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Ecological Evaluation of Sponge City Landscape Design Based on Aquatic Plants Application

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Abstract: Urbanization increases the impervious surface of land and disrupts the hydrological cycle of urban water resources. Optimum landscape design based on climatic and geographical factors can reduce the destructive effects of urban development on surface and subsurface flows. The construction of a sponge city is an essential step towards achieving this structure. Aquatic plants are the most important component of the ecological regeneration of urban landscapes. The land cover changes caused by aquatic plants reduce the speed of water and increase the penetration of runoff into the porous environment. In addition, not only can the use of aquatic plants as the main component of water saving for ecological restoration control water erosion, but it can also have a positive effect on landscape architecture. Therefore, the aim of this study was to develop a multi-objective urban landscape design model based on the use of aquatic plants. Moreover, the limitations of improving the urban ecosystem with aquatic plants were analyzed based on the theory of ecological restoration in a sponge city. The required area for the cultivation of these plants was calculated according to the flood return periods and the two objective functions of land slope and runoff rate. The results show that surface runoff decreased by 15% and that rainfall and flood decreased by 21% for a 50-year return period.

Keywords: aquatic plants; ecological restoration; multi-objective management; sponge city

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1. Introduction

Urban development in China has made considerable achievements in recent years. In 2017, the urban population accounted for more than half of the country's total population for the first time, increasingly more labor flowed into cities, and urban construction became more industrialized and modernized [1,2]. However, with the development of urban construction, the problems of resources and environment are increasingly arising, and they restrict sustainable development. Among them, the contradiction between the supply and demand of the urban water cycle is especially prominent and difficult to solve. In order to solve the main contradiction between urban rainfall drainage and urban water resources shortage, the concept of sponge city construction was proposed [3,4]. A sponge city, by combining biophysical technology to implement surface water diversion and to speed up infiltration, realizes the decentralized control of runoff pollution sources and achieves the urban benign hydrological cycle to effectively solve the problems of urban rainwater, urban water pollution, and urban water resources shortage. At present, the use of aquatic plants for the ecological restoration of a sponge city is considered due to its low cost and environmental protection. Aquatic plants are the primary producers in water ecosystems and an important part of wetland ecosystems [5,6]. Many aquatic plants can adapt to water or similar environments, forming some typical adaptive characteristics to water environments. Generally, according to the lifestyle and plant morphological characteristics of aquatic samples, aquatic plants are divided into three life forms: emergent, floating, and submerged. Therefore, in the selection of aquatic plants for ecological restoration systems, we should follow certain plant screening principles and select excellent aquatic plant species so as to give full play to the wetland plant function, improve the wetland sewage treatment capacity, create a suitable ecological environment, improve and stabilize the ecological system, and achieve the purpose of ecological restoration. Aquatic plants can absorb nutrients in wetland systems and remove harmful components in sewage, and they are a key group for the restoration and reconstruction of degraded water ecosystems [7,8]. At the same time, the root zone of aquatic plants can also provide aerobic and anaerobic environments for microorganisms so as to realize the in situ remediation of water bodies. In recent years, urban construction has increasingly used aquatic plants to purify water bodies in order to treat domestic sewage; urban greening and the purification of metal elements have been extensively studied [9].

Simulation–optimization modeling is one of the main components in the design and evaluation of sponge city plans [10,11]. Various objective functions have been evaluated in sponge city optimization problems, such as socio-cultural factors [12,13], urban water allocation [14], construction costs and environmental benefits [15], the runoff rate and life cycle cost [16], and design parameters [17]. She et al. [15] proposed a multi-objective optimization model to minimize the runoff and construction costs of sponge cities and to maximize the environmental benefits using simulated annealing algorithms. An annual runoff control coefficient of less than 0.22 was obtained using the developed model in the sponge city construction pilot implementation plan. Huang et al. [16] employed genetic algorithms for the optimization of an urban runoff simulation model. The proposed framework was constructed based on the Storm Water Management Model (SWMM) and Environmental Protection Agency (EPA). The results proved that the genetic algorithm was feasible for sponge city planning in urban areas. In another study, the runoff control rate was estimated to be about 75% when using a distribution optimization method in a new sponge city in Shaanxi province [18]. Zhi et al. [19] developed a new framework for sponge city design by using cost-effectiveness optimization and by integrating a robustness analysis, which can provide guidance for design, especially in response to rainfall events with high variability. Wan et al. [20] used the non-dominated sorting genetic algorithm (NSGAII) to design a sponge city project. The model involved three dimensions of objectives, namely, facility efficacy, project cost, and landscape quality.

