

Article

Identification of Critical Areas of Openness–Vitality Intensity Imbalance in Waterfront Spaces and Prioritization of Interventions: A Case Study of Xiangjiang River in Changsha, China

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Abstract: To alleviate the contradiction between high-density urban spatial environments and high-frequency citizens' activities, it is vital to determine the degree of openness of waterfront space, figure out the matching relationship between spatial openness and vitality intensity, identify imbalanced spatial zones and divide the order of intervention, and compensate for the limitations of subjective judgment in traditional planning decisions. This paper uses the Changsha Xiangjiang River waterfront space as a research sample based on multi-source data. It constructs the evaluation indicators system and research framework for the degree of openness of waterfront space. Then, by evaluating the openness and vitality intensity of the waterfront space and adopting the quadrant division method, waterfront space zones with a mismatched openness and vitality intensity were identified. Finally, planning interventions are prioritized based on a priority index. The results show the following: (1) The openness and vitality of the waterfront space of Xiangjiang River show the spatial distribution characteristics of “high in the middle and low in the north and south” and “high on the east bank and low on the west bank”. (2) Fifteen low-quality waterfront spatial zones with “low vitality intensity and low openness” and one with a severe imbalance of “low openness–high vitality intensity” were identified. These waterfront spatial zones cannot meet the requirements for the high-quality development of waterfront space. (3) The study delineates five priority levels for planning interventions. Among them, three waterfront space zones belong to priority V, mainly distributed north and south of the Xiangjiang River. Five waterfront spatial zones belonging to priority IV are concentrated in the middle of the Xiangjiang River. The above areas need to be prioritized for improvement to accurately promote the overall balanced development of the waterfront space.



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1. Introduction

Urban waterfront open spaces can not only enrich the urban landscape and maintain ecological balance but also positively affect residents' quality of life, which is crucial for enhancing and restoring the vitality of urban development [1,2]. In modern cities, waterfront open spaces are essential for future high-quality urban development. From the perspective of material space requirements, waterfront open spaces provide a place carrier for citizens' activities, carrying their daily recreation, mental health, and other material and spiritual needs [3]. From the perspective of urban spatial form and sustainable development, rivers and other high-level water systems are crucial to urban development. Many cities rely on waterfront key locations to form the core of urban vitality agglomeration and to build a planning pattern of development along the river or across the river [4,5], such as New York's Hudson River [6,7], the Seine River in Paris [8,9], and the Huangpu River in Shanghai [9,10]. The quality of spatial components is closely related to the vitality of waterfront spaces, and

high-quality landscape elements, traffic elements, and functional elements can provide positive support for citizens' activities [11,12]. However, in the rapid urbanization process [13], the area of waterfront space has been shrinking. In addition, under the impact of market profitability, the "green gentrification" phenomenon has intensified, and the openness of waterfront space has been violently attacked. Meanwhile, rapid urbanization has led to the development of urban waterfront spaces, facing severe challenges [14–16], such as the decline in ecological quality, low accessibility, and limited service functions. All of these factors are detrimental to the concentration of spatial vitality in the city [17,18]. The above problems reflect the irrational allocation and even waste of spatial resources, which, if not constrained by planning, will inevitably cause the degradation of the quality of urban waterfront open spaces and the dissipation of vitality. Therefore, there is an urgent need to establish a systematic evaluation system for the degree of openness of waterfront open spaces by comprehensively selecting the spatial elements closely related to spatial vitality. Meanwhile, assessing the level of openness for each waterfront space zone and accurately identifying zones where the openness level and spatial vitality intensity do not align can help to carry out precise planning for the area of prominent contradiction. This will form systematic and forward-looking strategies for implementing waterfront space planning.

Space vitality reflects the actual operating status of a spatial system [19] and comprehensively reflects the activity, openness, resourcefulness, and reasonableness of the relevant constraints of spatial components [20,21]. Facing the challenges of insufficient spatial openness, a lack of vitality, and an uneven distribution of vitality, many scholars have carried out relevant empirical studies from multi-dimensional perspectives, and many mature research methods have emerged. (1) Most early studies focused on the renewal aspects of waterfront space sites, including renewal models, renewal concepts, and renewal programs [22]. With the popularity and application of big data, existing studies have started to quantitatively analyze the spatial components of waterfront space in terms of accessibility [23], environmental quality [24,25] (e.g., the distribution of green space, the proportion of green space services, and built environment), and diversity of functional facilities [26] (e.g., educational facilities, commercial facilities, and cultural facilities). (2) The methodology, current research methods on spatial components and spatial vitality, can be divided into three categories. Among them, the observation and summary method is mainly used in environmental behavioral studies to analyze the law between the spatial environment and spatial vitality based on empirical observations and records [27,28]; the subjective preference method [29,30] quantifies the weight of the influence of each factor on a specific group of people through semantic analysis, fuzzy evaluation, hierarchical analysis, etc. The relevance analysis method applies mathematical and statistical methods (e.g., relevance analysis, and regression analysis) to study the relationship between spatial constituent elements and spatial vitality [26,31].

In summary, some studies have summarized the spatial components affecting the degree of waterfront space vitality and analyzed the correlation between spatial components and spatial vitality. However, there are still the following limitations: (1) Most of the existing waterfront space studies started from a single element, without a multi-dimensional systematic evaluation index system of the openness of waterfront space from the ecological quality, traffic system, space construction, and functional facilities [25,32]. On the one hand, traditional spatial constraint indicators fail to truly meet the citizens' needs. For example, evaluation metrics such as the green space ratio, building density, and floor area ratio only consider physical construction aspects and do not comprehensively analyze the actual spatial form, pattern quality, and accessibility of waterfront spaces. On the other hand, the components of waterfront spaces are highly complex, necessitating a comprehensive and systematic set of constructed indicators to impose holistic and all-encompassing constraints on the physical entities of waterfront spaces. (2) Many researchers focused on the positive and negative impacts of spatial components on spatial vitality. They put forward improvement opinions on spatial components at the micro level according to the research results [10,12,24,33] and lack of macro control on optimization strategies for

the research zones within the functional area, which leads to a significant reduction in the applicability of the research. (3) Previous studies on the vitality of waterfront spaces were mainly measured through traditional data surveys [20,34], including statistics from government departments and data collected through field research. Statistical data from government departments are relatively comprehensive but not specific enough. Field research data are cumbersome, time-consuming, and challenging to carry out on a large scale. Therefore, it is difficult to quantitatively analyze the dynamic change characteristics of spatial vitality through traditional survey data. Given the practical problems and social significance of the waterfront space, studying the overall openness of the waterfront space, analyzing the positive and negative roles played by the constituent elements of the waterfront space, and laying out the order of the waterfront space improvement in an orderly manner are an effective way to formulate the sustainable development plan for the waterfront space.

