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Spatial Prioritizing Brownfields Catering for Green Infrastructure by Integrating Urban Demands and Site Attributes in a Metropolitan Area

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Abstract: Global urbanization and post-industrialization have resulted in the emergence of a large number of brownfields. The integration of brownfields into green infrastructure (GI) has been widely recognized as a sustainable development strategy in metropolitan areas. It is important to spatially prioritize brownfields catering for GI, which can enable the greatest enhancement of urban functions. Various studies have assessed brownfield site attributes or urban demands to define the priority of brownfields transformed into GI, but it is key to consider the coupling coordination between urban demands and site attributes in order to achieve more accurate matches. In this paper, an approach is proposed for assessing the priority of brownfields catering for GI in Xuzhou, China; this involved calculating the coupling coordination degree between site attributes and urban function demands, including heat island mediation, stormwater regulation, disaster prevention, landscape aesthetics improvement, and leisure and recreation increments. The results showed that 42.52% of the brownfields have a high degree of coupling coordination ("good coordination" and "primary coordination") between site attributes and urban demands. Furthermore, 40.82% of the brownfields (120 plots) were selected to be integrated into urban GI; these are not only located in high urban functional demand areas, but also have a high coupling coordination degree. These brownfields were divided into three priority levels, and 4.42% and 17.69% of the total brownfields are of very high and high priority. Our proposed approach offers an accurate decision-making tool for urban GI optimization in high-density built-up metropolitan areas, and offers guidance for brownfield redevelopment.

Keywords: brownfield; priority; green infrastructure; urban demands; site attributes; coupling coordination; matching relationship; suitability; multi-functionality

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1. Introduction

The emergence of brownfields poses severe risks to both the ecological environment and human health, with continuous global urbanization and industrial restructuring. Therefore, brownfield restoration and redevelopment has become a key means of protecting the urban natural ecosystem and promoting sustainable land use [1]. The goals of brownfield reuse are diverse, including establishing upgraded industrial land, commercial land, residential land, and green space. Since the dawn of the 21st century, rapid global urbanization and its consequent demand for land, have brought significant challenges to urban natural space, especially in densely populated urban centers [2]. Therefore, transforming brownfields into urban Green Infrastructure (GI) has become one of the most important ways to achieve sustainable urban development, and it is widely practiced in cities around the world. A great number of related studies have emerged on topics including the benefit and potential of brownfield greening [3–6], priority assessment [7,8], planning process [9], restoration technology [10], and performance assessment [11] of turning brownfields to GI, as well as sustainable assessments based on the full life-circle theory [12].

The benefits of brownfield regeneration catering for GI are typically characterized by ecosystem services, such as mitigating the risks of temperature rises and rain flooding due to global climate change [8,11], providing habitats for endangered animals in urban areas [13], purifying air and reducing noise, increasing opportunities for human natural experiences, and enhancing residents' health and well-being [14]. In addition, this nature-based solution can limit urban sprawl and optimize the urban GI network, thus playing an important role in increasing urban resilience, and even promoting real estate value [15] and alleviating a range of socio-economic problems caused by shrinking cities [16,17]. However, the soft use of brownfields as GI has been limited by high land prices and restoration costs, making it difficult to implement at a large scale [18]. Therefore, the key concern is how to achieve maximum benefits with minimum costs in the process of brownfield regeneration into GI, by allocating limited resources (funds, personnel, time, and energy) to the most critical and efficient brownfield locations [2]. Therefore, the priority of brownfield catering for GI in this study is essential to the optimization of the layout of urban green space.

Site attributes are crucial factors in the priority assessment of brownfield catering for GI [19,20], including site area, slope, hardening rate, vegetation coverage, pollution level, etc. It was indicated that the larger the site area the more diverse and resilient the habitats that can be established in the brownfield, which can thus resist strong external interference [4]. The higher its hardening rate, the lower the infiltration and retention of rainwater into the subsoil, resulting in higher runoff and a lower capacity to mitigate flood risks [4]. The vegetation structure and natural succession on the site are also important factors in the ecosystem services provided by brownfields [5]. In addition, the potential success of brownfield catering for GI is influenced by the location of the site and the status of the surrounding area [21,22]. Sanches and Mesquita Pellegrino [4] integrated factors, such as adjacent land use, population density, distance from existing green spaces and accessibility, into the priority assessment.

With the development of GIS technology, there is a trend towards locating brownfields in urban areas in order to systematically evaluate the priority of brownfield catering for GI [23]. The goals of the brownfield priority assessment have developed from increasing GI connectivity [7] to urban multi-function improvement [24]. For instance, relevant studies have been conducted with the single objective of heat island mediation, stormwater regulation, or green space equity improvement [25–27]. In these paper, instead of site attributes, the focus is the spatial relationship between brownfield location and urban functional demands, as we seek to maximize GI functionality. For example, it has been proven that there is a high spatial correlation between brownfields and high cooling demands when overlaying brownfields and the distribution of social heat vulnerability and urban heat island intensity [26].

Most studies on brownfield priority catering for GI have only considered site attributes or urban functional demands. However, the potential to transform brownfields into GI is not only related to the site attributes of brownfields, but also closely related to the urban functional demand, because the efficiency with which social and ecological functions are performed also depends on the location of brownfields [28,29]. For example, a brownfield with a large area and high native vegetation coverage may have a high cooling effect, but there is the possibility that the brownfield is not located in the highest temperature area of the whole city. It means there is probably a spatial mismatch between site suitability and urban demand, which was confirmed by a few researchers. Motzny [11] evaluated the maximum demand for flood mitigation, as well as the site attribute of brownfields suitable for GI at a community scale, showing that high-demand areas and highly suitable sites do not entirely spatially match.

However, few methods exist that integrate these two dimensions at the urban scale. We proposed a spatial assessment method to prioritize brownfields catering for GI to address this knowledge gap: the site attributes and urban multi-functional demands are integrated, using matching analysis and a coupled coordination degree (CCD) model. We hypothesized that the higher the coupling degree between site attributes and urban demand, the higher the priority of brownfield catering for GI, which maximizes the improvement of urban multi-functions with the minimum cost. The method was applied in the urban area of Xuzhou, Jiangsu province, China. The following research aims were proposed: (1) to establish a comprehensive index system to quantitatively prioritize brownfield catering for GI; (2) to reveal the coupling relationship between brownfield site suitability and urban functional demands; and (3) to determine the key factors of site attribute and urban demand, which affect the priority of brownfield catering for GI.

2. Materials and Methods

2.1. Methodological Framework

The potential of brownfields catering for GI is not only determined by site attributes, but is also closely related to the location's functional demands. The key issue to be addressed in this study is to quantitatively measure site GI suitability, as well as urban functional demands, and to prioritize brownfields according to the degree of coupled coordination between the two. Three steps must be performed to achieve these research goals, as shown in the framework (Figure 1): firstly, the suitability of brownfield sites in terms of catering for GI was assessed by overlaying individual site attributes, such as area, vegetation coverage, surrounding land use type, etc.; secondly, the urban functional demands of brownfield locations were derived by superposing the following five functions by weight—heat island mediation, stormwater regulation, disaster prevention, landscape aesthetics improvement and increased leisure and recreation; finally, the degrees of coupling coordination of site suitability and urban functional demands were obtained using the CCD model, then the matching degree of the two was analyzed by quadrant division. The brownfields with high demand and high coupling coordination were selected to be integrated into GI, and their priorities determined based on their CCD values.

2.2. Study Area

The study was conducted in Xuzhou (116°22′–118°40′ E, 33°43′–34°58′ N), Jiangsu province, China. As the central city of Jiangsu, Xuzhou covers approximately 11,765 km^2, with a total population of 9.03 million at the end of 2021 and an urbanization rate exceeding 66.2%. Xuzhou is dominated by plains with low elevation, and has a warm temperate sub-humid monsoon climate. It is also located in the "Tancheng–Yingkou seismic zone" in North China, and has been affected by earthquakes throughout its history.

Xuzhou is a national historic and cultural city, and has a one-hundred-year coal mining history. Over the last century, the industry in this area has been structurally dominated by heavy chemicals, and has undergone upgrades and transformations. A large number of brownfields, including abandoned lands, low-efficiency lands, and vacant lands, urgently need to be restored and reused. In July 2022, Xuzhou was listed as a Chinese Sustainable Development Innovative Demonstration zone, with the brownfield regeneration area one of the most important areas of focus. Presently, Xuzhou has greatly succeeded in transforming brownfields into green spaces, such as the Pan'an National Wetland Park, which was converted from a former coal mining subsided area. Over the past 10 years, the average annual increase in green space in Xuzhou has been 2.12 km^2, and the growth rate of green spaces in built-up areas is 22.5%.

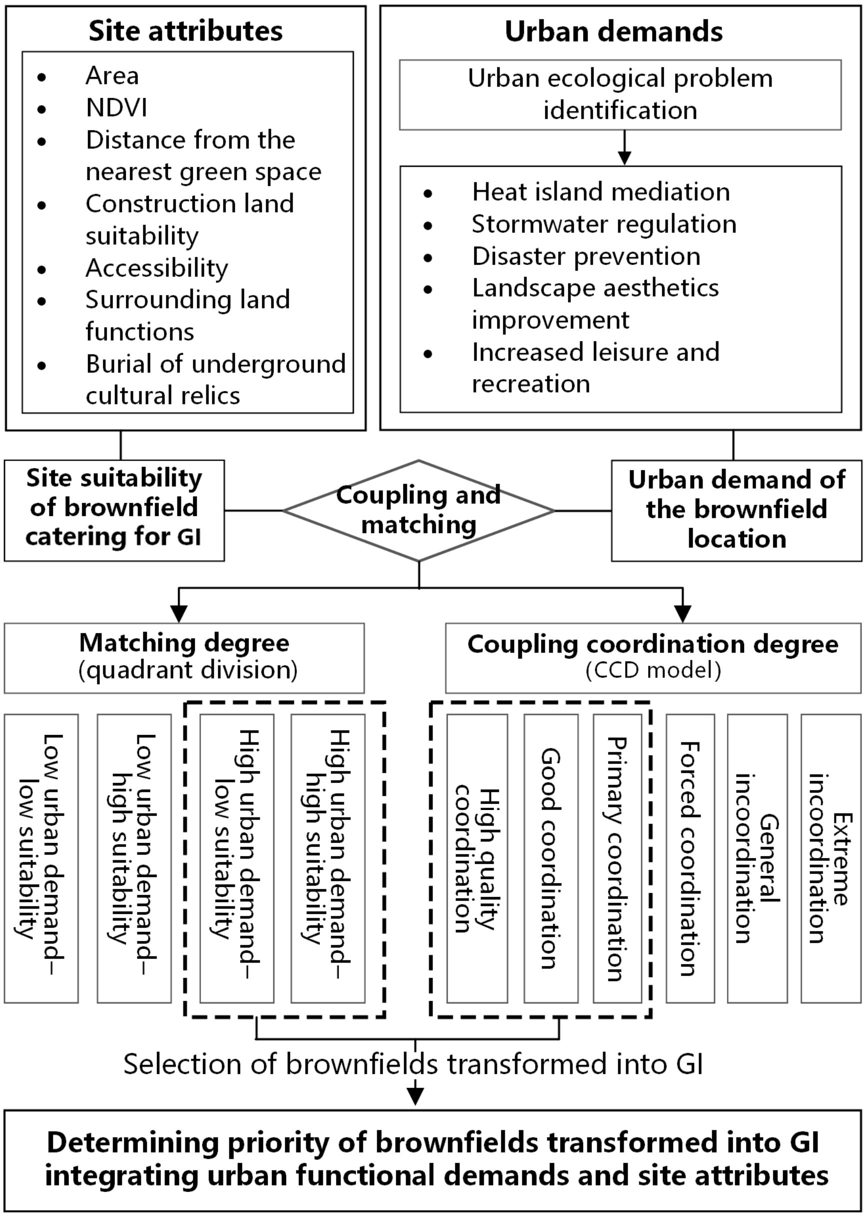

Figure 1. Technical and methodological framework.