On the basis of combining the growth habit and evolution mechanism of aquatic plants, as well as the relevant theories of green planting, the problems that may be faced in the ecological practice of sponge city restoration are classified and discussed so as to provide a reference application mode for the “sponge” construction of the urban ecological landscape in China in the future [21]. Moreover, this also gives an objective outlook on future development directions. At the same time, a risk control system for urban rainwater and flood should be established, and the large-scale construction of sponges to reduce rainwater runoff pollution and to improve the utilization rate of rainwater resources should be promoted. Ecological restoration technology uses biological life activities to absorb extra rainwater so as to achieve the effect of purifying roads. Through a comparative advantage analysis, we can determine the similarities and differences in the growth of green aquatic plants, gain advanced knowledge, put forward improved methods and approaches combined with the development of new methods, and expect to provide a theoretical basis for the ecological restoration and management of sponge cities.

One of the principles of designing and creating a sustainable decision model is the use of optimization models and the selection of appropriate objective functions. In this paper, an intelligent multi-objective model based on non-dominated sorting was proposed to develop a decision-making framework and to determine the level of application and the type of aquatic plants. Another decision-making component was to test the indicators of different types of aquatic plants in terms of the growth law and pollutant removal, which can more effectively combine the needs of urban features and select plants for effective ecological restoration.

2. Materials and Methods

2.1. Model Description

With the development of urban modernization, more sponge cities are being used to ensure the self-control and regulation abilities of rain and floods in urban areas or those in a specific range. People use the concept of a sponge city to ensure that the city has good flexibility in adapting to environmental changes and natural disasters in a similar manner to sponges. Road construction and high-rise building construction in cities have caused many problems in rainwater diversion, water storage, and infiltration, breaking the normal water cycle of nature, while the construction of a sponge city requires the use of almost entirely natural discharge and collection methods to realize the spontaneous exchange of rainwater in nature, as well as realizing the transformation from an artificial city to a natural ecological city. Sponge city construction should follow the principle of ecological priority and combine natural methods with artificial measures on the premise of ensuring the safety of urban drainage and waterlogging prevention; maximizing the accumulation, infiltration, and purification of rainwater in urban areas; and promoting the utilization of rainwater resources and ecological environment protection. The advantage of a sponge city is the upgrading of the drainage system of the city, as well as the more environmentally coordinating and mobilizing of all links to maximize the role of the city itself.

2.2. Aquatic Plants

Different types of aquatic plants that can be harvested for ecological restoration were considered, and their characteristics were investigated. After preliminary evaluations, five aquatic plants were selected, namely, reed, lotus, black algae, water hyacinth, and soft-stem club-rush. Reed plants grow in lowland areas and transfer oxygen from their shoot zone to their root zone. Lotus (Nelumbo lutea) is a conspicuous emergent aquatic plant that frequently grows in local ponds. Black algae is an extremely resistant strain of algae. It grows well in water on walls, floors, and surfaces. Water hyacinth is an aquatic plant native to South America, naturalized throughout the world, and often invasive outside its native range. Soft-stem club-rush plants tend to flourish in damp conditions, often being found close to or in standing water. These evergreen perennials are popularly used in ponds or water gardens, providing shelter and a food source for wildfowl. Traditionally, some species are woven into baskets, mats, and even homes.

All the experimental data were arranged by big data. By drawing, the data were analyzed using a de-trend analysis and a redundancy analysis, and the relationship between the aquatic plants and environmental factors was analyzed. RDA is based on a statistical method and is used to evaluate the relationship between one variable or a group of variables and another group of multivariable data. RDA was used to judge the interpretation amount of environmental factors on the spatial distribution of species and to determine the primary and secondary impact relationships of each environmental factor; then, an interpretation of the RDA ranking chart of key factors affecting the distribution of the species was made. The length of the species arrow indicates the amount of interpretation of the species and the species arrow. The angle between the two species indicates the significance of the correlation, the length of the environmental factor arrow indicates a greater impact of the environmental factor on the species, and the foot between the species arrow and the environmental factor arrow represents the correlation. The comprehensive trophic state index method was used to evaluate the ecological restoration state of the aquatic plants for rainwater collection data.