Changsha is a critical secondary central city in China's Yangtze River Economic Belt, and the development of a typical "one river, two banks" urban pattern along the Xiangjiang River is an ideal case for studying waterfront space optimization strategies. As an important ecological corridor and natural landscape axis in Changsha, the Xiangjiang River is the core place for citizens' daily leisure, entertainment, and social interaction. In addition, the waterfront space of Xiangjiang River carries all kinds of artificial facilities, including transportation, architectural, and cultural facilities in Changsha, which significantly enriches the living experience of urban residents. Under the current trend of increasing access to data, big data such as cell phone signalling, Baidu heat, and POI can provide real-time and accurate feedback on the spatial distribution characteristics of citizens' activities through its high precision, fast update, firm dynamics, and many other advantages [35–37]. In summary, this paper takes the Xiangjiang River waterfront space as an example. It establishes an evaluation index system for the openness of urban waterfront space integrating a comprehensive evaluation of ecological function attributes, comprehensive evaluation of transportation accessibility, comprehensive evaluation of spatial development intensity, and comprehensive evaluation of public service facilities; quantitatively researches the openness of Xiangjiang River waterfront space; and analyzes the reasons for it. In addition, the vitality intensity of the Xiangjiang River waterfront space and its distribution characteristics are clarified through big data. Finally, based on the results of the above quantitative analysis, the order of the Xiangjiang River waterfront space planning intervention is clarified. The research results can be used to optimize urban waterfront spaces of similar scale and characteristics.

2. Materials

2.1. Study Area

Waterfront space is a high-incidence area for daily human activities in urban life [38]. According to the degree of proximity to the water body, waterfront space can be divided into five parts from near to far: water space, waterfront space, waterfront road, waterfront hinterland, and inner-city functional area. Referring to related literature [39–41] and based on the limited attractiveness of waterfront space and the activity cost of citizens, the waterfront space studied in this paper is initially defined as waterfront space, waterfront road, and waterfront hinterland that are adjacent to the water space (Figure 1a).

The Xiangjiang River is an important tributary of the Yangtze River and the mother river of Changsha [42]. Since the excavation of the Lingqu River in the Qin Dynasty, the Xiangjiang River has become the central vein of Changsha's development by relying on its ecological resource advantages and transportation advantages [9,43,44]. However, the main urban construction activities are concentrated on the east bank of the Xiangjiang River. With the construction of the Changsha infrastructure, the Xiang River's west bank has gradually expanded. To date, the urban spatial structure of Changsha has entered a new phase of "one river, two banks, cross-river development" [45,46].

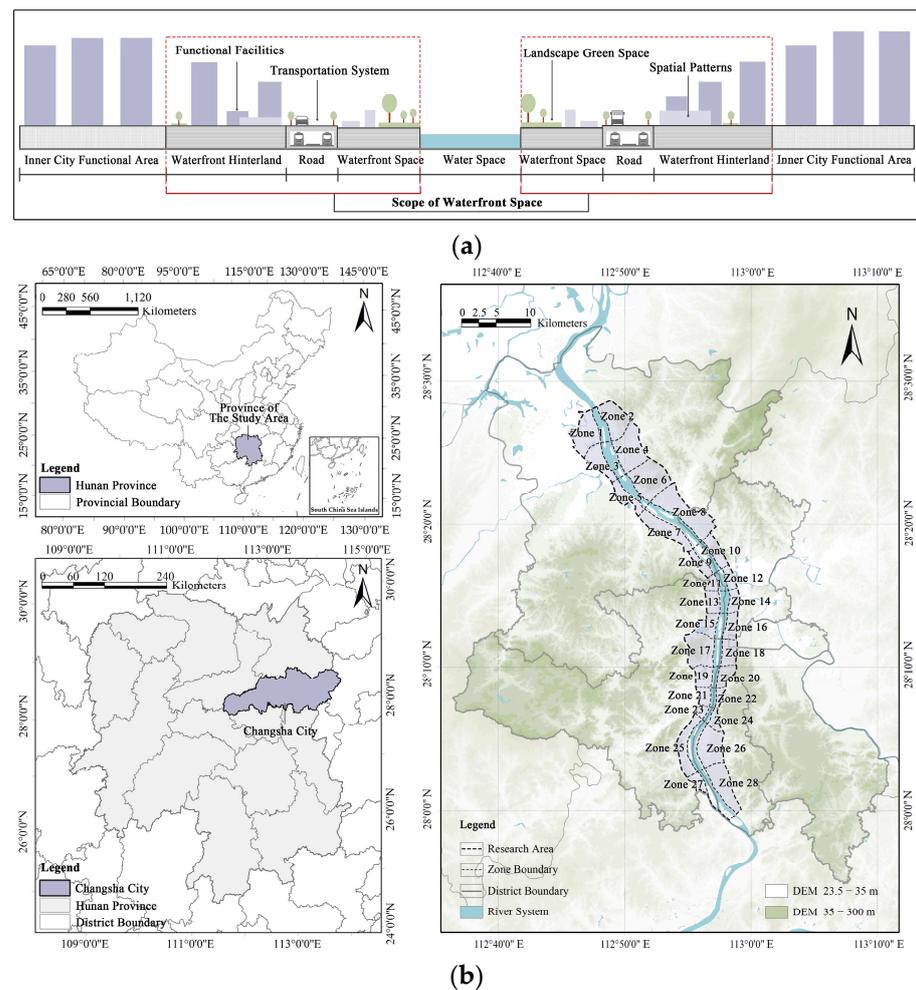


Figure 1. Delineation of the study area: (a) the extent of study waterfront space; and (b) study area.

The delineation of the study area in this paper is based on the spatial boundaries of the Xiangjiang River waterfront as stipulated in Changsha's Xiangjiang River Waterfront District Overall Urban Design and Xiangjiang River Hundred Mile Gallery Master Plan, combining elements such as major public service facilities, critical functional areas, and historical sites, and referring to the urban arterial roads to determine the study area. The total length of the study area is about 140 km, with a total land area of 238.87 square km. In Changsha's land use master plan, the urban arterial road usually serves as the demarcation line for different functional zones. The unified superior plan guides the development and construction within the boundary, and its spatial development and facility configuration are relatively co-ordinated. Therefore, concerning the established studies [10,47], this paper divides the waterfront space of Xiangjiang River into 28 research zones using the urban arterial road as the dividing line, which can accurately reflect the degree of spatial openness and vitality intensity of different research zones. The specific zoning is shown in Figure 1b.

2.2. Data Sources and Pre-Processing

The research data are mainly obtained from official sources and web data provided by open data platforms such as OpenStreetMap and Baidu Map. (1) Point-of-interest data were accessed on 5 June 2023, from Baidu Map (<https://map.baidu.com/>), which provides an accessible API interface that can be used to crawl the detailed location information of various types of geographic entities, including commercial facilities, office facilities, cultural facilities, etc., using Python. This paper cleans and reclassifies the acquired interest point data to ensure the study's accuracy. Finally, it obtains the interest point data con-

taining commercial and entertainment, science, education and culture, sports and leisure, business office, essential services, and scenic spots, totaling six medium categories and seventeen subcategories (Table 1). (2) The urban road network data were accessed on 5 June 2023, from OpenStreetMap (<https://www.openstreetmap.org/>), an open-source mapping platform, including expressway, main road, secondary road, branch road, and public transportation station facilities data, using Arc GIS10.2 platform, combined with Google Earth remote sensing images in 2023 to supplement, correct, and integrate the road network data. (3) Vitality data were obtained from the Baidu Huiyan data platform (<https://huiyan.baidu.com/products/platform>) on 6 July 2023, to obtain the thermal data of the population in the study area. The vitality intensity of each study zone was analyzed through the cropping and density analysis tools of the Arc GIS 10.2 platform. (4) The development intensity is based on the geographic information and spatial data obtained from Baidu Maps (<https://map.baidu.com/>) on 15 June 2023, and the data calculation tool of Arc GIS10.2 platform to calculate the study area's building density product and volume ratio. The residential population density of the study area was calculated on 27 June 2023, concerning the seventh census data of the population of Changsha City (http://www.changsha.gov.cn/zfxxgk/fdzdgknr/tjxx/tjgb_134828/202107/t20210729_10094327.html), based on the standard of 2.62 persons per household in the seventh census data. (5) The current land use data were accessed on 24 March 2024, from the remote sensing monitoring data of the current land use status in 2023 from the Center for Resource and Environmental Science and Data of the Chinese Academy of Sciences (<https://www.resdc.cn/data.aspx?DATAID=360>) and the land use of the study area was analyzed through the Arc GIS10.2 platform.