The site of the case study in this paper is the central area of Xuzhou, with a total size of 573.19 km^2 (Figure 2). This high-density built-up area is characterized by high population densities, a growing impermeable surface, as well as the presence of many valuable tombs and historical relics situated underground. Therefore, some social and ecological problems have persisted, such as urban heat islands and increased rain-flood risks. In addition, although the per capita green space area in the central area is 22.71 m^2 per person, green space inequality is a serious issue, especially due to the insufficient supply of GI in the old urban area.

Meanwhile, traditional industries have moved beyond the Third Ring Road due to industrial upgrading, and the brownfields left behind have thus become an important element in mitigating or solving the urban problems described above. There are presently 294 brownfields, covering a total area of 9.21 km^2 (Figure 2); some of these brownfields are adjacent to each other, in a state of agglomeration. In general, the distribution of brownfields is described as "more in the north and south, less in the center".

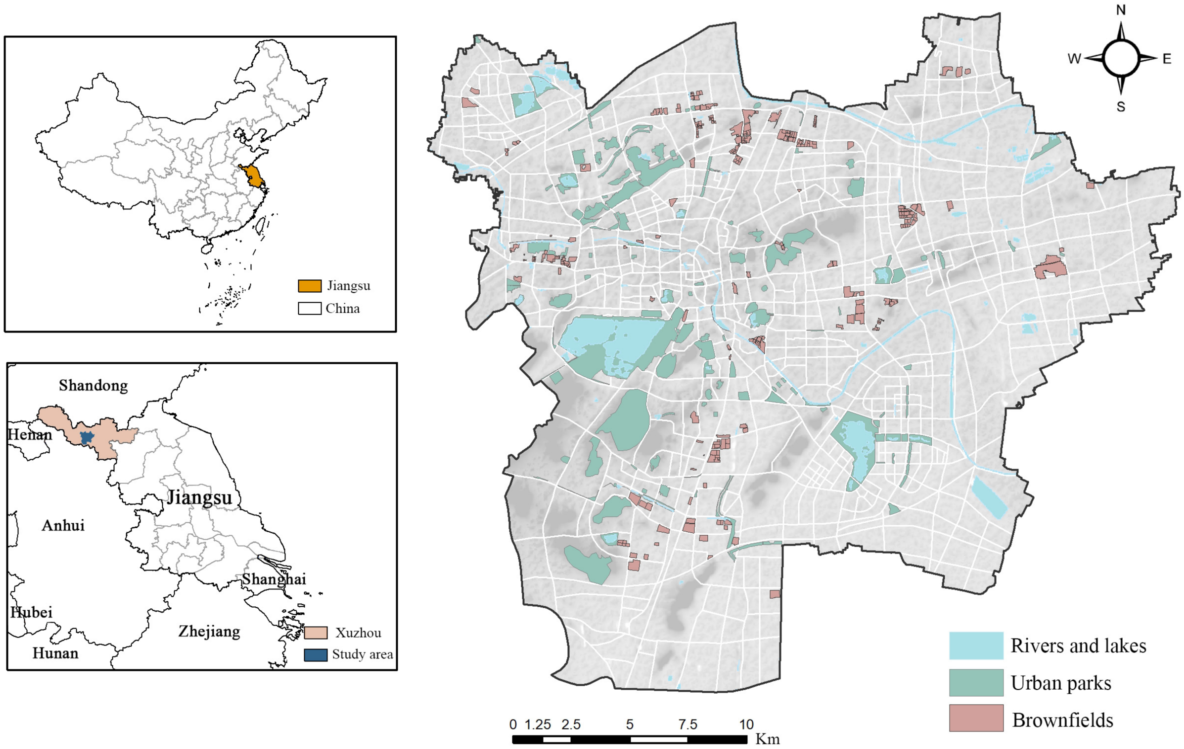

Figure 2. Location and brownfields of the study area.

2.3. Data and Processing

The data employed in this study include Remote Sensing Image, Digital Elevation Model and Google Maps data, as well as planning data from Xuzhou, Point of Interest of Baidu maps, population data and Open Street Map data (Table 1). In addition, brownfield data were derived from "The research report on renewal of low-efficient land in Xuzhou" with a total of 294 brownfields. The assessment unit of urban functional demand is a block, which is divided by the road network. Based on the Land use status map of Xuzhou City in 2019, the study area is divided into 637 blocks (Figure 2).

Table 1. Data used in the study.

Data	Application	Source
RSI Landsat 8	Assessment of heat island mediation demand, NDVI, and land use classification	United States Geological Survey (30 m × 30 m, date: 2 August 2020), https://earthexplorer.usgs.gov (accessed on 4 June 2021)
DEM	Assessment of stormwater regulation demand	Chinese Geospatial Data Cloud (10 m × 10 m), https://www.gscloud.cn (accessed on 4 June 2021)
Crowdsourced score of urban park	Assessment of landscape aesthetics demand	POI from Baidu Map, http://map.baidu.com (accessed on 19 June 2021)
Disaster prevention area	Assessment of disaster prevention demand	Disaster prevention and reduction plan of Xuzhou urban area (2019)

Table 1. *Cont.*

Data	Application	Source
Urban Park	Assessment of leisure and recreation demand; calculation of distances from the nearest green space	Urban green space system plan of Xuzhou urban area (2019)
Population	Assessment of urban demands	Reference [30]
Land function	Assessment of site suitability for converting brownfields to GI	Land use status map of Xuzhou urban area (2019)
Underground cultural relics		Historic and cultural conservation plan of Xuzhou urban area (2019)
Construction suitability		Land assessment map of Xuzhou urban area (2019)
Urban road		Road system status map of Xuzhou urban area (2019), http://www.Openstreetmap.org (accessed on 7 June 2020)

2.4. Spatial Priority Assessment of Brownfield Catering for GI Integrating Urban Demands and Site Attributes

2.4.1. Site Suitability Assessment of Brownfields Catering for GI

Land suitability evaluation is the most widely used approach to determine suitability in relation to a specific land function. The site suitability (S_s) of a brownfield catering for GI determines its suitability for use as urban green space by considering its attributes. A site suitability assessment index system of brownfield conversion into GI was constructed (Table 2), selecting seven site attribute index factors, including area, Normalized Difference Vegetation Index (NDVI), distance from the nearest green space, suitability of construction land, accessibility, surrounding land functions, and the burial of underground cultural relics, all built with reference to existent green space suitability assessment indexes [7,31]. Meanwhile, classification criteria were established considering the characteristics of each index by referring to relevant literature, according to which the assessment values of each index were obtained.

Next, the weight of each index was determined via the analytical hierarchy process (AHP) method, which is a widely used methodology for multi-criteria decision-making regarding land suitability analysis of different land uses [19]. A total of 10 experts in landscape architecture and urban planning were invited to conduct a questionnaire survey on index weights (see Appendix A). They were asked to rate the importance of the selected criteria using a scale from one to nine. Finally, the comprehensive weight of each index relative to site suitability of a brownfield was calculated by the arithmetic average method. Using the weighted overlay tool in ArcGIS 10.2, the assessment results of each index were superimposed according to the above weights to obtain the S_s value. The calculation formula is as follows:

$$S_s = \sum_{i=1}^{n} W_i X_i \tag{1}$$

where S_s is the site suitability of the brownfield in terms of catering for GI, X_i is the score of each site attribute index, and W_i is the weight of each index.

Table 2. Index grading criteria for the site suitability of brownfields catering for GI.

Index	Grading Criterion	Value	Explanation
Area	area $\geq$ 50 hm^2	5	The index indicates that the larger the area, the greater the species diversity [4], and the greater the benefits related to reducing local temperature, collecting rainwater, providing recreational space, etc. The classification was based on the "Urban Green Space Planning Standard" (GB/T 51346-2019)
	20 hm^2 $\leq$ area < 50 hm^2	4	
	10 hm^2 $\leq$ area < 20 hm^2	3	
	5 hm^2 $\leq$ area < 10 hm^2	2	
	area < 5 hm^2	1	
NDVI	NDVI $\geq$ 0.8	5	The index indicates the retention status of original vegetation in the brownfield. The higher the index, the more diverse and stable is the composition of vegetation community. The classification is based on reference [32].
	0.6 $\leq$ NDVI < 0.8	4	
	0.4 $\leq$ NDVI < 0.6	3	
	0.2 $\leq$ NDVI < 0.4	2	
	NDVI < 0.2	1	
Distance from the nearest green space	distance = 0 m	5	The index reflects the distance between the brownfield and adjacent green space patches; the closer the distance, the higher the aggregation of green space, and the higher the efficiency of green space services. The classification is based on reference [4].
	0 < distance < 100 m	4	
	100 m $\leq$ distance < 500 m	3	
	500 m $\leq$ distance < 1000 m	2	
	distance $\geq$ 1000 m	1	
Suitability of construction land	non-construction area	5	According to China's Urban and Rural Land Use Evaluation Standard, this index proposes that, from the perspective of construction suitability, the more unsuitable the area is for construction, the greater its ecological and human potential, and the more suitable it is for GI [33].
	unsuitable for construction	4	
	available for construction	3	
	suitable for construction	1	
Accessibility	very high	5	The index reflects the ease of access to the brownfield [4]. The distance was calculated between the brownfield's geological center and the nearest urban main road, and the results were divided according to the natural breakpoint method. The smaller the distance, the higher the accessibility.
	high	4	
	medium	3	
	low	2	
	very low	1	
Surrounding land functions	very high	5	The index represents the land use status around the brownfields. The higher the proportion of residential, commercial and public service lands in the surrounding area, the higher the potential to use brownfields as GI and the more people they serve [4]. Referring to the Chinese policy goal of "Seeing green within 300 m", the proportion of land use within 300 m was calculated, and the results were divided according to the natural breakpoint method.
	high	4	
	medium	3	
	low	2	
	very low	1	
Burial of underground cultural relics	located in the burial area	5	Compared with residential and commercial construction, green space causes the least damage to the ground. Therefore, it is believed that brownfields with cultural relics buried underground are more suitable for GI transformation [33].
	not located in the burial area	1	

2.4.2. Urban Functional Demand Assessment of Brownfield Location

The assessment of urban functional demand involves measuring the ability of a brownfield to meet urban demands when integrated into urban GI. Different cities have different characteristic ecological problems [34].

