Evaluation of Site Suitability for Rain gardens in Sponge Cities Based on GIS

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Abstract. The Rain Garden is widely used in the construction of sponge cities due to its excellent rainwater management effects. A scientifically reasonable site selection is key to ensuring its effective benefits. In response to the current issues of relying on experience and low efficiency in the site selection of rain gardens in sponge cities, this paper constructs a suitability evaluation index system for the site selection of rain gardens based on the fuzzy analytic hierarchy process, considering the actual construction needs of rain gardens. By using ArcGIS for multi-criteria overlay analysis, a suitability evaluation model for rain garden site selection was established, and the suitability of rain garden site selection in the Fengdong New City area was evaluated. The evaluation results show that the total area available for construction in Fengdong New City is 52.25 km², accounting for 32.8% of the total study area, with suitable areas generally exhibiting characteristics of "more in the west and less in the east, distributed along rivers, and concentrated in the southwest."

Keywords: Rainwater management; Rain Garden; GIS; Site selection; Suitability evaluation for construction.

1. Introduction

The increase in human activities and the rapid development of urbanization have led to more frequent urban flooding phenomena. The reasons for this are not only due to human activities causing extreme rainfall events to occur more frequently [1], but also because urbanization has significantly reduced the original permeable natural ground [2].

In response, countries around the world have proposed new rainwater management systems to effectively alleviate water environment issues in urban construction. These include Low Impact Development [3], Sustainable Urban Drainage [4], Water Sensitive Urban Design [5], and Best Management Practices [6]. In China, the concept of sponge cities was proposed at the Central Urbanization Conference in 2013, aiming to enhance the city's ability to infiltrate, store, purify, and utilize rainwater runoff through methods such as source reduction and mid-course transmission [7].

In sponge city facilities, rain gardens are widely used due to their excellent runoff control capabilities and rainwater purification effects [8]. At the same time, a large number of scholars [9,10] have studied the factors influencing their construction benefits, mainly including filler types, combination designs, and construction techniques. However, to effectively address urban water environments, it is essential to consider not only the facilities themselves but also the impact of urban spatial layout on the construction of rain gardens. This means that the suitability of construction should be considered from a regional perspective, ensuring the scientific and rational selection of sites in the early stages of construction.

Ecological adaptability assessment [11] is a comprehensive research method that provides technical support for the adaptability evaluation of engineering construction from environmental, economic, and other aspects. In addition, with the emergence of GIS technology, many scholars have combined ecological adaptability assessment methods with GIS to improve the accuracy and scientific nature of evaluation results in various disciplines, such as environmental impact assessment and regional planning [12]. This not only enriches the methods of suitability assessment but also provides a basis for the suitability evaluation of rain garden site selection.

In recent years, although the construction of rain gardens has achieved good results, the site selection for their construction has often relied on empirical methods, lacking scientific planning that takes into account regional characteristics. This not only slows down the construction speed but also leads to some facilities not being able to fully exert their effectiveness. Therefore, this study takes Fengdong New City as an example, constructs a land suitability evaluation framework using the FHAP method, determines indicator weights, and utilizes GIS to extract and overlay information on land use status and natural factors in the region. It conducts a suitability evaluation for the site selection of sponge city rain gardens, aiming to achieve scientific site selection for rain gardens. The research can provide a reference for the scientific site selection of rain gardens in the future.

2. Overview of the Research Area and Data Sources

2.1 Overview of the Research Area

Xi'an Fengdong New City (33°25′12″~34°27′00″N， 107°24′00″~109°29′24″E) is located in the Xixian New Area of Xi'an City, Shaanxi Province. It is bordered to the east by the West Third Ring Road of Xi'an, to the west by the eastern bank of the Feng River, to the south by the Xi'an-Han Highway, and to the north by the Wei River, covering an area of approximately 159.3 km². According to the 2022 Xi'an Water Resources Bulletin, Fengdong New City receives an annual rainfall of 290.85 million m³, with a long-term average rainfall of 166.79 million m³, and surface water resources of 28 million m³. Statistical results indicate that Xi'an Fengdong New City has abundant rainfall resources and possesses the potential for developing sponge city construction.