Table 1. Integration of POI types.

Types of POI	Specific Details
Commercial facilities	Commercial shopping, hotels, and restaurants.
Educational facilities	Schools, training institutions, and cultural centers.
Sports facilities	Stadiums, recreation centers, and fitness clubs.
Office facilities	Corporate, office housing, and financial bond services.
Public service facilities	Government agencies, hospitals, clinics, and lifestyle services.
Scenic spot	Scenic spots, and attractions.

3. Methods

3.1. Research Framework

The degree of spatial openness is a comprehensive manifestation of waterfront space's attractiveness, diversity, and competitiveness, directly affecting spatial vitality [48–50]. This paper constructs the evaluation index system and research framework (Figure 2) of the degree of openness of waterfront space, which is mainly divided into the following three steps: (1) Considering the accessibility and representativeness of the indicators, this paper screens and summarizes the constituent elements affecting the degree of openness of urban waterfront space and constructs the evaluation indicators of the degree of openness of waterfront space from a multi-dimensional perspective (including ecological value attribute, traffic accessibility, spatial development density, and functional diversity of four aspects with a total of 15 indicators) to assess the degree of openness of waterfront space comprehensively. (2) Through the Arc GIS platform, spatial analysis of all-day multi-moment thermal data of typical weekdays, holidays, and rest days in the study area was carried out to understand the spatial distribution characteristics of the vitality of waterfront spaces on both sides of the Xiangjiang River as a whole. (3) Based on the evaluation results and weights of each index, analyze the degree of openness and matching of vitality intensity of each waterfront space zone and introduce the concept of planning intervention priority to classify the order of planning intervention of waterfront space zones. According to the simulation and analysis results, the macro layout strategy of waterfront space is adjusted,

which can provide a scientific basis for the rational planning of urban waterfront space and allocation of public resources.

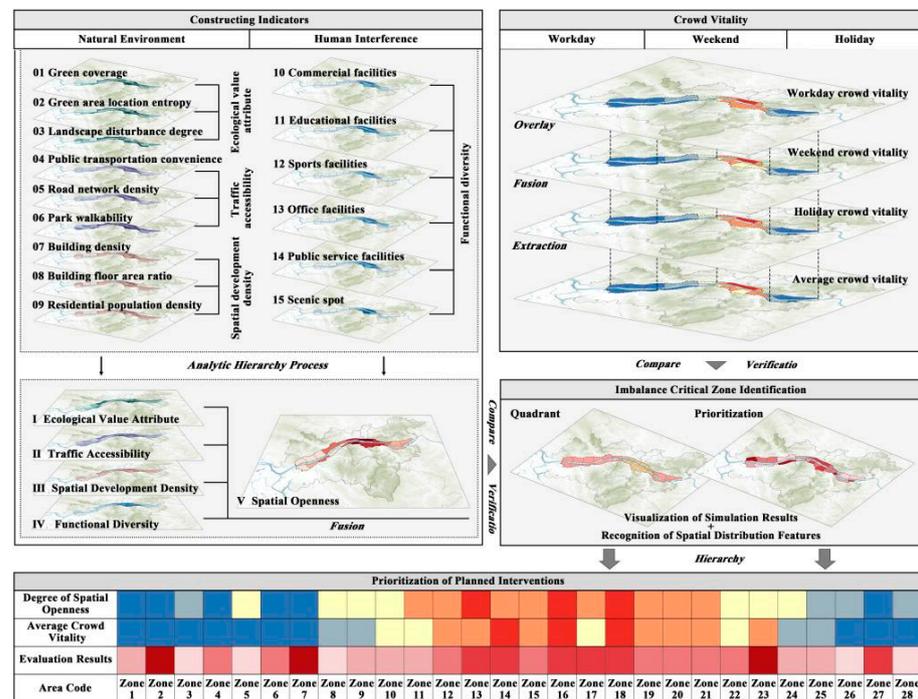


Figure 2. Technology pathway diagram.

3.2. Methodology

3.2.1. Construction of Evaluation Indicator System for Openness of Waterfront Space

This study systematically reviews the existing research results [2,10,25] and relevant planning guidelines, combines relevant expert consultation, and selects the elements influencing the degree of openness of Xiangjiang River waterfront space. On this basis, this paper summarizes the actual demand of citizens for waterfront space. From the perspectives of the scale of use, the opportunity of use, degree of use, and behavior of use, the influencing factors of the degree of openness of waterfront space are categorized into four dimensions: ecological value attribute, traffic accessibility, spatial development density, and diversity of functions [51]. Among them, the ecological value attribute reflects the scale of waterfront space available to the public; the traffic accessibility corresponds to the opportunity and possibility of the public to use the waterfront space; the density of spatial development represents the in-depth degree of the public’s use of the waterfront space; and the diversity of functions reflects the various types of behavioral activities that the public can make when using the waterfront space. The evaluation indices of the degree of openness of the waterfront space are shown in Table 2, and the degree of openness of the waterfront space is comprehensively evaluated according to Formula (12).

Table 2. Classification and weighting of indicators.

Category	Indicator	Description	Weight Coefficient
Ecological Value Attribute Analysis	Green coverage.	Ratio of ecological green space area to zone area	0.1103
	Green area location entropy	Ratio of park area to total park area within the waterfront space zone	0.0794

Table 2. Cont.

Category	Indicator	Description	Weight Coefficient
	Landscape disturbance degree (negative)	Sensitivity of different landscape components to external disturbances	0.0501
Traffic Accessibility Analysis	Public transportation convenience	Number of bus stops, subway stops, and parking facilities per zone area	0.0915
	Road network density	Ratio of road length to footprint within each zone	0.0761
	Park walkability	Ratio of serviceable area to zone area covered by each park	0.1061
Spatial Development Intensity Analysis	Building density	Ratio of building footprint to floor area within each zone	0.0604
	Floor area ratio	Gross floor area to floor area ratio within each zone	0.0586
	Residential population density	Ratio of total residential population to area within each zone	0.0812
Functional Diversity Analysis	Commercial facilities	Density of distribution of various types of commercial and recreational facilities	0.0489
	Educational facilities	Density of distribution of various types of scientific, educational, and cultural facilities	0.0398
	Sports facilities	Density of distribution of various types of sports and leisure facilities	0.0491
	Office facilities	Density of distribution of various types of business office facilities	0.0416
	Public service facilities	Density of distribution of various types of amenities	0.0525
	Scenic spot	Density of distribution of various scenic spots	0.0544

1. Ecological value attribute analysis

The ecological value is the externalized performance of the ecological service quality of waterfront space, which can provide open interactive space for citizens and stimulate the area's vitality [52,53]. Therefore, this paper evaluates the spatial distribution and area share of park green space resources and their sensitivity to other land use types in Xiangjiang River waterfront space through the degree of green coverage, the entropy of green space distribution, and the degree of landscape disturbance according to Equation (13) to test the ecological value attributes (SG) of Xiangjiang River waterfront space.