In our study, the core ecological problems related to urban environment and human demands were identified via reviewing the literature and government statistics (see details in Appendix B). Urban high temperature, stormwater risk and lack of ability of disaster prevention, are all prominent functional problems in Xuzhou. According to statistics, in 2022, the average number of high temperature days (with average temperatures over 35 °C) in Xuzhou was 25.8, which was the most days since 1960, and the maximum temperature was 39.4 °C. The flood disaster in 2018 had a maximum local rainfall of 516 mm, causing seven deaths and 18 injuries. In the past, Xuzhou has been affected multiple times by earthquakes in neighboring areas, since there are multiple potential earthquake sources around the central area. In addition, it has been the most important target for constructing high quality and equal urban green space for residents based on the urban greening policy in China. Thus, the following five functional demands were selected: heat island mediation, stormwater regulation, disaster prevention, landscape aesthetics improvement and increased leisure and recreation.

Based on the natural and social data of Xuzhou, five urban functional demands were assessed, among which the demands of heat island mediation and stormwater regulation were reflected by the vulnerability and runoff coefficient, and the other three demands were indicated by per capita service coverage area and degree of attention.

After obtaining the above five urban functional demands, the urban demand values of brownfield locations were calculated by the zonal statistical tool in Arc GIS 10.2, which were then divided into five levels using the natural breakpoint method, with 1–5 representing "very low", "low", "medium", "high" and "very high", respectively. Via the above AHP method, the same 10 experts were invited to conduct a questionnaire survey to determine the weight of each index relative to the comprehensive demand value of a brownfield location (see Appendix A). according to the index weights, different demand values were superimposed to obtain the comprehensive demand value of the brownfield location. The calculation formula is as follows:

$$D_u = \sum_{i=1}^{n} W_i X_i \quad (2)$$

where D_u is the comprehensive demand value of the brownfield location, X_i is the value of each urban functional demand of the brownfield location, and W_i is the weight of each demand.

- Heat island mediation demand

The difference in urban heat island demand is determined by land surface temperature and population distribution. The land surface temperature distribution was obtained by inverting the surface temperature using remote sensing images. Landsat 8 remote sensing images from 2 August 2020 were selected for their good quality, lack of cloud cover and significant heat island effect. The data were pre-processed by radiometric calibration, atmospheric correction and image clipping in ENVI5.3 software, and land surface temperature was inverted by the radiative transfer equation method. Then, the heat island mediation demand was calculated with the population data from Ref. [30]. The formula is as follows:

$$D_{hm} = T_i \times P, \quad (3)$$

where D_{hm} is the heat vulnerability, representing the demand for heat island mediation; T_i is the inversion temperature of each pixel point in the study area; and P is urban population.

- Stormwater regulation demand

The comprehensive surface runoff coefficient was used to determine the level of rain-flood risk, and thus the stormwater regulation demands. The higher the comprehensive surface runoff coefficient, the greater the burden of urban drainage, and the higher the rain-flood risk. The method for calculating the comprehensive runoff coefficient was derived from previous research [35,36]. In total, 13 topographic land classes were obtained by superposing five types of land surface (construction land, forest land, grassland, bare land

and water area) and three types of slopes (flat, undulation, steep). Specific topographic land classes thus correspond to a specific runoff coefficient, relating to the various rainwater holding capacities of different land types with different slopes, which could be used to represent the urban stormwater regulation demands.

- Disaster prevention demand

The disaster prevention function service radius was defined as 1000 m, according to the radii derived from the walking index in [37]. In ArcGIS10.2, buffers within 1000 m were selected as the service scope of existing disaster prevention parks. The total area served by the disaster prevention parks were accumulated according to the proportion of the area of the buffer in the evaluation unit. The per capita disaster prevention area in the unit was then obtained and combined with the population data. The larger the per capita area, the smaller the urban demand. The calculation formula is as follows:

$$D_{dp} = \left(\frac{\sum_{i=1}^{n} S_i \times C_{ij}}{P}\right)^{-1}, \tag{4}$$

where D_{dp} is the disaster prevention demand; S_i is the i-th disaster prevention park area, C_{ij} is the area proportion of the j-th evaluation unit in the buffer zone of the i-th disaster prevention park, and P is the population of the j-th evaluation unit.

- Landscape aesthetics demand

Public scores of geographical indications on social websites were used to assess landscape aesthetic demands [38]. The effective scores of urban parks were obtained using POI from the Baidu map, which was provided by the map service provider that has the highest number of users in China. Using a block as the mapping unit, the average landscape aesthetics scores in each unit were calculated. The landscape aesthetics demand is negatively related to the landscape aesthetics score, and the calculation formula is as follows:

$$D_{la} = \left(\frac{\sum_{i=1}^{n} P_i}{n}\right)^{-1}, \tag{5}$$

where D_{la} is the landscape aesthetic demand; P_i is the landscape aesthetic score of the i-th urban park in the mapping unit, and n is the number of park scores in the mapping unit.

- Leisure and recreation demand

The leisure and recreation demand are mainly related to the density of the population and the quantity and scale of urban green spaces. Here, it is represented by the per capita urban park area in the mapping unit. The larger the per capita urban park area, the lower the demand for leisure and recreation [38]. The urban parks were divided into five grades by area, and we defined the service scope of each urban park by delimiting buffer zones (500, 800, 1200, 2000, and 3000), according to the Urban Green Space Planning Standard (GB/T 51346-2019). By superimposing the service scopes and mapping units, the per capita urban park area of each evaluation unit was calculated, which is negatively correlated with the leisure and recreation demand. The calculation formula is as follows:

$$D_{lr} = \left(\frac{\sum_{i=1}^{n} S_i \times C_{ij}}{P}\right)^{-1}, \tag{6}$$

where D_{lr} is the leisure and recreation demand, S_i is the i-th urban park area, C_{ij} is the area proportion of the j-th evaluation unit in the buffer zone of the i-th urban park, and P is the population of the j-th evaluation unit.

2.4.3. Priority Assessment of Brownfields Catering for GI Integrating Site Suitability and Urban Demands

- Assessment of coupling coordination relationship between S_s and D_u

The coupling coordination degree model is the most widely used approach for illustrating the interaction between systems, and is based on the coupling coordination degree, which reflects the degree of mutual promotion or antagonism between different systems [39,40]. The model, offering simple operability and intuitive results, was used to reveal the coupling coordination relationship between the site suitability of brownfield sites and the comprehensive urban functional demands. The calculation process is as follows:

$$C = \frac{\sqrt{S_s \times D_u}}{(S_s + D_u)}, \tag{7}$$

$$T = \alpha \times S_s + \beta \times D_u, \tag{8}$$

$$D = \sqrt{C \times T}, \tag{9}$$

where S_s and D_u represent the value of the site suitability of the brownfield and the value of the urban comprehensive functional demand related to the brownfield location, respectively; C, T and D represent system coupling degree, system comprehensive coordination index and system coupling coordination degree, respectively; and α and β are undetermined parameters; with reference to previous research, $\alpha = \beta = 0.5$. The classification standards of the value of D are shown in Table 3 [40].

Table 3. Criteria for classifying the coupling coordination degree.

Coupling Coordination Degree (*D*)			
(0.00~0.20]	Extreme incoordination	(0.50~0.60]	Primary coordination
(0.20~0.40]	General incoordination	(0.60~0.80]	Good coordination
(0.40~0.50]	Forced coordination	(0.80~1.00]	High-quality coordination

- Analysis of matching degree of S_s and D_u

The matching degree of S_s and D_u was analyzed using quadrant division. The x-axis represents the site suitability of brownfields catering for GI (S_s), and the y-axis represents the urban comprehensive functional demand (D_u). The four quadrants divide the matching degree between S_s and D_u into four types: high demand–high suitability (quadrant I), high demand–low suitability (quadrant II), low demand–low suitability (quadrant III), and low demand–high suitability (quadrant IV).

- Prioritizing brownfields catering for GI coordinating site suitability and urban demand

Based on the above results of the coupling coordination degree and the matching degree, brownfields simultaneously satisfying two conditions were identified. The first condition was that the D value be greater than or equal to 0.5, that is, with a coupling coordination degree (D) of "primary coordination", "good coordination" or "high quality coordination". The other condition was that the brownfield be located in quadrant I (high demand–high suitability) or quadrant II (high demand–low suitability). The priority criteria of brownfields catering for GI are defined in Table 4.

Table 4. Prioritization criteria for brownfields catering for GI.

Matching Degree / **D Value**	**High Demand-High Suitability**	**High Demand-Low Suitability**
Good coordination (0.6~0.8]	Very high priority	Low priority
Primary coordination (0.5~0.6]	High priority	Very low priority

3. Results

3.1. Site Suitability of Brownfield Catering for GI (S_s)

The site suitability values of 294 brownfields catering for GI were obtained by superimposing the results of the indicators of seven site attributes on the weights in Table 5 (the results of each indicator are shown in Appendix C). The results (Figure 3) show that the S_s values of brownfields fluctuated between 1.2374 and 3.4666. There were some differences between the suitability values, but in general the scores were low. Among them, the quantity of brownfields with S_s values greater than 2.5 was 69, accounting for 23.47% of the total number of brownfields, and the total area of these was approximately 191.7 × 104 m^2, mainly distributed in the urban center, as well as in the northeast of the study area. The brownfields with S_s values less than 2.0 were aggregately distributed in the north and south of the study area. Therefore, there was no obvious spatial distribution law dictating the site suitability values, but brownfields in the proximity of urban centers tended to have higher suitability values.