2.2 Data Sources and Processing

The DEM data in this study includes 30 m digital elevation data from the ASTER GDEM of Xi'an Fengdong New City in 2022, obtained from the Geospatial Data Cloud, as well as remote sensing imagery data with 30 m accuracy from Landsat 8 OLI_TIRS.

Using ArcGIS 10.8, after preprocessing the images, operations such as clipping and resampling were performed to reduce the map resolution to 1 m accuracy. Further image stitching was conducted to obtain the DEM data for the study area. Supervised classification of the images was carried out using ENVI 5.3 to identify land use types, including built-up land, water systems, forest land, and bare land. Kappa validation was conducted to verify the land classification results, yielding a Kappa coefficient of 0.9157.

3. Construction Suitability Evaluation System for Rain gardens

3.1 Construction Suitability Indicator Factors

In this study, the feasibility of land construction is determined from two aspects: utilization type and topography. Five factors are selected as indicators: land use, distance to buildings, elevation, slope, and slope aspect, to construct a suitability evaluation system for the construction of rain gardens in sponge cities [13]. The layered framework is shown in Figure 1 below.

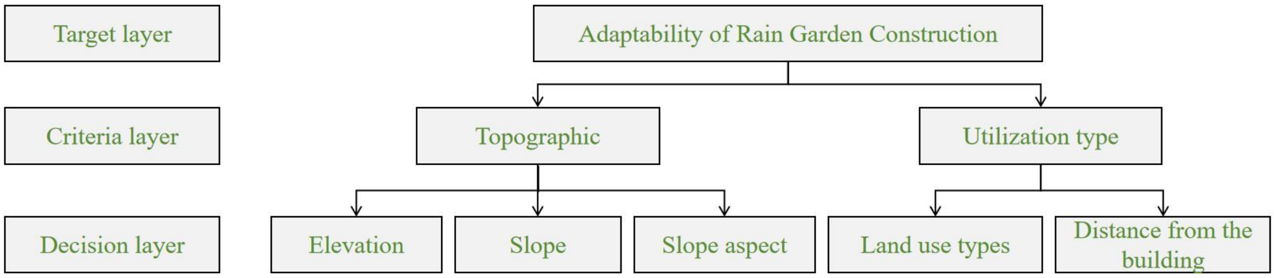


Fig. 1 FAHP Hierarchical Model

Land use type: The "Technical Regulations for Urban Rainwater Utilization Projects" stipulate that "rain gardens should be set within a block of green space of 100 m2," which means that the construction of rain gardens has certain requirements regarding land type and area. Only by meeting a certain construction area can the rain garden effectively increase its water storage volume and enhance its runoff reduction capacity [14]. Therefore, when selecting land use types, larger areas of grassland or vacant land should be chosen as suitable sites for the construction of rain gardens.

Distance from buildings: The "Technical Regulations for Urban Rainwater Utilization Projects" also stipulates that the distance from the edge of a permeable rain garden to the building should not be less than 3 meters to prevent soaking the foundation. This distance can be used to establish a buffer zone for analysis based on the Euclidean distance from buildings.

Elevation: Areas with lower elevation are more conducive to collecting rainwater runoff, improving rainwater recovery efficiency and reducing water resource waste. Additionally, this facilitates construction and lowers construction costs.

Slope: The degree of the slope directly affects the effectiveness of rainwater runoff control. The smaller the slope, the slower the surface runoff speed, the longer the time it spends in the buffer zone, and the more fully the rainwater infiltrates, which also increases the efficiency of pollutant retention. Therefore, areas with gentler slopes are more conducive to the construction of rain gardens.