The formula for calculating green coverage is as follows:

$$GC_i = \frac{G_i}{S_i} \times 100\% \quad (1)$$

where GC_i represents the green coverage of zone i , G_i represents the total green area within zone i , and S_i represents the land area of zone i .

The formula for calculating the locational entropy of green space distribution is as follows:

$$GE_i = \frac{n_i}{N_i} \quad (2)$$

where GE_i represents the locational entropy of green space distribution in zone i , N_i denotes the total park green space area within the study area, and n_i denotes the park green space area in zone i .

The formula for calculating landscape disturbance is as follows:

$$GD_i = aC_i + bO_i + cD_i \quad (3)$$

In the formula, GD_i represents the degree of landscape disturbance in area i ; C_i , O_i , and D_i represent the degree of landscape fragmentation, landscape separation, and landscape subdimensionality, respectively; a , b , and c correspond to the weights of the indices of landscape fragmentation, landscape separation, and landscape subdimensionality; and $a + b + c = 1$, where a , b , and c are 0.6, 0.3, and 0.1, respectively.

2. Traffic accessibility analysis

As the basic structure of waterfront space, the traffic system is the hot spot where citizens' activities gather, and it is also the important foundation for shaping the open waterfront space [23]. Combined with the construction of the transportation system in the study area and the actual people's travel situation, this paper selects the public transportation system, motor vehicle transportation system, and walking system for the waterfront space, and selects the public transportation convenience, road network density, and park walkability, respectively, and calculates the comprehensive accessibility of the traffic (SP) of each waterfront space zone by Formula (14).

The formula for calculating the convenience of public transportation is as follows:

$$GD_i = aC_i + bO_i + cD_i \quad (4)$$

where PC_i represents the accessibility of public transportation in zone i ; Q_{ib} , Q_{im} , and Q_{ip} represent the total number of bus stops, subway stations, and parking facilities in zone i , respectively; and S_i represents the land area of zone i .

The road network density formula is as follows:

$$PD_i = \frac{L_{i\alpha} + L_{i\beta} + L_{i\gamma} + L_{i\delta}}{S_i} \quad (5)$$

where PD_i represents the road network density in zone i , $L_{i\alpha}$ represents the total length of expressways in zone i , $L_{i\beta}$ represents the total length of primary roads in zone i , $L_{i\gamma}$ represents the total length of secondary roads in zone i , $L_{i\delta}$ represents the total length of feeder roads in zone i , and S_i represents the land area in zone i .

The park walkability index is calculated using the following formula:

$$PW_i = \frac{M_i}{S_i} \quad (6)$$

In the formula, PW_i represents the park walkability index of zone i , M_i represents the sum of the area of the 800 m buffer zone (i.e., 15 min walkable range, not stacked calculation) of each park green space in this waterfront spatial zone, and S_i represents the land area of zone i .

3. Spatial development intensity analysis

An appropriately concentrated building layout not only contributes to a compact urban structure, but also provides citizens with dense and abundant living options, increasing the attractiveness of the area and the density of activities [24,54]. In order to measure the two-dimensional planar construction and three-dimensional spatial construction in the study area, the study analyzes the spatial development intensity (*SD*) of Xiangjiang River waterfront space through building density, floor area ratio, and residential population density according to Equation (15).

The formula for calculating building density is as follows:

$$BD_i = \frac{D_i}{S_i} \quad (7)$$

where BD_i represents the building density of zone i , D_i represents the total building footprint of zone i , and S_i represents the site area of zone i .

The formula for calculating the floor area ratio is as follows:

$$FAR_i = \frac{T_i}{S_i} \quad (8)$$

where FAR_i represents the floor area ratio of zone i , T_i represents the gross floor area of zone i , and S_i represents the site area of zone i .

The formula for calculating residential population density is as follows:

$$PD_i = \frac{H_i \times \omega}{S_i} \quad (9)$$

where PD_i represents the residential population density of zone i , H_i denotes the number of residential households in zone i , ω is the average household population (refer to the bulletin of the seventh national census of Changsha City, $\omega = 2.62$), and S_i represents the site area of zone i .

4. Functional diversity analysis

Spatial openness is the basis for supporting functional diversity and increased vitality. In a specific area of a city, the number of POI types and density are closely related to the functional activities occurring in that area [10,26]. Combining the established research [26,55] and the needs of citizens' activities, the functional diversity is subdivided into 18 indicators in 6 categories: commerce, education, sports, office, public services, and scenic spot (Table 1). The calculation formula is as follows:

$$MU_j = \frac{\sum_{i=1}^n Q_{ij}}{S_i} \times W_j \quad (10)$$

where MU_j represents the distribution density of the item facilities of category j , W_j represents the weight of the facilities of category j , Q_{ij} represents the total number of POI of category j in zone i , $j = 1, 2, 3, \dots, 6$, and S_i represents the land area of zone i .

3.2.2. Calculation of Average Crowd Vitality Intensity in Waterfront Spaces

Baidu map thermal data have proven to be a reasonable proxy for measuring the dynamics of human activities in different areas [56], which provides technical support for digging deeply into the activities of residents and exploring the relationship between urban vitality and spatial environment [57,58]. In this study, the daily average thermal data of weekdays, weekends, and holidays are selected, and the raster calculation tool of Arc GIS software is used to calculate the average value of thermal intensity in each waterfront zone, to comprehensively understand the characteristics of the distribution of spatial vitality of Xiangjiang River waterfront. The formula for calculating the average crowd vitality intensity of waterfront space is as follows:

$$SV_i = \frac{\sum_{i=1}^n A_{id} \times W_d + A_{ie} \times W_e + A_{if} \times W_f}{n * S_i} \quad (11)$$

where SV_i represents the average spatial vitality of zone i . A_{id} represents the average spatial vitality on weekdays, A_{ie} represents the average spatial vitality on weekends, and A_{if} represents the average spatial vitality on holidays. S_i represents the area of zone i . $n = 6:00, 8:00, 10:00, \dots, 22:00$, a total of 9 time periods. W_d, W_e , and W_f are the weights of the waterfront spatial vitality index on weekdays, weekends, and holidays, respectively, and $W_d + W_e + W_f = 1$, where W_d, W_e , and W_f are 0.5, 0.35, and 0.15, respectively.

3.2.3. Determination of Indicator Weights

Using the hierarchical analysis method [2], the evaluation model of the degree of openness of waterfront space is established. According to the logical structural relationship between the influencing factors, the evaluation matrix of the degree of openness of waterfront space is established, and the weights of each influencing factor are determined by judging the overall order of relative importance of each spatial constituent element. After analyzing and calculating, the maximum characteristic root of this model is 16.237, the corresponding RI value is 1.584, and $CR = CI/RI = 0.056 < 0.1$, which passes the test. Based on the above analysis, the weights of each influence factor were obtained (Table 2).