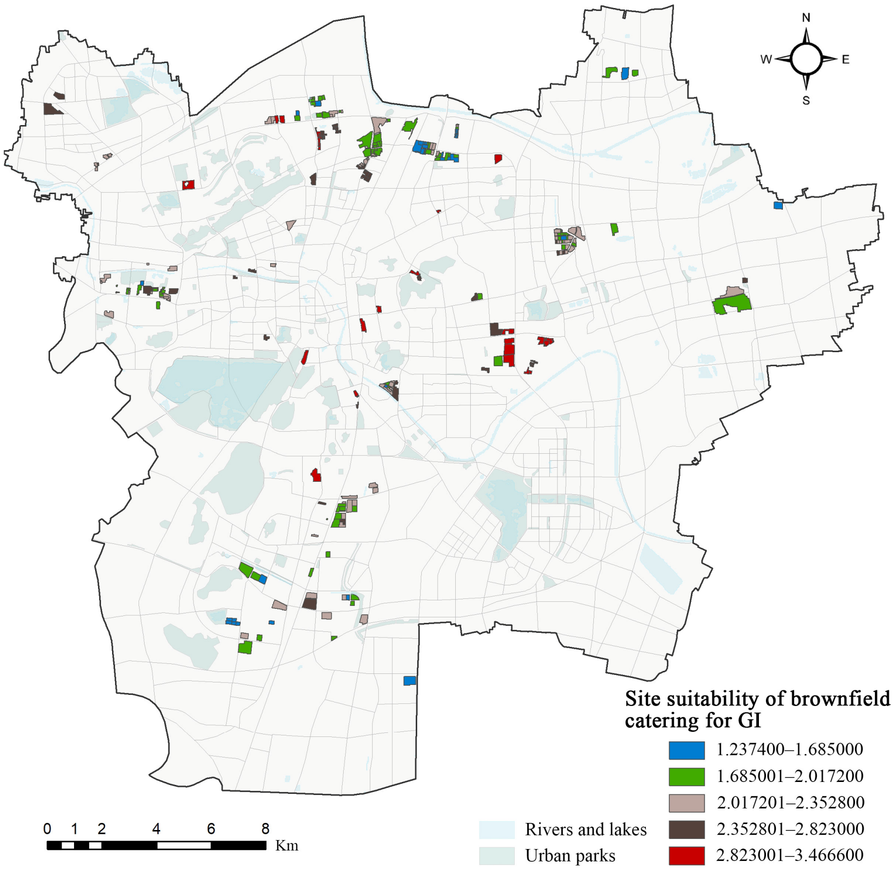

Figure 3. Values of site suitability of brownfields catering for GI.

The single index results show that the scores of natural factors represented by area and NDVI were generally low. The quantity of brownfields with area values less than or equal to two (area ≤ 10 hm^2) accounted for 93.2% of the total number, and the number of brownfields with NDVI values less than 0.4 was 195, accounting for 66.33% of the total. Among the social and economic factors, the accessibility scores and distance from the nearest green space were much higher than others, and the number of brownfields with scores in these two indexes greater than or equal to three were 228 and 208 accounting for 77.55% and 70.74% of the total number of brownfields respectively. The scores of the other three indexes—suitability of construction land, land functions of surrounding areas, and burial of underground cultural relics—were generally lower. For example, the quantity of brownfields with buried cultural relics was 52, accounting for only 17.69% of the total number. Regarding the land functions of surrounding areas, the quantity of sites with scores less than two was 249, accounting for a very high proportion of the total number of brownfields, namely 84.69%.

Table 5. Weights of site suitability indexes.

	Index	Weight
Site suitability of brownfields catering for GI (S_s)	Area	0.0546
	NDVI	0.1058
	Distance from the nearest green space	0.0638
	Suitability of construction land	0.1304
	Accessibility	0.1816
	Land functions of surrounding areas	0.2374
	Burial of underground cultural relics	0.2264

3.2. Urban Functional Demand of Brownfield Location

The comprehensive demand value and its spatial distribution were obtained by superposing the results of five urban functional demands on weight, as shown in Table 6. Figure 4 shows that the urban functional demand values of brownfield location (in relation to heat island mediation, stormwater regulation, disaster prevention, landscape aesthetics improvement, and leisure and recreation) increases. Figure 5 shows that the comprehensive demand values of brownfield locations ranged from 2.0048 to 5, indicating that their D_u values were relatively high overall. The quantity of brownfields with D_u values between four and five was 127 (accounting for 43.2% of the total number), and the area of these was approximately 289.52×10^4 m^2 (accounting for 31.43% of the total area). That is, more than one-third of the brownfields showed a very high demand in relation to urban comprehensive functions. There were 113 brownfields with D_u values between three and four, accounting for 38.44% of the total, and these were also located in areas with high urban functional demands.

Table 6. Weights of urban functional demand indexes.

	Index	Weight
Urban demand of brownfield location (D_u)	Heat island mediation demand	0.1470
	Stormwater regulation demand	0.3600
	Disaster prevention demand	0.1844
	Landscape aesthetics demand	0.0668
	Leisure and recreation demand	0.2418

Although the values for comprehensive urban demand were high, there were differences in the values of each single demand type. From the value percentages of individual urban demands associated with brownfield location (Figure 6), we see that most of the brownfields were located in areas with high demands for stormwater regulation, disaster prevention and landscape aesthetics. In relation to these demands, the proportions of brownfields with "very high demand" out of the total reached 69.39%, 67.01% and 89.46%, respectively. In contrast, the values of demand for leisure and recreation were distributed more evenly, but the demands for heat island mediation were obviously lower than the other four functional demands. In total, 74.49% of the brownfields (219 plots) were located in areas with "very low" and "low" demands for heat island mediation. As seen in Figure 4, the locations of brownfields in the study area did not closely spatially coincide with a high intensity of heat vulnerability.

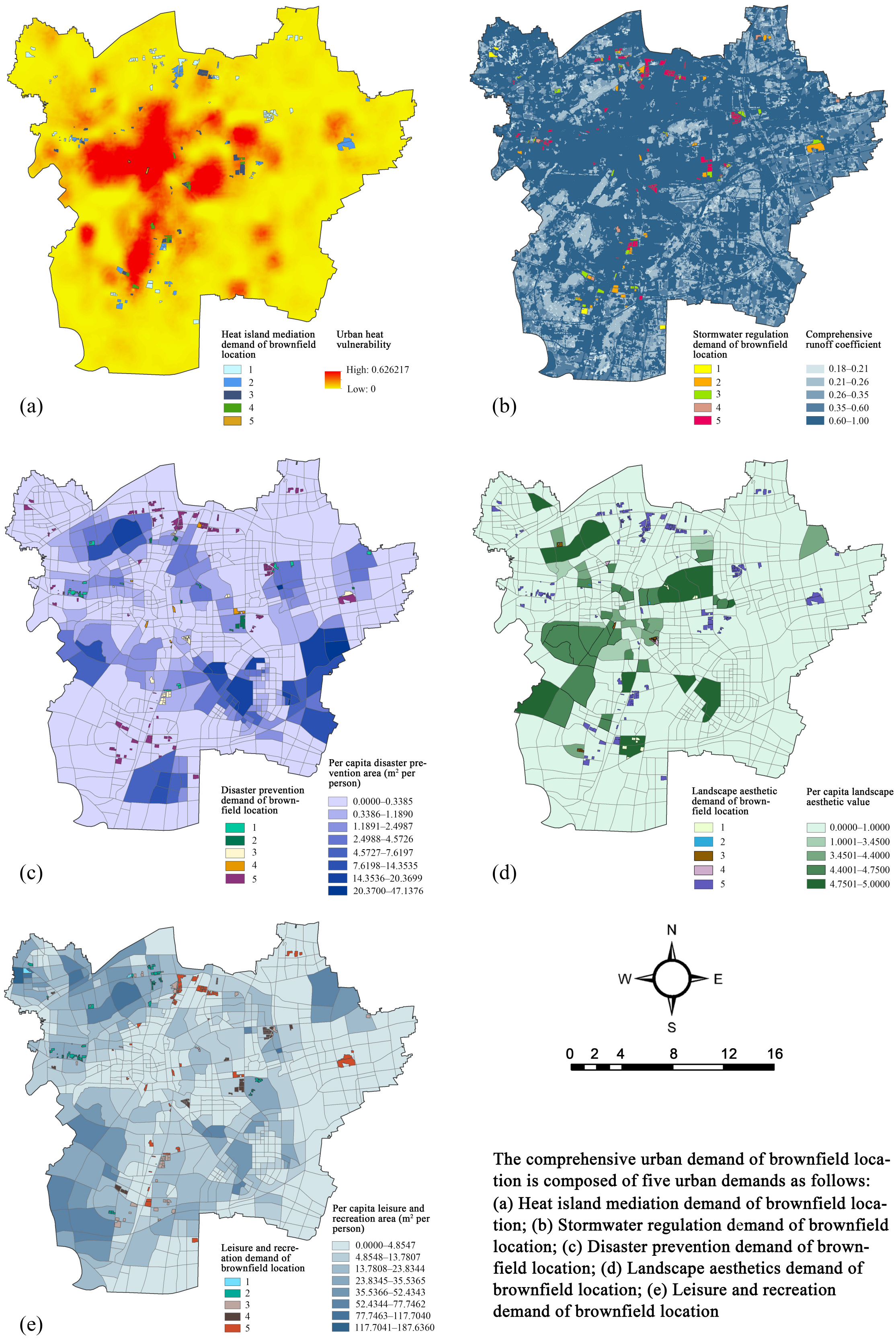

Figure 4. Values of the five categories of urban demand in the brownfield location. (**a**) Heat island mediation; (**b**) stormwater regulation; (**c**) disaster prevention; (**d**) landscape aesthetics; (**e**) leisure and recreation.

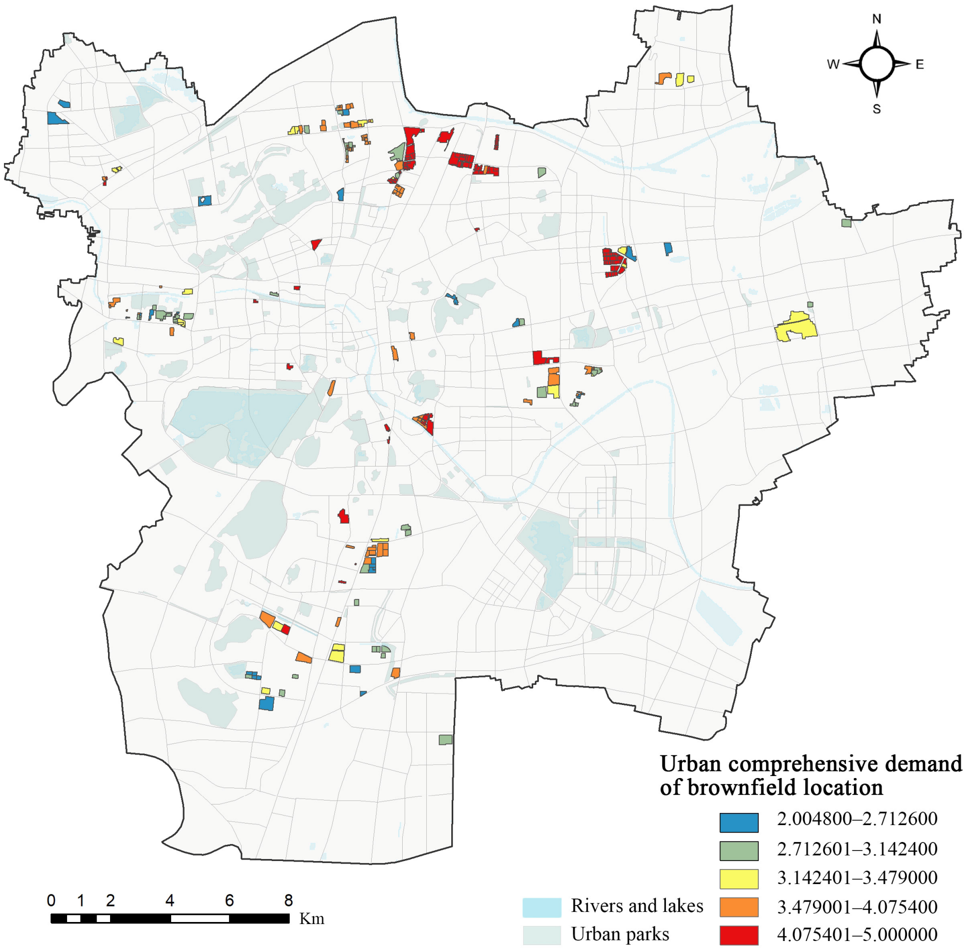

Figure 5. Values of comprehensive urban demand in the brownfield location.