The importance value index (IVI) is a measure used to evaluate the domination of a species in an ecosystem [22], and it can be obtained as follows:

$$AVI = RF + RC + RA \tag{1}$$

where *RF* = relative frequency (total no. of a particular species found in all quadrants/total no. of quadrants sampled), *RC* = relative coverage (total no. of a particular species found in all quadrants/total area sampled), and *RA* = relative abundance (basal area of a particular species/total basal area).

2.3. Model Structure

A framework based on multi-objective programming was developed to formulate the deep percolation and runoff simultaneously. For this, the obtained outputs of the simulation model were incorporated to provide a multi-objective optimization structure. However, the objective functions were considered in different iterations using the non-dominated sorting method [23] and were specified to the whale optimization algorithm (NSWOA) for evaluating the Pareto front.

In addition to studying the interaction of the surface and subsurface flow, the maximization of the percolation parameter was considered as an objective function, and it was simulated using Equation (2):

$$Min\ ROR = (R - E - TR - P)/\Delta V \ \ \forall \ \ i = 1,\ 2,\ \ldots,\ nt \tag{2}$$

where *ROR* is the runoff rate (mm), ΔV is the volume of the stored water in the subsurface zone (mm), *R* is the rainfall (mm), *E* is the evaporation (mm), and *P* is the percolation (mm). The second objective function was a minimization of Equation (3):

$$Min\ S = \left(Qn/AR^{2/3}\right)^2 \tag{3}$$

where *S* is the hydraulic gradient, *A* is the cross-sectional value; *Q* is the discharge, *n* is the roughness coefficient of the Manning function, and *R* is the hydraulic radius. The percolation rate could be formulated using Equation (4):

$$P = P_s\left(1 + C\frac{MSMC - SMC}{MSMC}\right) \tag{4}$$

where *P* = percolation rate under the saturated condition; SM_m = soil moisture content; *SM* = soil water content; and *C* = the permeability coefficient. Evaporation and transpiration were calculated using Equations (5) and (6), respectively:

$$E = 0.675\left(\sum\left(\frac{\tau_i}{5}\right)^{1.514}\right)^3 - 77.1\left(\sum\left(\frac{\tau_i}{5}\right)^{1.514}\right)^2 + 17920\left(\sum\left(\frac{\tau_i}{5}\right)^{1.514}\right) + 0.49 \tag{5}$$

$$Tr = KcKswKcs\frac{\left(0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)w(e_s - e_a)\right)}{(\Delta + (1 + 0.34w))} \tag{6}$$

where τ = mean temperature in month *i*; *Kc* = a coefficient for indicating crop transpiration based on the land canopy cover; θ = local thermal parameter; *Ksw* = soil moisture coefficient (*Ksw* < *1*); *Kcs* = cold stress index (*Kcs* < 1); R_n = net radiation at the crop surface (MJ/m^2·day); Δ = slope of saturation vapor pressure versus air temperature (kPa = °C); *G* = soil heat flux density (MJ/m^2·day); γ = psychrometric constant (kPa/°C); *T* = mean daily air temperature at 1.5–2.5 m height (°C); *w* = mean daily wind speed at 2 m height (m/s); e_s = saturation vapor pressure (kPa); and e_a = actual vapor pressure (kPa).

The simulation model was optimized using the non-dominated sorting theory and the whale optimization algorithm. In the first step, a random population was initially prepared. Next, the objective functions were calculated for each streamflow strategy. The modified populations were sorted into different fronts, where the best level of solutions is called the Pareto front. The crowding distance theory [23] was implemented for improving the Pareto front solutions to frontier solutions.

The basic concept of the whale optimization algorithm (WOA) was simulated according to the social life of whales. In this optimization method, answers are determined in a search space based on the position of the whale. Therefore, a random population should be defined as follows:

$$x_i = L_i + rand(0,1) \times (U_i - L_i), \quad x_i \in X,\ i = 1,\ 2,\ 3,\ \ldots,\ N \tag{7}$$

