drainage capacity, and the consistency between internal flood risk and external flood risk.
2	Implementation Objectives	Description of project background and basic concepts, construction scope, overall objectives, and annual phased objectives of project implementation (such as annual runoff control targets, flood control and drainage standards, flood risk reduction); system construction objectives including water quantity protection, water quality protection, low-impact development (LID) control targets, rainwater utilization, and sustainable development; urban flood risk emergency management objectives, including the establishment of urban flood monitoring and early warning systems, emergency response systems, technical standards and specifications, emergency management organizations and staffing, and hazard emergency preparedness.
3	Implementation Project Content	Compilation and approval status of special plans related to overall urban planning and sponge city construction; implementation requirements for sponge city construction, strict water resource management systems, and proposed “infiltration, detention, storage, purification, utilization, and discharge”; key project layout and demonstration projects; selection of technical routes through technical–economic comparison; determination of implementation content for various projects; investment scale and funding sources; annual implementation plans; and implementation guarantees for sponge city construction.
4	Safeguard Measures	Standard system construction, investment mechanism construction, performance assessment and supervision mechanism construction, supporting institutional mechanism construction, and capacity-building measures to ensure implementation.
5	Other Explanatory Items	Other relevant supporting explanatory materials provided according to evaluation content.

Based on a review of relevant literature and in conjunction with the *Guidelines for the Survey of Basic Information on Sponge City Construction in Chongqing*, this study conducts an evaluation of the completed sections of the sponge city based on the ecosystem services concept.

4.1 Determination of the Factor Set and the Evaluation Set

According to the characteristics and conditions of sponge cities, and based on the fuzzy comprehensive evaluation method, the performance evaluation target domain U of sponge city construction is divided into six mutually complementary and intersecting factors, namely

$$U = \left\{u_1, u_2, u_3, u_4, u_5, u_6\right\},$$

where u_1 represents water ecology, u_2 represents the water environment, u_3 represents water resources, u_4 represents water security, u_5 represents institutional development and implementation, and u_6 represents visibility [3].

Based on the indicators determined in **Figure 2**, the evaluation set is denoted as

$$V=\{v_1,v_2,v_3,v_4,v_5\}$$

where v_1 represents a "five-star sponge city," v_2 represents a "four-star sponge city," v_3 represents a "three-star sponge city," v_4 represents a "low-impact development sponge city," and v_5 represents a "general sponge city."

4.2 Weight Vector of First-Level Evaluation Indicators

4.2.1 Pairwise Comparison Judgment Matrix

To comprehensively evaluate sponge city construction performance, six evaluation indicators are selected, namely

$$U=\{u_1,u_2,u_3,u_4,u_5,u_6\}$$

According to the relative importance of the indicators, the single ranking of factors at each level with respect to the corresponding factor at the upper level is analyzed. Combined with expert scoring, a judgment matrix of the upper level with respect to this level is established. The calculation results are shown in **Table 4**.

Table 4. Pairwise Comparison Judgment Matrix of V with respect to U

U	u_1	u_2	u_3	u_4	u_5	u_6	M_i	W_i	$\overline{W}_i$
u_1	1	1	1/3	1/2	1	1	0.167	0.742	0.117
u_2	1	1	1	1/2	1/2	1	0.250	0.794	0.125
u_3	3	1	1	1	1	2	6.000	1.348	0.212
u_4	2	2	1	1	2	3	24.000	1.698	0.267
u_5	1	2	1	1/2	1	2	2.000	1.122	0.176
u_6	1	1	1/2	1/3	1/2	1	0.083	0.661	0.104

where $M_i=\prod_{i=1}^{n}a_i$; $W_i=\sqrt[n]{M_i}$;$\overline{W}_i=\frac{W_i}{\sum_{i=1}^{n}W_i}$.

4.2.2 Consistency Test

Based on Table 4, the judgment matrix A is established as

$$A=\begin{bmatrix}1&1&1/3&1/2&1&1\\1&1&1&1/2&1/2&1\\3&1&1&1&1&2\\2&2&1&1&2&3\\1&2&1&1/2&1&2\\1&1&1/2&1/3&1/2&1\end{bmatrix} \tag{13}$$

By computational programming, the maximum eigenvalue is obtained as $\lambda_{\max}=6.190$, $n=6$. Substituting these values into Eq. (8) yields $CI=0.038$. According to Table 2, the corresponding random consistency index is RI = 1.24RI = 1.24RI = 1.24. Substituting into Eq. (9) gives $RI=0.031<0.1$. Therefore, the judgment matrix passes the consistency test.

4.3 Fuzzy Evaluation

According to the method for determining the weight vector of first-level indicators, judgment matrices of second-level indicators relative to their corresponding first-level indicators are established separately and calculated using the analytic hierarchy process. Based on the Hierarchical Structure of the Sponge City Evaluation System, quantitative indicators are obtained through a review of engineering documents and relevant statistical analysis methods, while qualitative indicators are evaluated by 15 experts engaged in sponge city planning, engineering management, and environmental engineering research.

After mathematical and statistical processing, the fuzzy evaluation matrix is constructed, and the final evaluation result vector is obtained as:

$$Y=\begin{bmatrix}0.117&0.125&0.212&0.267&0.176&0.103\end{bmatrix}\begin{bmatrix}0.234&0.486&0.916&0.486&0.352\\0&0&0.667&0.333&0\\0&0.260&0.740&0&0\\0&0.429&0.571&0&0\\0.584&0.349&0.566&0.777&0.504\\0.200&0.600&0.600&1.000&0.600\end{bmatrix}$$

$$=\begin{bmatrix}0.151&0.350&0.661&0.338&0.192\end{bmatrix}$$

According to the principle of maximum membership degree, the Yuelai Sponge City in Chongqing is classified as a “three-star sponge city.”

Conclusions

(1) Sponge city development is an important measure for China to promote the transformation of new-type urbanization and a key component of ecological civilization construction. The construction of the Yuelai Sponge City in Chongqing has achieved certain results and formed distinctive “Chongqing characteristics.” In the future, it is still necessary to advance the development of investment and financing mechanisms, introduce social capital, and establish performance assessment and incentive mechanisms as well as preferential policies for industrial implementation.

(2) Sponge city construction involves multiple dimensions and exhibits holistic, systemic, and comprehensive characteristics. From a top-level design perspective, this paper proposes a conceptual framework for constructing a sponge city evaluation system. Through the study of stormwater discharge patterns and based on the construction process of low-impact development (LID) stormwater systems, feasible evaluation indicators are identified and extracted.

(3) The evaluation model classifies sponge city performance into five levels: "five-star sponge city," "four-star sponge city," "three-star sponge city," "low-impact development sponge city," and "general sponge city." The evaluation results indicate that the Yuelai Sponge City in Chongqing is a “three-star sponge city.”

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