The evaluation model of the openness of Xiangjiang River waterfront space is composed of the following formula:

$$OW = 0.2398 \times SG + 0.2737 \times SP + 0.2002 \times SD + 0.2863 \times \overline{MU} \quad (12)$$

Among the above factors, the following relationships were observed:

$$SG = 0.1103 \times GC + 0.0794 \times GE - 0.0501 \times GD \quad (13)$$

$$SP = 0.1155 \times PC + 0.0967 \times PD + 0.1237 \times PW \quad (14)$$

$$SD = 0.0604 \times BD + 0.0586 \times FAR + 0.0812 \times PD \quad (15)$$

$$\begin{aligned} \overline{MU} = & 0.0489 \times MU_1 + 0.0398 \times MU_2 + 0.0491 \times MU_3 + 0.0416 \times MU_4 \\ & + 0.0525 \times MU_5 + 0.0544 \times MU_6 \end{aligned} \quad (16)$$

3.2.4. Z-Score Normalization

The Z-score normalization method can reduce the difference in quantitative scale and compare the indicators of different zones or quantitative scale more intuitively and precisely, and has certain advantages in zoning management and precise division [59]. Therefore, this paper adopts the Z-score normalization method to standardize the results of the comprehensive evaluation of the degree of openness of waterfront space and the comprehensive evaluation of vitality intensity. It matches the results of normalizing the two and divides them into quadrants. The x-axis indicates the degree of openness of waterfront space after normalization. The y-axis indicates the vitality intensity of waterfront space after normalization, constituting four quadrants. The first quadrant is "high openness–high vitality intensity", the second quadrant is "low openness–high vitality intensity", the third quadrant is "low openness–low vitality intensity", and the fourth quadrant is "low openness–low vitality intensity".

3.2.5. Prioritization of Planning Interventions

In waterfront space remediation and renewal, scientific delineation of the degree of intervention priority of different spatial zones has a vital application value for developing prospective, systematic, and efficient waterfront space planning programs [59]. The priority index calculates the ratio between the degree of openness of waterfront space and the intensity of vitality, further revealing the imbalance between the two. Through the prioritization index, the order of planning interventions is delineated, and the critical spatial zones that

need the most priority interventions in the construction of waterfront space are identified, which can ensure that the disadvantaged waterfront space receives sufficient policy and resource support. The calculation formula is as follows:

$$PRI = \frac{(OW)}{(SV)} \quad (17)$$

where *PRI* is the priority index of waterfront space, *OW* is the comprehensive openness of waterfront space, and *SV* is the comprehensive vitality intensity of waterfront space. When the degree of comprehensive openness of the waterfront space is larger, the smaller the comprehensive vitality intensity is, the higher the priority index is, the more imbalance there is between the vitality intensity and the degree of openness, and more priority needs to be given to planning interventions.

4. Results

4.1. Calculation of Waterfront Space Openness

4.1.1. Ecological Value Attribute Analysis

The ecological function attribute analysis (Figure 3) shows that the ecological function of Xiangjiang River waterfront space presents a distribution pattern with a high mean value but significant fluctuation on the west bank and a low mean value but relatively balanced distribution on the east bank. The areas with the highest ecological function are concentrated in 17 and 20 Zones; the corresponding areas include Yuelu Mountain Scenic Area, Nanjiao Park, etc. The distribution of parks and green spaces in the above areas is dense, and the land is mainly parks and green spaces and forests, with a low degree of landscape interference and low ecological risk; the ecological function attributes of 5, 8, 15, 19, 21, and 22 Zones are in the IV level, and the overall coverage level of urban green spaces is relatively good, with a good coverage uniformity. It is worth noting that under the influence of the functional layout of Changsha City's land use, Zones 9–13 and 23–25 have a more extensive landscape disturbance index. Their ecosystems are subject to a high degree of external interference, resulting in a sharp decrease in the strength of the ecological value attributes of the above zones.

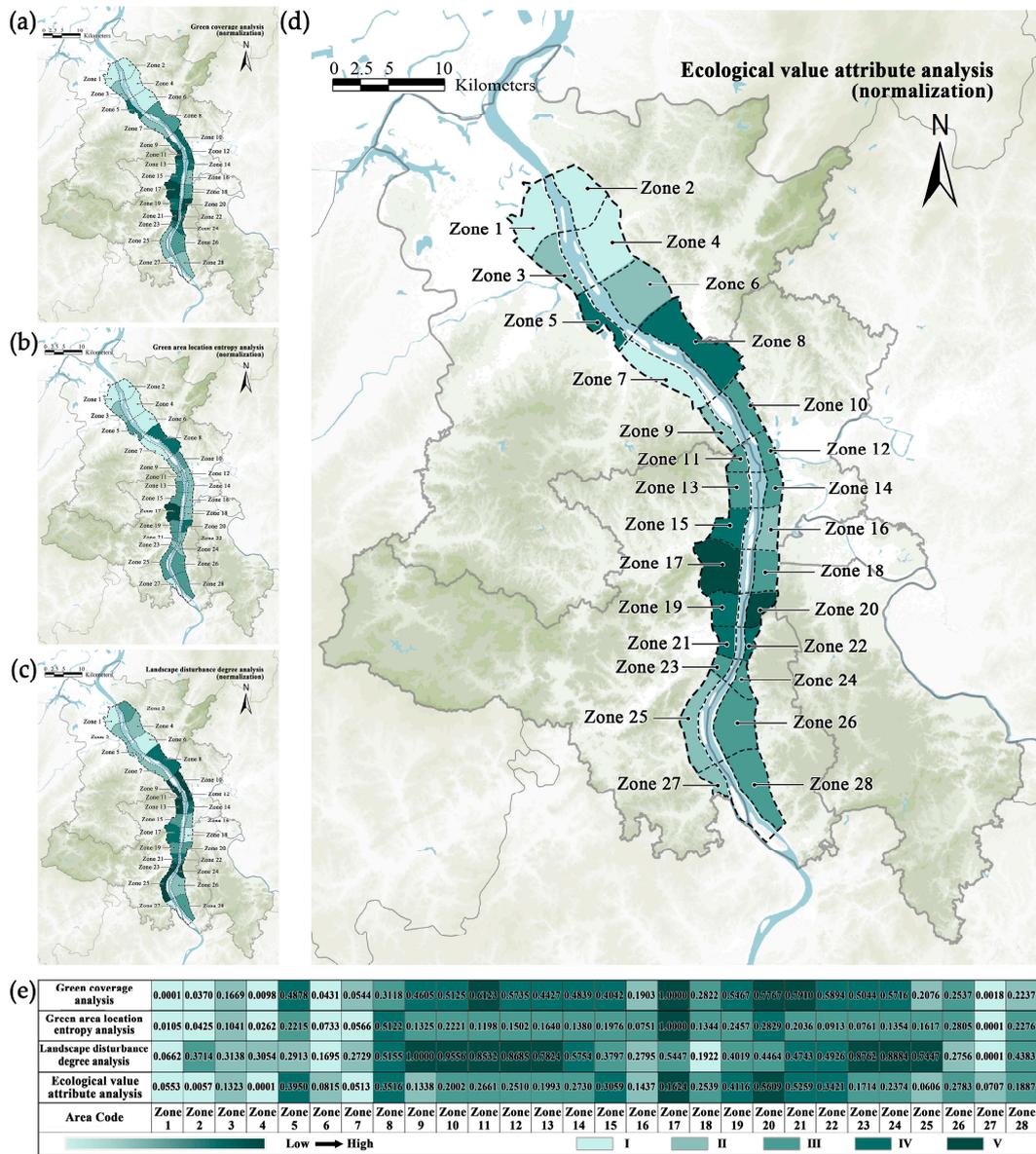


Figure 3. Ecological value attribute analysis: (a) green coverage analysis; (b) Green area location entropy analysis; (c) landscape disturbance degree analysis; (d) ecological value attribute analysis; and (e) grading of ecological value attributes.