Equation (7) calculates the objective function of each position x_i that the best position x_i is considered as x_{best}. In the next step, the encircling and the bubble-net methods are two approaches that are evaluated by the whales to attack their prey. Mirjalili et al. [24] reported that the position of each whale can be updated according to the distance D_i between the current position $x_i(t)$ and the best position x_{best} (t) at iteration t, as formulated in Equation (8):

$$D_i = |H \odot x_{best}(t) - x_i(t)| \tag{8}$$

where ⊙ = the element-wise generation factor. W and H indicate the coefficient vectors (Equations (9) and (10)):

$$H = 2r \tag{9}$$

$$W = 2w \odot \mathrm{r} - \mathrm{w} \tag{10}$$

where r = a vector that is randomly generated from 0 to 1. w = a control value based on iterations between 2 and 0 (Equation (11)).

$$w = w - t\frac{w}{t_{max}} \tag{11}$$

where t_{max} = the maximum iteration number. There are two methods that mimic the behavior of the bubble network used to simulate the second attack. In the first method, the value of w is reduced proportionally to the iteration, and the second method is proposed based on a spiral process. Equation (12) cab be considered as a strategy to obtain x_{best} [24,25]:

$$x(t+1) = D' \odot e^{bi} \odot \cos(2\pi l) + x_{best}(t) \quad D' = |x_{best} - x(t)| \tag{12}$$

where b and l provide the logarithmic spiral factor and a random variable, respectively, which can be varied between −1 and 1. Equation (13) simulates the swimming of the whales around the prey (x_{best}):

$$x(t+1) = \begin{cases} x_{best}(t) - W \odot D & \text{if } p \geq 0.5 \\ D' \odot e^{bi} \odot cos(2\pi l) + x_{best}(t) & \text{if } \ p < 0.5 \end{cases} \tag{13}$$

where $p \in [0, 1]$ is a factor for determining the spiral-shaped or shrinking circle strategies [26,27]. Moreover, the new location of a solution is estimated by x_{rand}. This mechanism is defined using Equations (14) and (15):

$$D = |\mathrm{H} \odot x_{rand} - x(t)| \tag{14}$$

$$x(t+1) = x_{rand} - W \odot D \tag{15}$$

This iterative process is repeated until a stop criterion is satisfied; after that, the output x_{best} is the optimal solution.

3. Results

3.1. Optimal Landscape Design

The multi-objective optimization model was executed based on the objective functions and constraints of the problem, and the Pareto front was obtained as shown in Figure 1. The planning of this model was based on the application of conflicting objective functions [28,29]. The choice of an optimal solution can be carried out according to the precipitation volume, with a return period of 25 years. This return period is recommended for designs related to rainfall and runoff [30,31]. Therefore, this was the basis for choosing rainfall with a severity of 18 mm/h and a height of 87 mm. For this return period, the ratio of cultivated area and the land slope for a sponge city were 21% and 0.002, respectively. Other cultivated areas and land slopes are illustrated in Figure 2 based on the different return periods. As shown in the figure, considering the return period with a higher level of confidence increases the sponge lands ratio. The illustrated results have a fuzzy domain that shows the extreme responses of the decision changes [32,33]. To prepare a landscape plan with a return period of 100 years, it is necessary to consider 42.3% of the sponge lands ratio, which varies between 33.8 and 44.6 under the fuzzy condition. Increasing the level of the return period can reduce the fuzzy response ranges of the land slope. This is because the land slope as a critical constraint cannot be increased equivalently to the runoff rate due to two reasons: the reduction in permeability and the power of flow destruction [34,35].

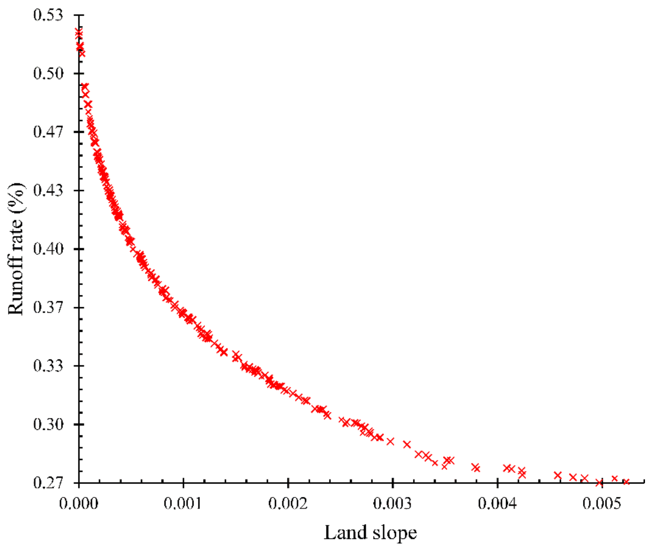

Figure 1. Optimal front of multi-objective planning.