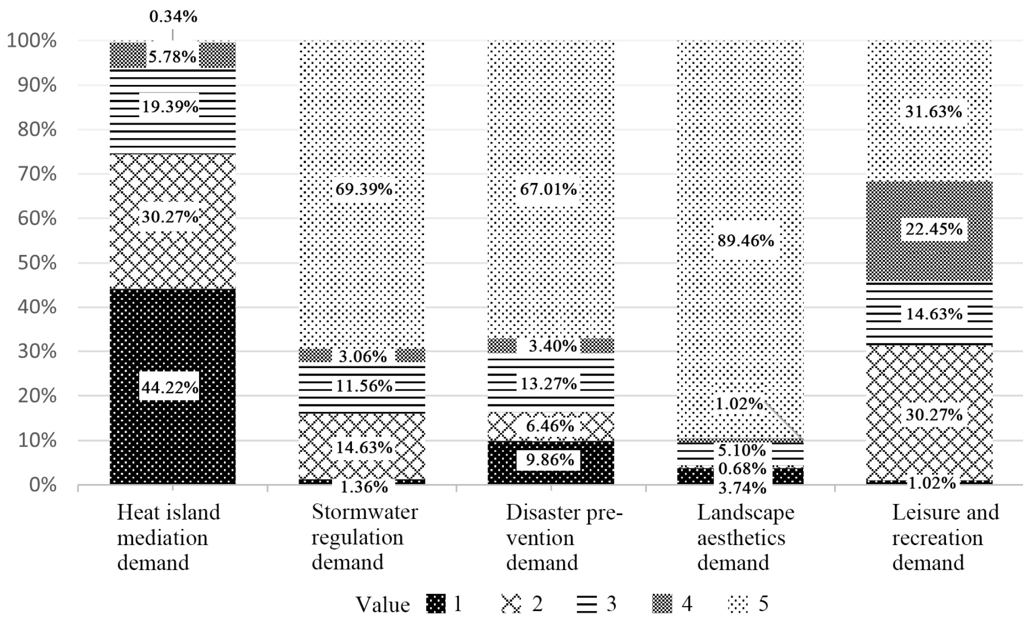

Figure 6. Percentages of urban demand values of brownfields.

3.3. Priority of Brownfields Catering for GI Integrating Urban Demand and Site Attributes

The coupling coordination degrees between the S_s and D_u values of brownfields fluctuated between 0.10225 and 0.68399, and the specific values could be divided into five categories: good coordination, primary coordination, forced coordination, general incoordination and extreme incoordination. The coupling relationship between site suitability and urban demand was not generally ideal. Nevertheless, the numbers of brownfields with good coordination and primary coordination were 13 and 112, respectively, accounting for 4.42% and 38.10% of the total number, that is, more than one third of the brownfields showed a more coordinated relationship between site suitability and urban demand. The number of brownfields with D values less than 0.40 was 48, accounting for 16.33% of the total, and these showed an uncoordinated coupling relationship between the above two values. In regards to the spatial distribution of the D values of brownfields (Figure 7), the brownfields with the best coordination were mainly concentrated in the urban center and the eastern part of the study area, and there was a spatial trend where the further away the site was from the urban center, the smaller the D value, and the greater the mismatch between site suitability and urban demand.

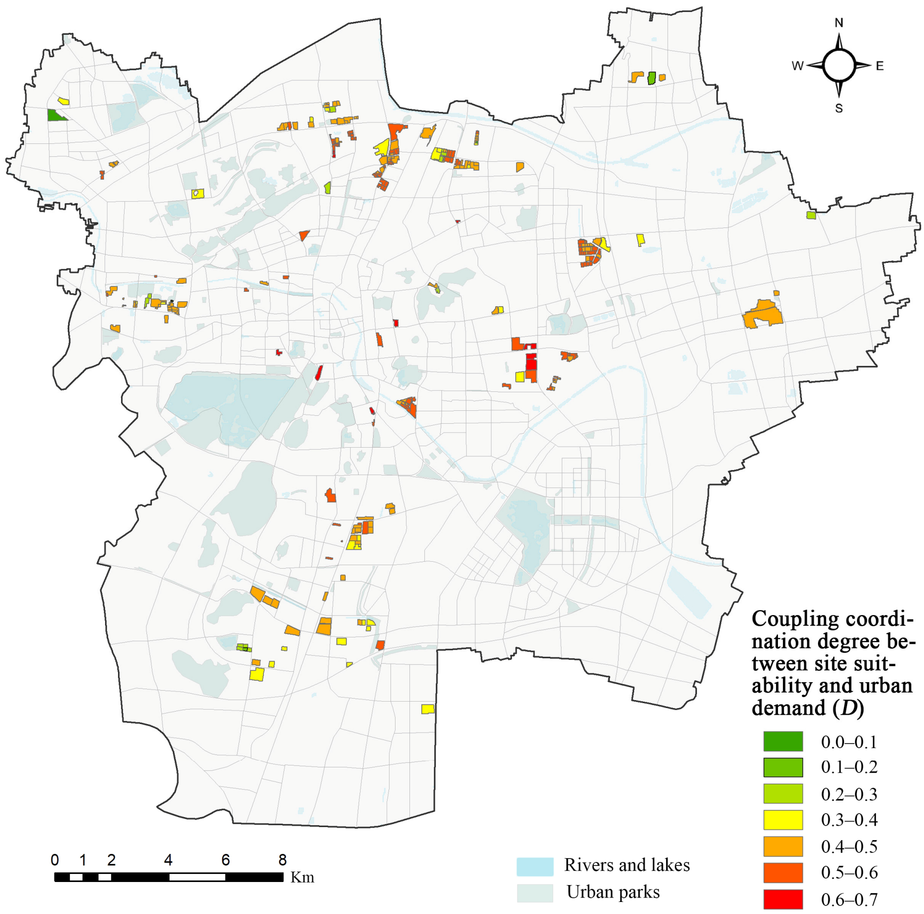

Figure 7. Coupling coordination degree between site suitability and urban demand.

The matching relationship between site suitability and urban functional demand was characterized using quadrant division. The median values of S_s and D_u were determined as 3.479 and 2.288, respectively, using the natural breakpoint method. The results show that the state of the match between site suitability and urban demand in the Xuzhou urban area could be divided into four types (Figure 8): high demand–high suitability (quadrant I), high demand–low suitability (quadrant II), low demand–low suitability (quadrant III) and low demand–high suitability (quadrant IV). There were 65 brownfields in quadrant I, accounting for 22.11% of the total, and 132 brownfields in quadrant II, accounting for

44.9% of the total. As such, the total number of brownfields located in the high-demand area was 197, that is, nearly two-thirds of the total number of brownfields (67.01%) could effectively fill the demand gap if turned into GI. In addition, different matching degrees were observed in each quadrant. For example, the brownfields in quadrant I, far away from the joint coordinates and origin, had a better matching relationship, and thus, would be better suited to integration into urban GI; in quadrant II, the brownfields that were further away from the joint coordinates and the origin showed greater mismatch between suitability and urban demand.

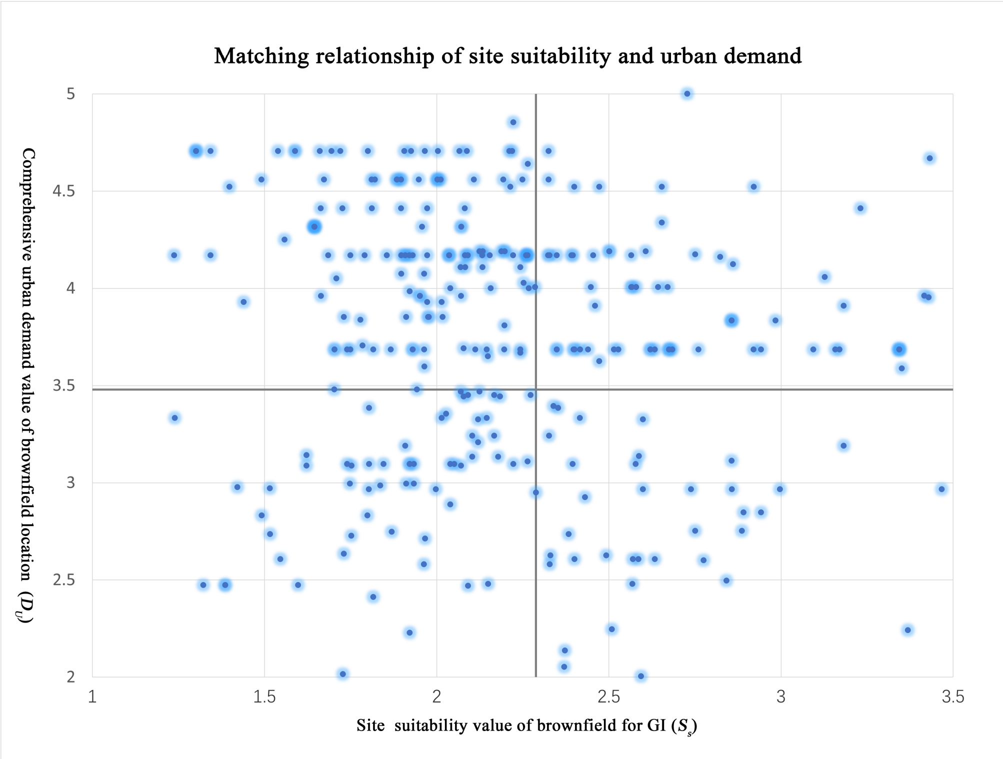

Figure 8. Quadrant division of matching degree between site suitability and urban demand.