4.1.2. Traffic Accessibility Analysis

The results of the comprehensive transportation accessibility analysis (Figure 4) show that the southern and northern Xiangjiang River areas are limited by the disadvantages of the location, low density of the road network, and lagging in the construction of public transportation facilities, resulting in a lower comprehensive transportation accessibility. The comprehensive accessibility of waterfront space in the middle of Xiangjiang River (Zone 11–Zone 20) is high. Among them, including Wuyi Square, Guansha Ling, Chazishan, and other 12, 13, 14, 16, and 18 Zones as the core of the city, the transportation infrastructure development is earlier, the transportation demand is strong, and the transportation comprehensive accessibility rating is the highest. It is worth noting that the Zone 17, including the Yuelu Mountain Scenic Area, has a lower level of comprehensive traffic accessibility, mainly because some of the sites in the area are in the scope of the scenic area restrictions and the closed nature of the region’s educational functions, such as Central South University and Hunan University, also hurt the comprehensive traffic accessibility.

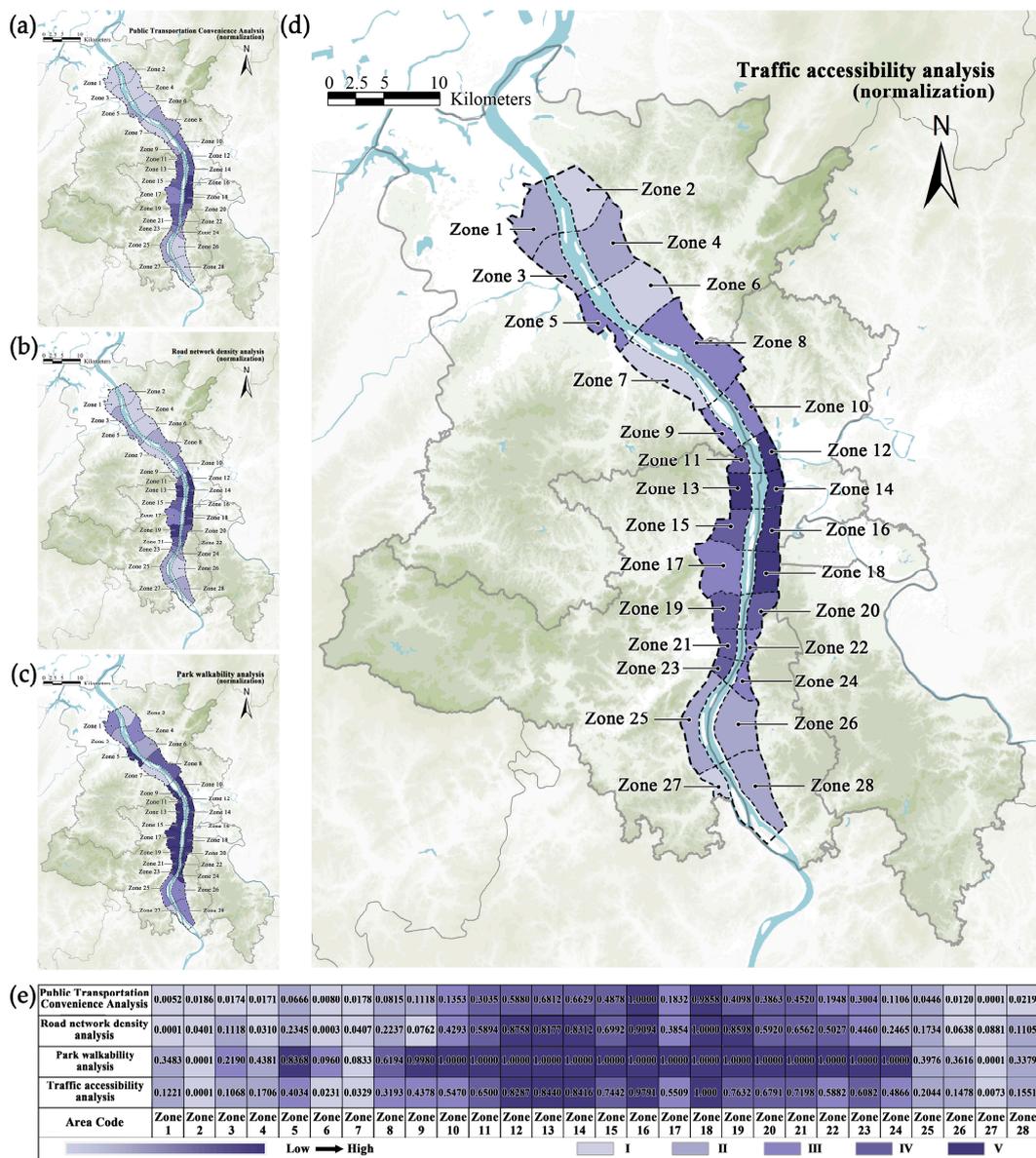


Figure 4. Traffic accessibility analysis: (a) public transportation convenience analysis; (b) road network density analysis; (c) park walkability analysis; (d) traffic accessibility analysis; and (e) grading of traffic accessibility.

4.1.3. Spatial Development Intensity Analysis

The results of the spatial development intensity analysis (Figure 5) show that the spatial zones with a high spatial development intensity in the study area are distributed in the form of multi-core clustering. Zone 2 has a relatively high development intensity in the northern part of the Xiangjiang River because Tongguan Town is located here, where buildings are dense and the population is concentrated. The central part of Xiangjiang River (Zones 11–20) has a high spatial development intensity. Zone 16 and Zone 18 have the highest levels: commercial and office areas with mature development and construction in the city. The areas with a low spatial development intensity are mainly located in the northern part of Xiangjiang River, including Zones 1–7 and 9. The land in the abovementioned areas is mainly farmland, cultivated land, and rural residential land, with a low development intensity. In addition, there are also relatively low values of spatial development intensity in the study area, such as Zone 11 and Zone 17. The primary reason for the low spatial development intensity in Zone 11 is its location in a semi-isolated urban island area

encircled by the North Second Ring elevated highway and major urban arterial roads. This setting has slowed the progress of urban development and construction, impacting spatial development's intensity. Zone 17 includes a significant amount of land for education. The plot ratio and building density in this area are significantly lower than those in other urban functional zones, which results in a relatively lower intensity of spatial development.