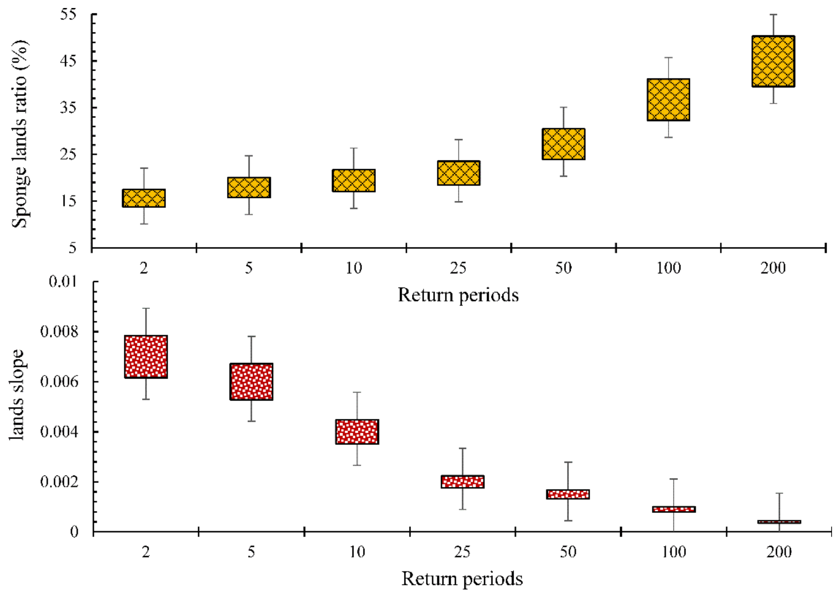

Figure 2. Sponge lands and design slope for different return periods.

3.2. Ecological Problems of Sponge City

As shown in Figure 3, the aquatic plants used are common, and each city can select appropriate plants according to its own situation. The highest important value index (IVI) (82.7%) was reported in reed. The medium IVI was estimated to be 54.5%, 58.2%, and 58.8%

in black algae, lotus, and water hyacinth, respectively. Meanwhile, the lowest IVI (45.8%) was found in soft-stem club-rush.

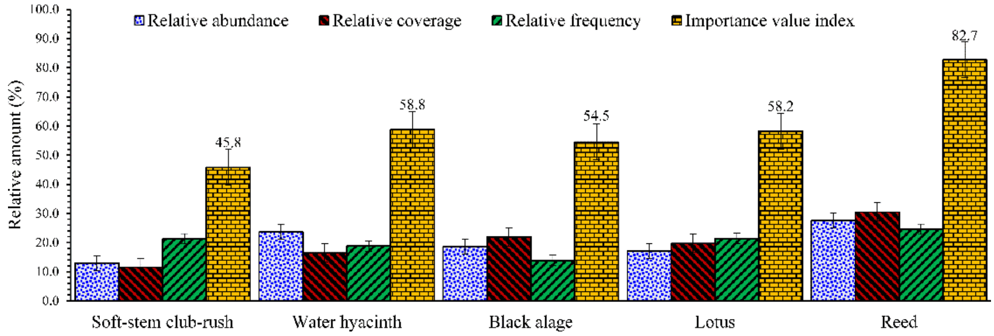

Figure 3. Average important value index of aquatic plants.

The impact of the aquatic plants in different return periods on the urban water cycle is shown in Table 1. According to the table, reed has a considerable effect in controlling and storing water in the subsurface layers. A design based on the 100-year return period for reed can reduce more than 90% of urban waterlogging and direct it to subsurface storage. Considering the implementation costs and the ability to update the urban landscape, it can be concluded that a 100-year return period is a suitable option for design [36,37]. The reduction in urban runoff and flooding via the introduction of aquatic plants in cities whose rainfall with a 100-year return period is more than 400 mm in an annual event should be evaluated using a multivariable probabilistic model.

Table 1. Impact of aquatic plants on urban water characteristics.