Slope Aspect: Different slope aspects lead to varying light conditions, which in turn affect plant growth in the rain garden. An appropriate aspect can enhance the efficiency of photosynthesis, promote plant growth, and improve the purification and water retention capacity of the rain garden. Therefore, areas with ample sunlight, such as south, southwest, and southeast directions, are suitable for construction.

3.2 Determination of Weight for Construction Suitability Indicators Based on FAHP

Based on the AHP principle, a decision matrix for the analytic hierarchy process was constructed using the scoring results from experts on various indicators. Through consistency testing, the FAHP method was used to calculate the weights of each indicator. The results show that the weight of land use type factors accounts for 13.65%, the weight of building distance factors accounts for 14.63%, the weight of elevation factors accounts for 18.36%, the weight of slope factors accounts for 46.34%, and the weight of slope aspect factors accounts for 7.02% (as shown in Table 1).

Table 1. Fuzzy Analytic Hierarchy Process Weight Results

Indicator	Land use types	Distance from the building	Elevation	Slope	Slope aspect	Weight
Land use types	1	1/2	1	1/4	3	0.1365
Distance from the building	2	1	1/3	1/3	2	0.1463
Elevation	1	3	1	1/4	2	0.1836
Slope	4	3	4	1	5	0.4634
Slope aspect	1/3	1/2	1/2	1/5	1	0.0702

3.3 Classification and Valuation of Indicator Factor Levels

By using the analysis tools in ArcGIS, the selected land use, elevation, slope, aspect, and distance to buildings are classified. Then, through reclassification, values are assigned to the classified resistance factors. The FAHP (Fuzzy Analytic Hierarchy Process) method is used to determine the weights of the selected resistance factors [15].

Table 2. Construction of suitability factor weight, grading, and assignment table.

Target layer	Criteria layer	Decision layer	Weigh	Grading	Score
Adaptability of Rain Garden Construction	Topographic factors	Elevation/m	0.1836	＞415	0
				398-415	60
				381-398	80
				＜381	100
		Slope/(°)	0.4634	＞15	0

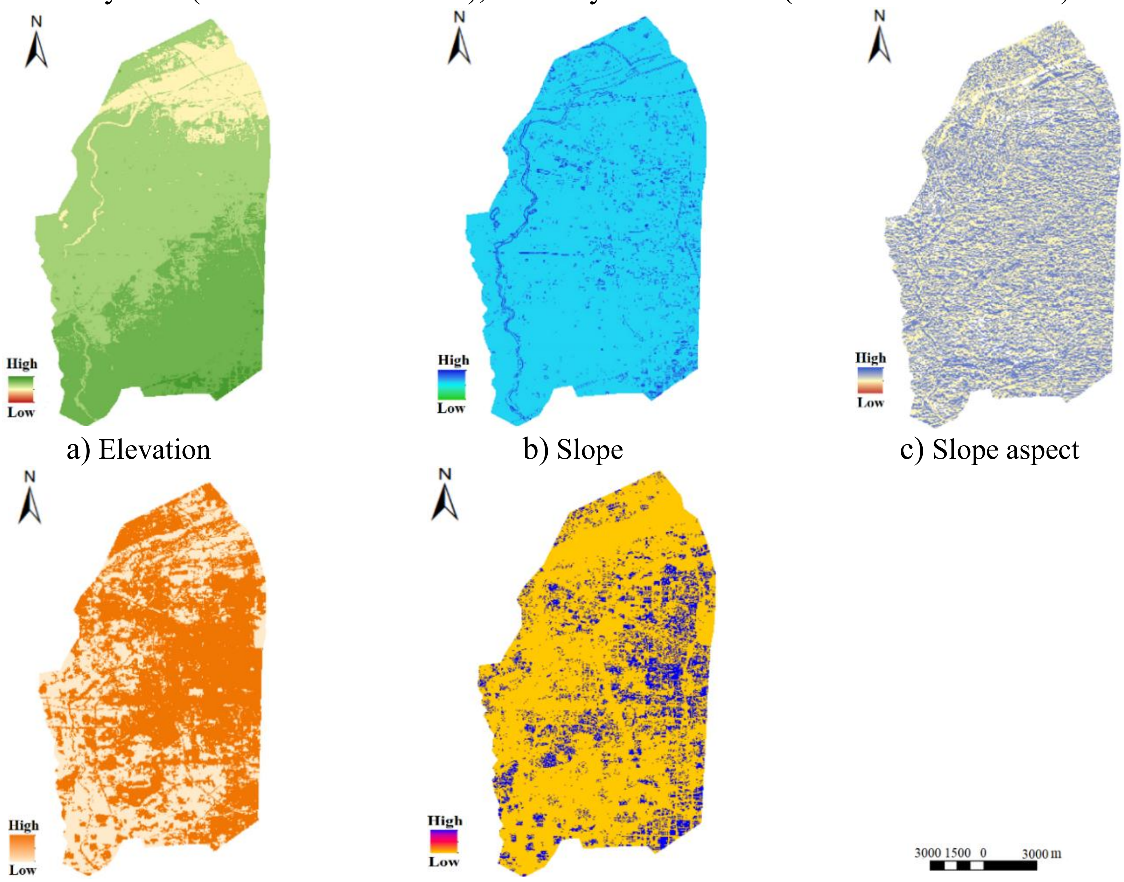
				10-15	60
				5-10	80
				0-5	100
		Slope aspect	0.0702	North	0
				Northeast, Northwest	60
				East, West	80
				South, Southeast, Southwest	100
	Utilization type	Land use types	0.1365	Water areas, construction land	0
				Vacant land	80
				Woodland, grassland	100
		Distance from the building	0.1463	0-3	0
				>3	100