According to Table 4, 120 brownfields (with an area of 240.32 × 10^4 m^2) were selected to be integrated into GI, accounting for 40.82% of the total number. These sites should meet two conditions, namely, being in a high-urban demand area and possessing a *D* value between 0.5 and 0.7. Such brownfields not only showed high site suitability, but were also located in areas with higher urban functional demand, which could be turned into green space (Figure 9). Since the *D* values of the brownfields in the high demand–low suitability quadrant were all less than 0.6, the priorities of brownfields catering for GI were classified into three levels: very high, high and very low. There are 13 brownfields in the very high priority class (with an area of 43.44 × 104 m^2), accounting for 4.42% of the total number of brownfields in the study area, and 10.83% of the number of selected brownfields catering for GI. The numbers of brownfields in the high priority and very low priority classes were 52 and 55, respectively, with a total area of 196.88 × 104 m^2. As shown in Figure 9, there was no obvious trend in the spatial distribution of brownfield priority. The brownfields with priority levels I and II were mostly located near the urban center, and some adjacent brownfields also presented these two priority classes.

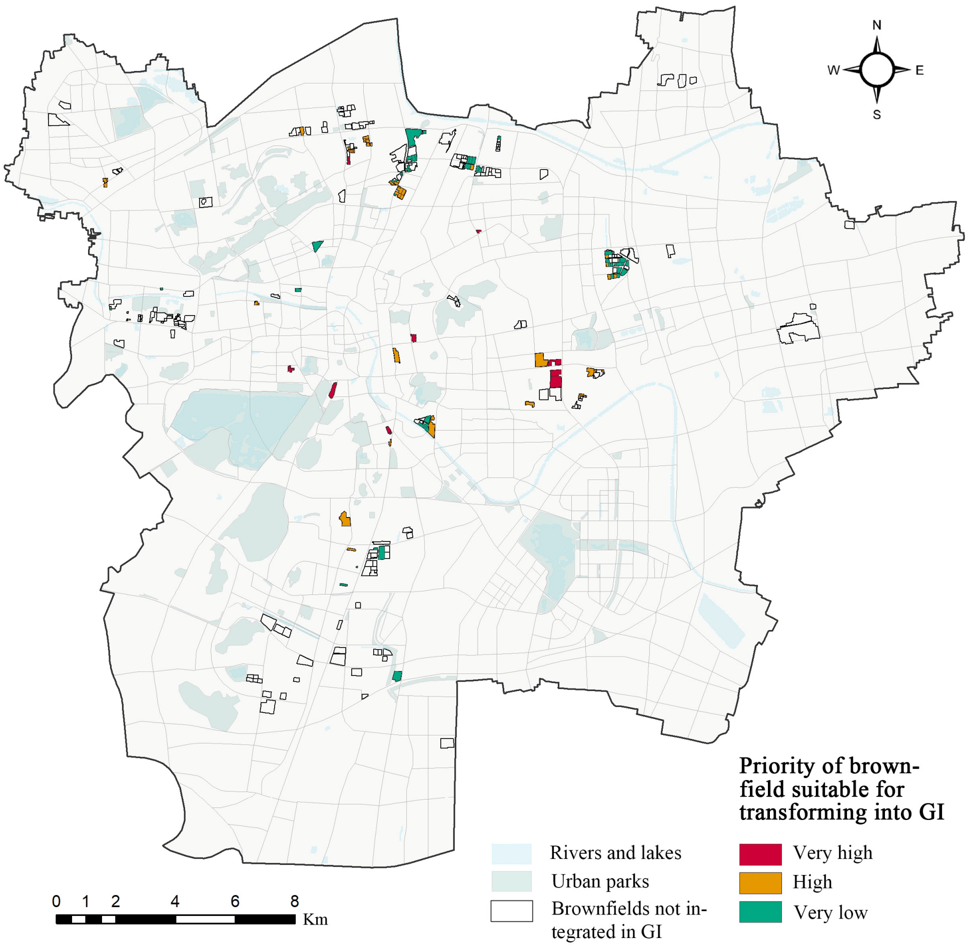

Figure 9. Priority of brownfields catering for GI.

4. Discussion

4.1. Key Factors of Site Attributes on Priority of Brownfield Catering for GI

The site attributes affecting a brownfield's priority for conversion into GI include the status of areas both within and surrounding the brownfield, such as the area, slope, hardening rate, vegetation coverage, accessibility, distance to existent green and blue GI and land use type [5,19]. Previous studies showed that there is a significant positive relationship between the brownfield's area and its potential ecological benefits and resilience [4]; the distance of the brownfield from adjacent green space has a close relationship with the efficiency of GI functionality, based on the landscape network principle [4,7]; and the NDVI reflects the native vegetation status of brownfields to a certain extent, revealing the potential to provide habitats and thus biodiversity [41]. In this study, brownfields with NDVI values greater than or equal to 0.4 comprised 33.67%, and these can be regarded as having higher vegetation coverage and plant species richness. The vegetation on the site should be preserved to avoid biodiversity loss when redeveloping the brownfield [42].

In addition, the factors affecting green space visitation, such as accessibility and surrounding land use, are also crucial in determining the frequency of urban residents' use of the green spaces and the quantity of cultural services provided [25,43]. As urban GI, if the brownfield displays high accessibility and all the required residential and commercial facilities in the surrounding area, people can enjoy the green space in a convenient way, thus assuring the delivery of "positive externality" benefits [44]. This study also shows that the closer the space is to the city center, the more complete the infrastructure will be, and the higher the mixing degree of land use function, meaning the potential for brownfield catering for GI will be greater.

4.2. Impact of Urban Functional Demand on the Priority of Brownfield Catering for GI

In previous studies, researchers mostly focused on a single prominent functional demand. Among these, the most addressed are urban heat island mitigation, rainwater regulation and GI equality improvement [26,45,46]. However, in this study, multi-functionality was deemed necessary when maximizing the comprehensive benefits of GI [26,47]. This study thus incorporated five types of urban functional demands into the priority evaluation framework for brownfields catering for GI. Compared with the site attributes, the assessment of urban functional demand related to the brownfield location provides a more accurate and complete means of integrating the brownfields into urban GI.

Most studies found a highly overlapping spatial relationship between brownfields and urban functional demands. For example, Kazmierczak [26] found that brownfield clusters overlapped significantly with areas of high heat island intensity and heat vulnerability in Manchester, UK. Similarly, in this study, it was found that there is a high degree of overlap between the distribution of brownfields and areas of high demand for urban comprehensive functions. Close to half, 43.2%, of brownfields are located in areas of extremely high demand for urban comprehensive functions. In other words, transforming brownfields located in high-demand areas into GI is a sustainable means of increasing the cooling service and stormwater regulation capacities of GI, and even to help improve residents' health and well-being [48].

The use of different urban demand indexes has different impacts on the interpreted potential of transforming brownfields in catering for GI. The brownfields in the study area were distributed in areas with different levels of demand for increases in heat island mediation and leisure and recreation facilitation, which had an obvious influence when determining the priority of brownfields to be converted to GI. In contrast, the brownfields were mostly located in areas of high demand for the three other types of urban functions, which had smaller effects on prioritization. In particular, an important first step in brownfield priority assessment is to identify the most urgent urban ecological problems and corresponding functional demands, as well as their weights, because there are big differences in the social ecological risks between cities around the world.

4.3. The Important Role of Matching Degree and the Coupling Coordination Degree Model in the Identification of Brownfield Priority Catering for GI

In this study, quadrant division and the CCD model were used to assess the coupling relationship between site attributes and urban demands. Compared to previous studies, our coupling result could be used to help select and prioritize brownfields in a more precise way, achieving efficient GI supplementation and functional improvement [8,23]. The CCD model can be used to accurately reflect the coupling coordination degree between site suitability and urban demand. However, this does not mean that all brownfields with high degrees of coupling coordination should be integrated into urban GI, as the method cannot exclude brownfields with high D values that also belong to areas of low suitability and low urban demand. Therefore, it is necessary to use quadrant division to determine the matching relationship between the above two factors in order to select the brownfields to be integrated into urban GI.

The results show that there was an obvious spatial dislocation between site attributes and urban functional demand. However, more than 22.11% of brownfields (in quadrant I) showed both very high site suitability and very high urban functional demands, suggesting that these should be preferentially integrated into urban GI, after which a secondary assessment of these brownfields should be developed, considering pollution status, land ownership, industrial heritage and so on, in order to more accurately assess the potential GI site. The brownfields with both low site suitability and low urban demand could be redeveloped for other urban land functions, such as use as residential, commercial, or public service facility lands.

It was also shown in this study that brownfields near urban centers generally have high priority in terms of transformation into GI. Because urban centers are characterized by high population density, good accessibility and a rich mixture of functions, the brownfields tended to be located in areas of high demand for urban GI functions, and will thus generate much higher social and economic value when turned into GI.

4.4. Research Value and Limitations

The integration of brownfields into GI has been recognized as an important approach to achieving urban sustainable development. However, the potential and suitability of brownfields as GI are determined by both site attributes and urban functional demands. Therefore, the priority assessment method proposed in this study, which couples both, could realize the efficient and accurate optimization of urban GI development in high-density built-up areas. By focusing on the central area of Xuzhou, this study demonstrates the usefulness and convenience of this method. Our study's results have practical value in guiding decision-makers in relation to investing funds in brownfield greening projects that will have the highest social-ecological benefits.

Nevertheless, the index system used in the study should be adjusted in practice according to the most relevant urban functional demands, and the trade-off and coordination relationships between various demands should be rigorously determined. In addition, due to limitations in terms of data accuracy and acquisition, this study only integrated population density in assessing urban demands, and did not consider much more detailed population characteristics such as age, gender, and income. Meanwhile, the pollution levels, land ownership, and industrial heritage status of brownfields were not been included in the site attribute factors. Future studies of brownfield priority should increase the precision of the study, and more deeply explore the potential brownfield to GI conversion by considering site biodiversity, the demands of vulnerable surrounding populations and multi-stakeholder participation in order to realize much more practical and effective approaches to the redevelopment of brownfields [49].

5. Conclusions

Transforming brownfields into urban GI has been widely recognized as a sustainable strategy for improving urban functionality. This paper introduced an approach that integrates site attributes and urban functional demand to prioritize brownfields in the urban area of Xuzhou. The site suitability value was calculated by overlaying seven indexes, including the area, vegetation cover, accessibility, distance from existent green space and so on; comprehensive values of the urban demands related to brownfield locations were obtained by assessing five urban functional demands—heat island mediation, stormwater regulation, disaster prevention, landscape aesthetics and increased leisure and recreation. Then, using quadrant division and the CCD model, the coupling and matching relationships between site suitability and urban demand were analyzed, and the most suitable brownfields for transformation into GI were identified and prioritized.

The main conclusions are as follows: (1) in terms of site attributes, the suitability values of brownfield conversion to GI (S_s) were generally low, fluctuating from 1.2374 to 3.4666, and brownfields close to urban centers had a higher suitability. (2) In terms of urban functional demands, the comprehensive demand value of brownfield location (D_u) ranged from 2.0048 to 5, with generally high scores. More than one-third of the brownfields showed high comprehensive demand scores in relation to the five function types. In terms of the single demand index, the brownfields were mostly localized in areas of high demand for stormwater regulation, disaster prevention and landscape aesthetics, and of medium or low demand for heat island mediation. (3) After integrating site attributes and urban demands, 40.82% of brownfields (120 plots) were suggested for integration into GI, and these were located in areas of high comprehensive demand and showed "good coordination" or "primary coordination" coupling relationships with site suitability. According to the matching and coupling degrees of the brownfields selected above, priority was classified into three levels: very high priority, high priority, and very low priority.