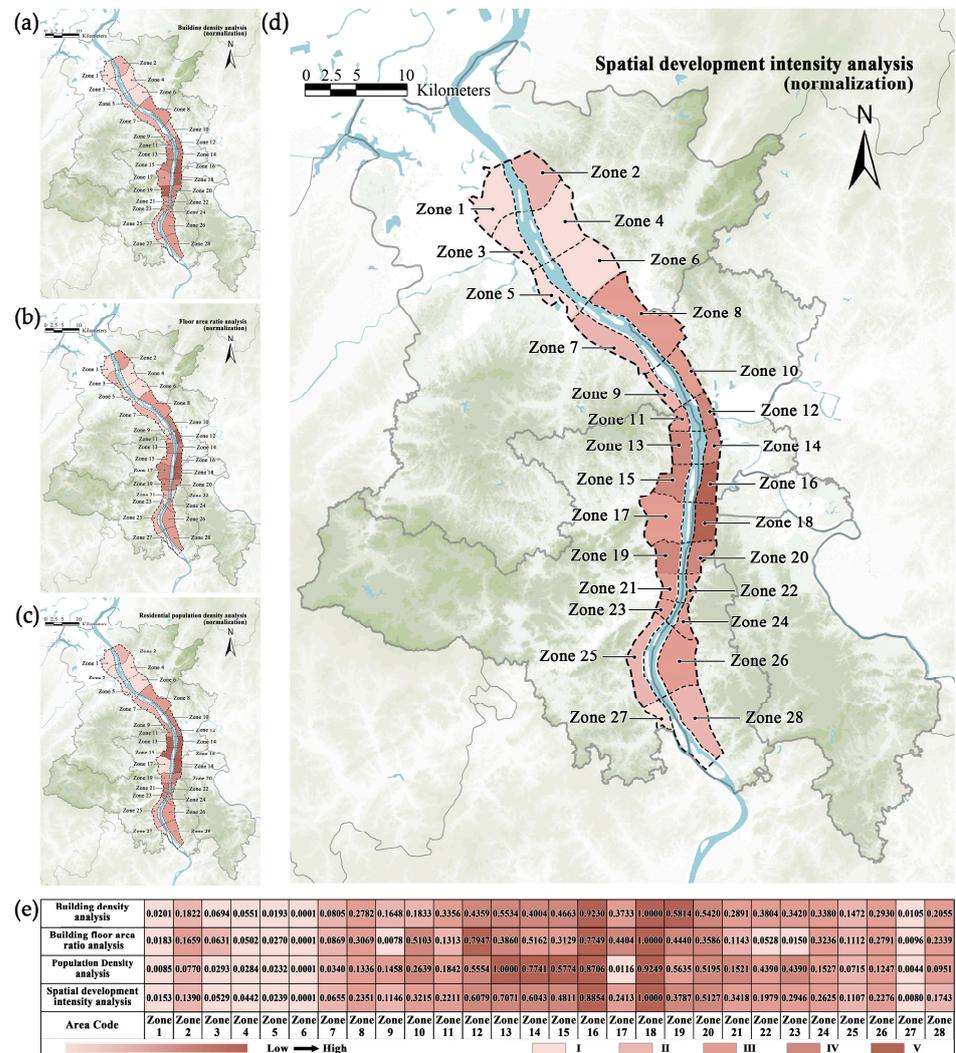


Figure 5. Spatial development intensity analysis: (a) building density convenience analysis; (b) floor area ratio analysis; (c) residential population density analysis; (d) spatial development intensity analysis; and (e) grading of spatial development intensity.

4.1.4. Functional Diversity Degree Analysis

The results of the functional diversity degree analysis (Figure 6) show that the overall level of functional diversity degree of Xiangjiang River waterfront space has a large gap, with obvious imbalance characteristics, showing a high distribution pattern in the middle of the area and a lower distribution pattern in the north and south ends of the area. Within the central part of Xiangjiang River (Zones 11–20), 16 and 18 Zones have the highest level of functional diversity, indicating that the distribution of service facilities in the above area is concentrated and all kinds of functional facilities are complete. The overall functional diversity degree of the northern part of the Xiangjiang River gradually decreases from south to north, but there is still a localized high value (Zone 2). Zone 2 was located in Tongguan Town, which has many external tourists and a dense concentration of internal native residents, which attracts all kinds of functional facilities to gather here and increases the degree of functional diversity in this area. Among the southern and northern Xiangjiang

rivers, Zones 1, 3–7, and 27–28 have the lowest functional diversity degree ratings, and the above zones are relatively scarce in terms of POI type and quantity.