4. Results and Discussion

4.1 Results of Suitability Indicators for Construction

Based on the assigned scores of the five feasibility indicators: elevation, slope, slope aspect, land use type, and distance to buildings, a reclassification is conducted, resulting in the final suitability evaluation results for each indicator, as shown in Figure 2.

The suitability evaluation results of various indicators are divided into four levels, from low to high: low suitability area (Ⅳ construction area), medium suitability area (Ⅲ construction area), high suitability area (Ⅱ construction area), and very suitable area (Ⅰ construction area).



a) Elevation b) Slope c) Slope aspect

d) Land use types e) Distance from the building

Fig. 2 Results of Suitability Indicator Evaluation

Topographic factors include elevation, slope, and slope aspect. In terms of elevation, the study area is located in the northwest of Xi'an City, transitioning from an alluvial plain to hilly terrain. The overall terrain is higher in the southeast and lower in the northwest and north, resembling a scoop shape. The lower elevation is conducive to water flow accumulation, improving rainwater utilization efficiency. Therefore, the most suitable construction areas are mainly distributed on the west side of the main urban area, which belongs to the plain region.

In terms of slope, the gentler the slope, the more sufficient the rainwater infiltration. Therefore, slopes of 0-5° are designated as Level 1 construction areas, 5°-10° as Level 2 areas, 10°-15° as Level 3 construction areas, and slopes above 15° as Level 4 construction areas. The analysis results show that the overall slope values in this area are relatively high, but the distribution is quite uniform.

For slope aspect, considering that Fengdong New City is located north of the Tropic of Cancer, the sun is predominantly in the southern direction throughout the year. Therefore, south, southeast, and southwest orientations receive ample sunlight, which is beneficial for the growth of plants in rain gardens, and should be designated as Level 1 construction areas. The east and west orientations are classified as Level 2 construction areas, while the northern slopes, which are opposite to the sun's direction and often shaded, are classified as Level 3 construction areas, with the north slope being designated as a Level 4 construction area.