This approach is characterized by simple operability, as well as flexibility and adaptability according to different urban ecological problems and demands, meaning it can be popularly applied in practice. The method can be used for the selection of sites for new GI spaces in metropolitan areas, and can also provide systematic decision-support tools for brownfield redevelopment.

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Data Availability Statement: Data is contained within the article and the details are shown in Table 1.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Questionnaire Survey on Weights of Indexes for Site Suitability of Brownfield (S_s) and the Comprehensive Demand Value of Brownfield Location (D_u)

Dear Expert:

Thank you very much for occupying your time to conduct this questionnaire!

Integrating brownfields to urban GI is regarded as a sustainable strategy around the world. The aim of this questionnaire is to carry out a survey of two index weights for assessing the priority of brownfield catering for urban GI. Please use your judgment according to the actual situation and practical experience. The detailed explanation of each index is as follows:

(1) Site suitability of brownfield (S_s)

The site suitability (S_s) of brownfield catering for GI is to assess the extent of the suitability for urban green space considering brownfield attributes. The site suitability assessment index system of brownfield transformed into GI was constructed selecting seven site attribute index factors (see details in Table A1).

The weight of each index was obtained by pairwise comparison, and you only need to complete Table A4 as follow.

(2) Comprehensive demand value of brownfield location (D_u)

The assessment of urban functional demand (D_u) is measuring the ability of a brownfield to meet urban demands when integrated into urban GI. Based on the literature review and data availability, five functional demands were selected in the research (see details in Table A2).

The weight of each index was obtained by pairwise comparison, and you only need to complete Table A5 as follows.

Note: this questionnaire is divided into two parts. The importance of index factors at the same level should be compared in pairs. The measurement standard is divided into five grades, corresponding to five scores as follows (Table A3):

Table A1. Index system of site suitability of brownfield (S_s).

	Index
Site suitability of brownfield (S_s)	Area
	NDVI
	Distance from the nearest green space
	Suitability of construction land
	Accessibility
	Surrounding land functions
	Burial of underground cultural relics

Table A2. Index system of comprehensive demand value of brownfield location (D_u).

	Index
Comprehensive demand value of brownfield location (D_u)	Heat island mediation demand
	Stormwater regulation demand
	Disaster prevention demand
	Landscape aesthetics demand
	Leisure and recreation demand

Table A3. Importance classification and meaning.

Rank of Importance	Meaning
1	equal importance
3	slightly important
5	obvious importance
7	very important
9	great importance

In the two tables below, if you choose the table box closer to X, then the X index is more important than the Y index, and if you prefer the box closer to Y, then the opposite is true. Please check the box according to your opinion.

Table A4. Importance comparison of site suitability index.

X	9	7	5	3	1	3	5	7	9	Y
Area										NDVI
Area										Distance from the nearest green space
Area										Suitability of construction land
Area										Accessibility
Area										Surrounding land functions
Area										Burial of underground cultural relics
NDVI										Distance from the nearest green space
NDVI										Suitability of construction land

Table A4. *Cont.*

X	9	7	5	3	1	3	5	7	9	Y
NDVI										Accessibility
NDVI										Surrounding land functions
NDVI										Burial of underground cultural relics
Distance from the nearest green space										Suitability of construction land
Distance from the nearest green space										Accessibility
Distance from the nearest green space										Surrounding land functions
Distance from the nearest green space										Burial of underground cultural relics
Suitability of construction land										Accessibility
Suitability of construction land										Surrounding land functions
Suitability of construction land										Burial of underground cultural relics
Accessibility										Surrounding land functions
Accessibility										Burial of underground cultural relics
Surrounding land functions										Burial of underground cultural relics

Table A5. Importance comparison of urban demand of brownfield location.

X	9	7	5	3	1	3	5	7	9	Y
Heat island mediation demand										Stormwater regulation demand
Heat island mediation demand										Landscape aesthetics demand
Heat island mediation demand										Disaster prevention demand
Heat island mediation demand										Leisure and recreation demand
Stormwater regulation demand										Landscape aesthetics demand
Stormwater regulation demand										Disaster prevention demand
Stormwater regulation demand										Leisure and recreation demand
Landscape aesthetics demand										Disaster prevention demand
Landscape aesthetics demand										Leisure and recreation demand
Disaster prevention demand										Leisure and recreation demand

Appendix B. Urban Demand Index Explanation and Origin

Demand Types	Indicator Explanation	Basis
Heat island mediation demand (dimensionless quantity)	This indicator characterizes the demand for mitigating the urban heat island effect based on surface temperature and population density data. A higher demand value at the brownfield location indicates a higher cooling service efficiency provided by a brownfield when it is integrated into GI.	According to statistics, the annual average temperature and extreme highest temperature in Xuzhou increased from 1990 to 2020, and the extreme high temperature reached 39.1 °C in 2017. Meanwhile, the study area is densely populated, with a population density of 7674 person/km^2 in Gulou district located in the city center (2015).
Stormwater regulation demand (dimensionless quantity)	This indicator measures the functional demand of a grid area to absorb rainwater and mitigate urban waterlogging using the comprehensive runoff coefficient. A higher demand value at the brownfield location means that the brownfield could provide more efficient stormwater regulation services when transformed into GI.	The risk of rainwater and flood disasters is prominent in Xuzhou. The central urban area is low-lying, and urban waterlogging happens when rain falls heavily in a short time during the summer. The "8.17 rainstorm" accident in 2018 had a maximum local rainfall of 516 mm, causing seven deaths and 18 injuries.
Disaster prevention demand (m^2 per person)	The indicator measures the demand for disaster prevention and mitigation based on the per capita area of disaster prevention and mitigation. A higher demand value of the urban block where a brownfield is located indicates a greater potential of brownfield catering for GI.	Xuzhou is located in the "Tancheng–Yingkou" seismic zone of North China. There are multiple potential earthquake sources around the central urban area. In the past, Xuzhou has been affected by earthquakes in neighboring areas several times, but there is a serious lack of infrastructure for urban disaster risk prevention and mitigation.
Landscape aesthetics demand (dimensionless quantity)	This indicator characterizes the aesthetic demand for urban landscapes by the average aesthetic score within an urban block. A higher demand value of the block where a brownfield is located indicates that there are fewer green spaces with high aesthetic scores, and the integration of a brownfield in the block into GI could increase the possibility of improving aesthetic services.	One of the core goals of the "14th Five-Year Plan" for urban landscaping and greening in Jiangsu Province (2021–2025)" is to continuously strengthen the ecological restoration of damaged mountains, water systems, brownfields, and abandoned land in cities, and create high-quality and culturally integrated urban green space network.
Leisure and recreation demand (m^2 per person)	This indicator characterizes the demand for leisure and recreation in the block by calculating the per capita green space area based on different service radii of green space areas. A higher demand in the location of the brownfield indicates the leisure and recreation services in the block will increase after brownfield greening, and the fairer the distribution of GI.	The inequality of green space in the central urban area is a prominent issue, with 39% of communities having inadequate green space. One of the significant objectives of the "Plan for Scientific Greening in Xuzhou City" (2022) is to utilize abandoned land to expand green space and enhance the quality of parks in the 10-min service radius.

Appendix C. Results of the Single Index of Site Suitability of Brownfield Catering for GI (S_s)

The results of seven site attribute indexes were obtained as follows. In the Figures A1–A7, the value was ranked from 1 to 5, which respectively indicates the site suitability of brownfield is very low, low, medium, high, and very high.

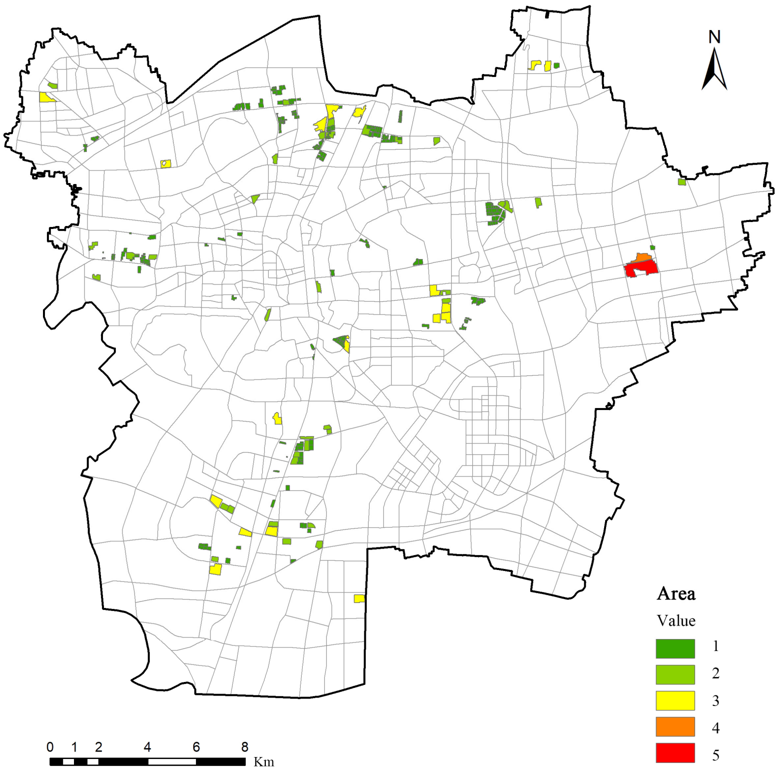

Figure A1. Single value of site suitability based on "area".

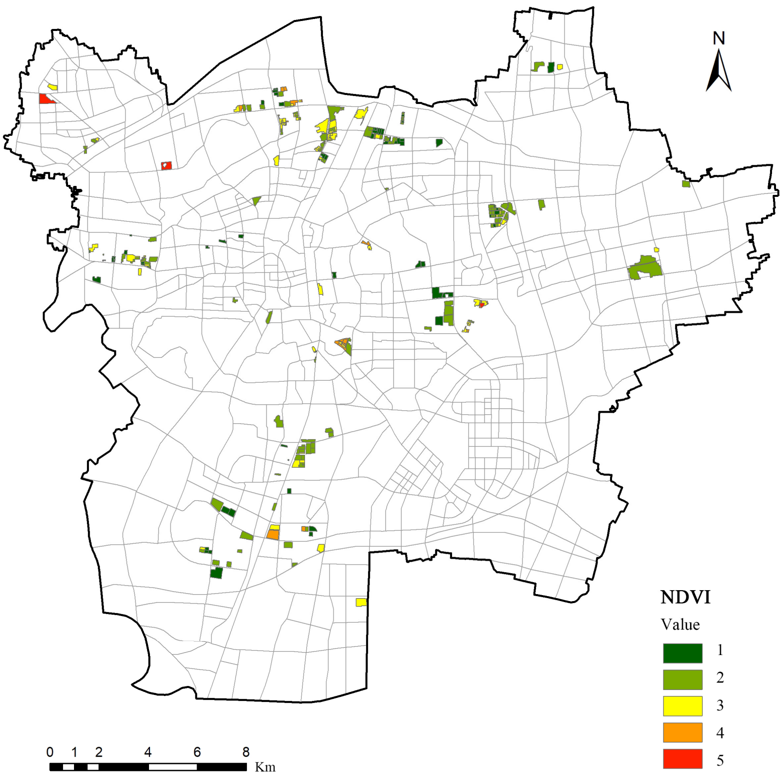

Figure A2. Single value of site suitability based on "NDVI".