Species	Return Period	Runoff	Urban Water Logging	Groundwater Storage
Reed	10	18	37	8
	50	34	63	13
	100	58	94	19
Lotus	10	14	31	6
	50	26	56	9
	100	48	78	14
Black algae	10	13	26	5
	50	24	47	8
	100	49	69	13
Water hyacinth	10	10	19	3
	50	18	39	8
	100	32	58	12
Soft-stem club-rush	10	7	14	1
	50	21	23	4
	100	43	40	10

4. Discussion

Today, population growth, urbanization, and climate change have transformed human life [38–40]. Therefore, it is necessary for urban ecosystems and the environment to adapt to these changes [41,42]. With the excessive reduction in land permeability, the construction of a composite aquatic ecological restoration system can improve the efficiency of ecological restoration. To understand the limitations of aquatic plants in the structure of urban planning, it is necessary to use a combination of aquatic plants to restore the ecology of a city, and this can be called a pattern of aquatic plant cultivation. Therefore, in the actual purification process, it is important to purify the water body and to create a complex system of aquatic plants.

The idea of sponge cities is to implement rainwater pipes in the traditional way while using less impactful development technology so that the hydrology and ecology are not affected, and they have a natural "elasticity" similar to a sponge [43,44]. Disasters in the construction of a sponge city should be controlled at the beginning, middle, and later stages with the help of a less impactful development technology plan. In addition to ecological restoration in the later stages, it is also suggested that environmental protection awareness should be realized in the early stages of urban construction. Green roofs, shallow ditches with vegetation, infiltration wells, and the early release of rainwater can be used to reduce rainwater infiltration. After large-scale rainfall, rainwater can be quickly diverted using permeable pavers and retention ponds. A wet pond, a sustainable pond, and a rain garden can also be built to improve the environment.

A deep understanding of and placing importance on the relevant actions should be provided ideologically. First of all, the relevant management departments of governments at all levels should implement the idea of environmental protection, integrate the idea of ecological cycles into work, and comprehensively improve the level of the rational use of rainwater. Second, publicity and public education should be strengthened so that people can fully understand the importance of rainwater as a resource; comply with public service advertising, special lectures, and other forms of communication; and participate in and support the exploitation of urban rainwater resources. The conceptual framework in Figure 4 is presented to promote the effective growth of aquatic plants and to use the rainwater harvesting system. The results show that the selection of suitable aquatic plants was the main parameter in the landscape design for the ecological restoration of sponge cities.

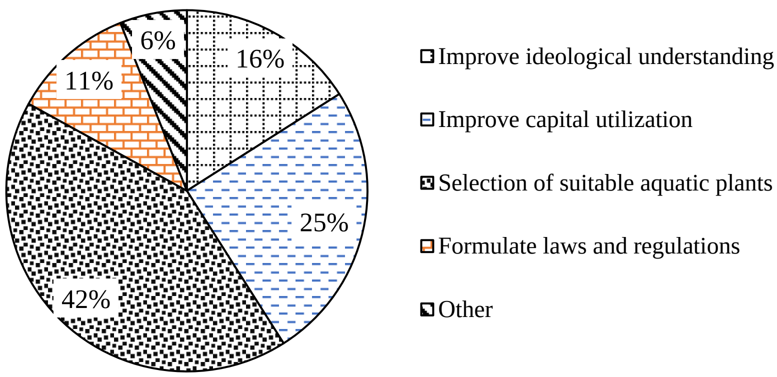

Figure 4. Ecological restoration measures of sponge city.

5. Conclusions

The construction of a sponge city has become an essential factor in solving urban ecological problems. Using the characteristics of aquatic plants in the construction of a sponge city can play an effective role in the ecological restoration process. The characteristics of the natural ecological system can help the designer of a sponge city to realize the effective control of urban rainwater runoff. Aquatic plants are the most important component of water ecological restoration technology, and they are particularly aligned with the ecological characteristics of sponge cities. Aquatic plants absorb excess water nutrients through developed roots to increase their growth without causing secondary pollution. According to urban needs, rain runoff can be regulated and controlled to improve the hydrological ecology of cities, protect the environment, and change the landscape of urban ecosystems. In order to further align sponge cities with urban structures, a multi-objective model based on non-dominated sorting was developed according to the longitudinal slope and runoff rate, which determined the design parameters in the different precipitation return periods. The results show that, in sponge cities that have a longitudinal slope, a smaller volume of runoff can be absorbed by the land. A return period of 100 years was determined to be the best choice for the design parameters. The optimum design was able to improve the urban ecological environment and enable people to realize the sustainable development of cities and towns by protecting the environment. The construction of a sponge city is of great importance to restore surface runoff to an undeveloped state as much as possible with the help of the ecological restoration function of aquatic plants.

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