In terms of land use types, grasslands and forests have a natural advantage in rainwater absorption and are easier to construct on, so they should be designated as primary construction areas. Vacant land without building interference is classified as secondary construction areas, while water bodies and existing built-up land cannot be used, thus they are classified as fourth-level construction areas. Regarding the distance from buildings, since rain gardens have the function of rainwater infiltration and utilization, to prevent nearby distances from causing infiltrated rainwater to affect building foundations, according to previous regulations, areas greater than 3 meters are classified as primary construction areas, while areas less than 3 meters are classified as fourth-level construction areas.

4.2 Results of Suitability Indicators for Construction

To ensure that the evaluated construction adaptability achieves the best effect, the study selects the first-level construction area as the buildable area. Combining the weights of various indicators and evaluation results, the ArcGIS weighted overlay tool is used to overlay five construction suitability evaluation indicators, ultimately deriving a comprehensive construction suitability value and forming a buildable area map for rain gardens in the Fengdong area (as shown in Figure 3 and 4).

From the comprehensive suitability map in Figure 3, it can be concluded that the area suitable for construction is 52.25 km², accounting for 32.8% of the total area of the study region. This area is mainly distributed in the southwestern part, the western plain area, and along the northern Wei River and Feng River channels. The northern Wei River floodplain is primarily characterized by an alluvial plain, with gentle surface undulations, vast territory, and diverse wetland types, which are conducive to the construction of rain gardens. In the central urban area, the distribution of buildings is dense, resulting in very little overall buildable area. In the western plain area, the buildable areas are scattered and significantly outnumber those in the main urban area. In the southwestern region, the buildable areas are widely and densely distributed, covering the largest area.

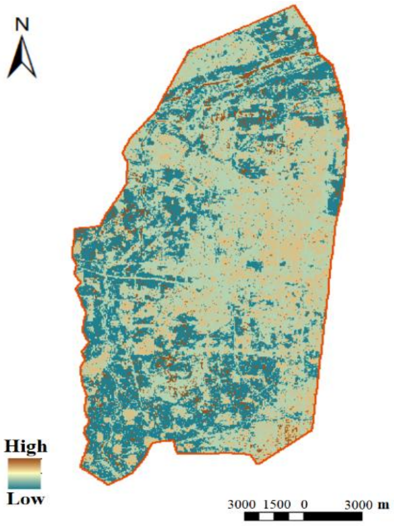


Fig. 3 Comprehensive construction suitability evaluation

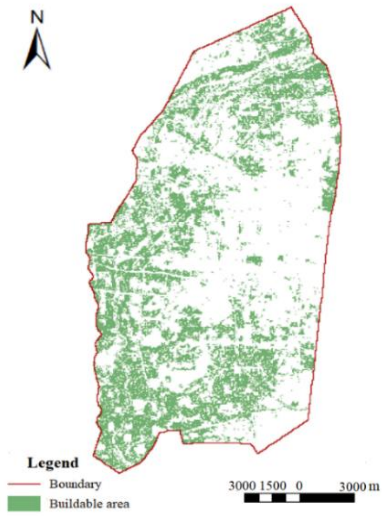


Fig. 4 Buildable area

5. Conclusion

This article studies the scientific site selection for the construction of rain gardens. Based on GIS, a site suitability evaluation model has been developed. The research conclusions are as follows:

The total area available for construction in Fengdong New City is 52.25 km², accounting for 32.8% of the total area of the study region. The buildable areas are mainly distributed in the southwestern part, the western plain area, and along the rivers. These areas can accommodate large-scale rain gardens, which will increase rainwater infiltration, effectively reduce water resource waste, and improve rainwater utilization rates. The area available for rain gardens in the main urban area is minimal, but small rain gardens can be constructed using the green belts on both sides of the roads and the green spaces adjacent to residential areas, thereby reducing the occurrence of flooding.

In addition to meeting the principles of suitability and scientificity, the site selection for rain gardens should also consider social and economic factors. The suitable construction areas for rain gardens proposed by the research institute can provide a reference for subsequent construction in the Fengdong New City, thereby reducing site selection time and improving construction efficiency.

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