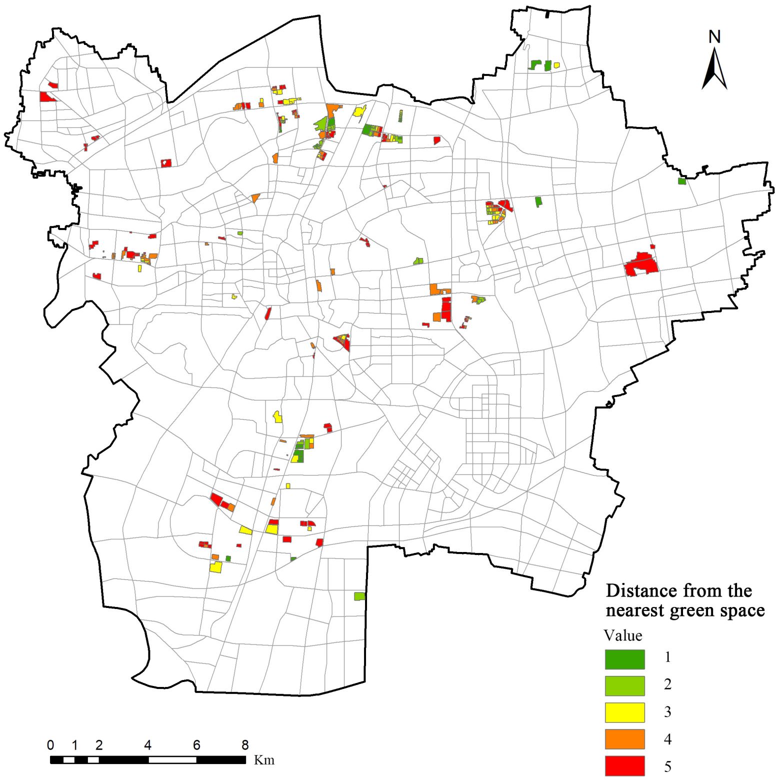

Figure A3. Single value of site suitability based on “Distance from the nearest green space”.

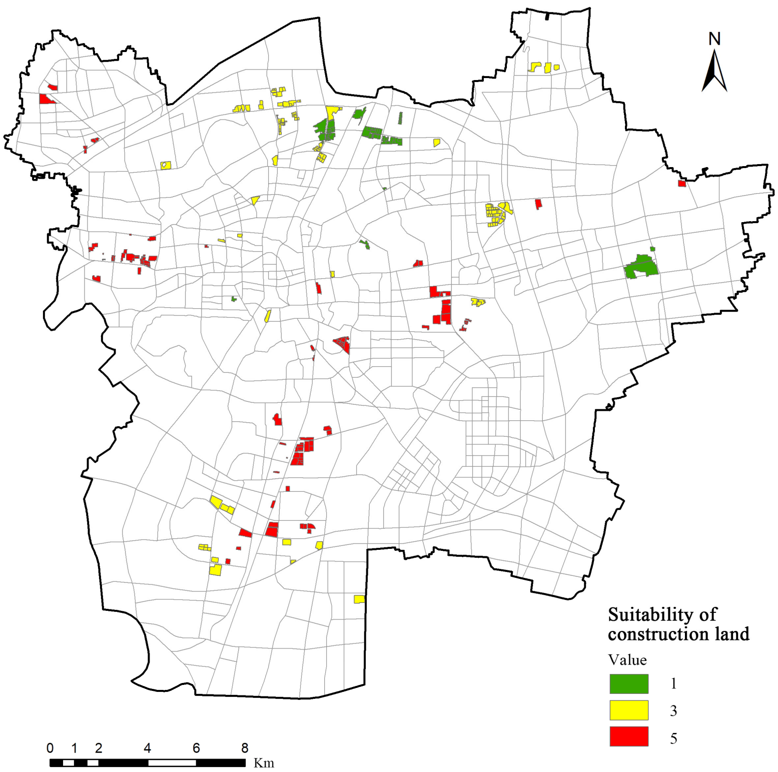

Figure A4. Single value of site suitability based on “Suitability of construction land”.

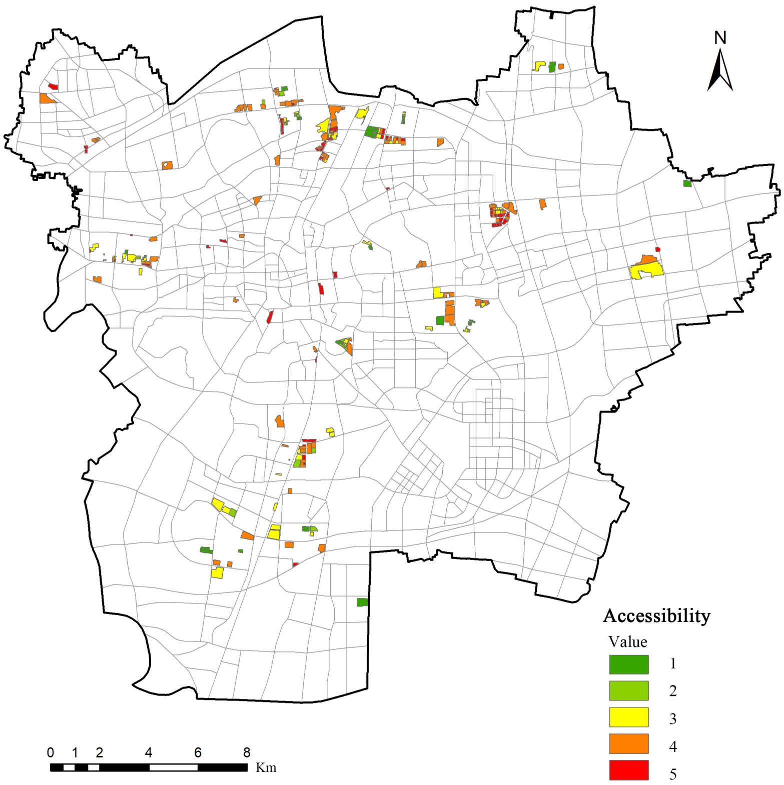

Figure A5. Single value of site suitability based on "Accessibility".

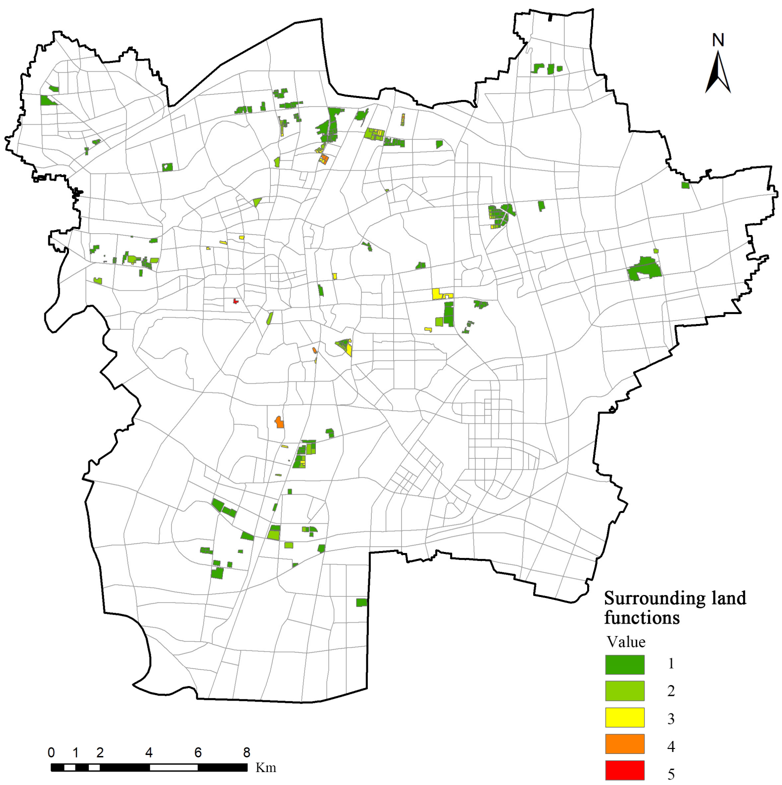

Figure A6. Single value of site suitability based on "Surrounding land functions".

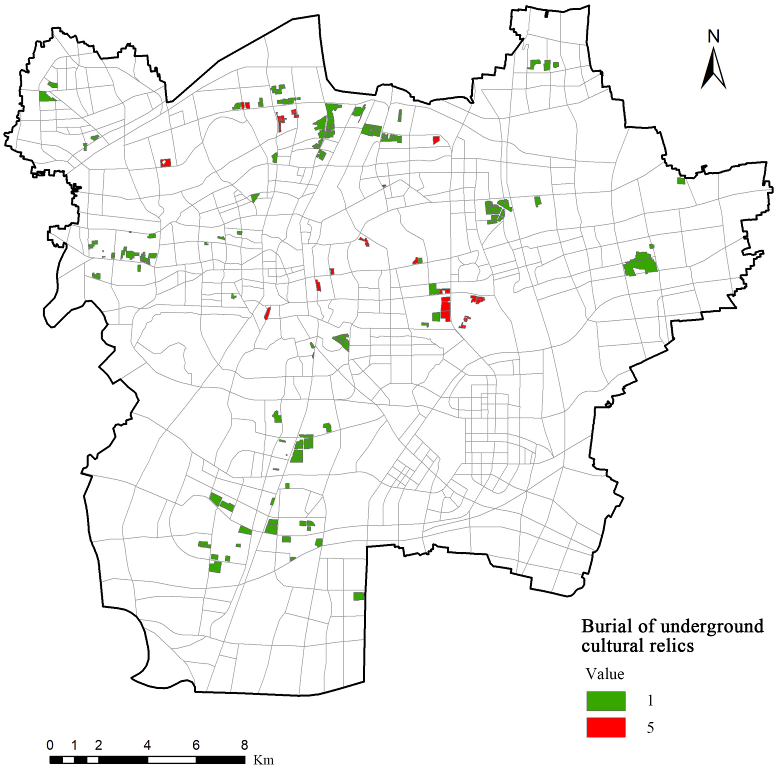

Figure A7. Single value of site suitability based on "Burial of underground cultural relics".

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