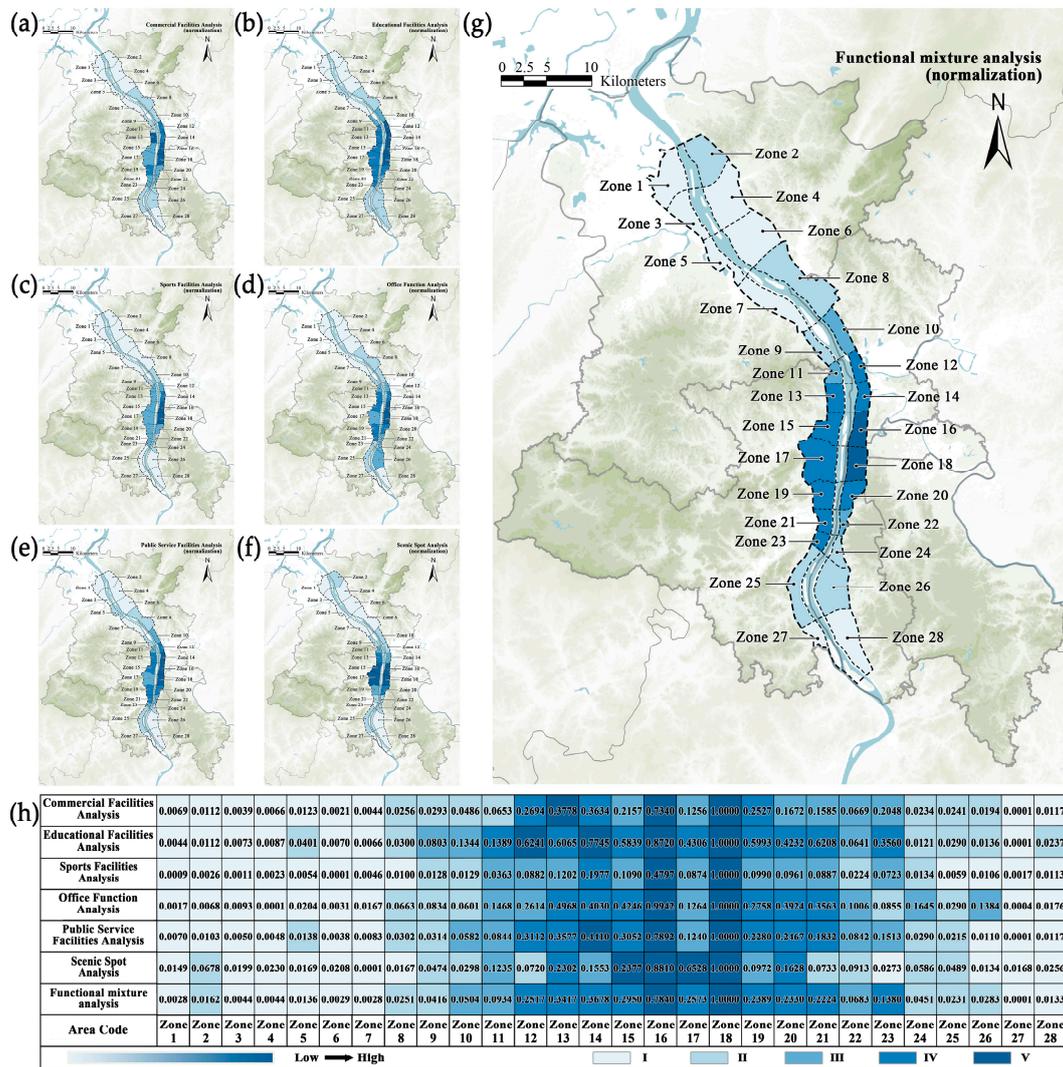


Figure 6. Functional diversity degree analysis: (a) commercial facilities analysis; (b) educational facilities analysis; (c) sports facilities analysis; (d) office facilities analysis; (e) public service facilities analysis; (f) scenic spot analysis; (g) functional diversity degree analysis and (h) grading of functional diversity.

4.2. Analysis of the Openness of Xiangjiang River Waterfront Space

Based on the results of the ecological value attribute analysis, traffic accessibility analysis, spatial development intensity analysis, and functional diversity degree analysis, the openness of Xiangjiang River waterfront space is calculated using Formula (1), and the results show the following (Figure 7): the high-level areas with a high degree of openness are concentrated in the middle of the Xiangjiang River, with overall spatial facilities being perfected and maturely constructed. Among them, Zones 11–12, 14–15, 17, and 19–20 are IV levels, while Zones 13, 16, and 18 are V levels. The openness of waterfront space zones in the northern part of the Xiangjiang River (Zones 1–10) and the southern part of the Xiangjiang River (Zones 21–28) lags behind the middle part of the Xiangjiang River in all aspects and is mainly of Grade I–III. This situation is because the spatial construction of the northern and southern Xiangjiang Rivers is affected by geographic deviation and the limitation of economic radiation diffusion. In addition, the west bank of the Xiang River

has been built for a shorter period. It has many mountains, resulting in a significantly lower degree of openness than the east bank of the Xiangjiang River.

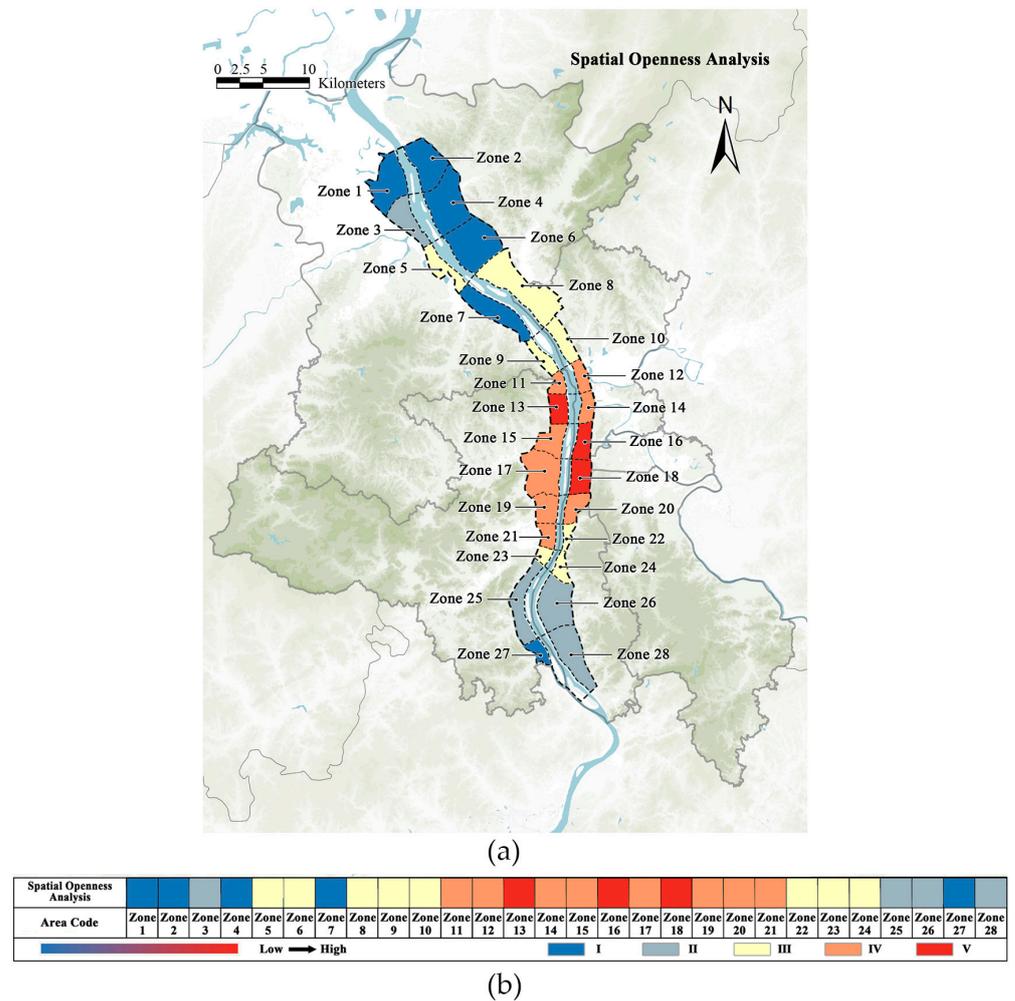


Figure 7. Analysis of the openness of Xiangjiang River waterfront space: (a) spatial openness analysis; and (b) grading of space openness.

4.3. Analysis of Average Crowd Vitality in Xiangjiang River Waterfront Space

The study describes the distribution of people in the Xiangjiang River waterfront space through the geographic location data of platform cell phone users in the Baidu heat map, and the calculation results are shown in Figure 8. The central part of Xiangjiang River (Zones 11–20) has rich functions and obvious location advantages, which can fully attract citizens and external tourists to carry out all kinds of activities in the area, and the overall thermal intensity is high. Among them, Zones 14, 16, and 18 have the highest grade of vitality intensity. It is worth noting that Zone 17 contains Yuelu Mountain and Hexi University Town, which are relatively well-constructed. However, some parts of the area are not open to the public, which lowers the overall vitality intensity. The overall thermal intensity in the northern part of the Xiangjiang River is lower, but there are still some sections in Grade II–IV, such as Zone 8–10 and Zone 21–25. Specifically, Zone 8 is an essential port in Changsha and relies on logistics and transportation to gather a certain number of people. Zones 23 and 25 are driven by large-scale public facilities such as the Yangshu Wetland Park, IKEA, and the Goddess of the Xiangjiang River Park, and have a higher vitality intensity. In addition, the overall vitality intensity on the east bank of the Xiangjiang River is significantly higher than that on the west bank of the Xiangjiang River.

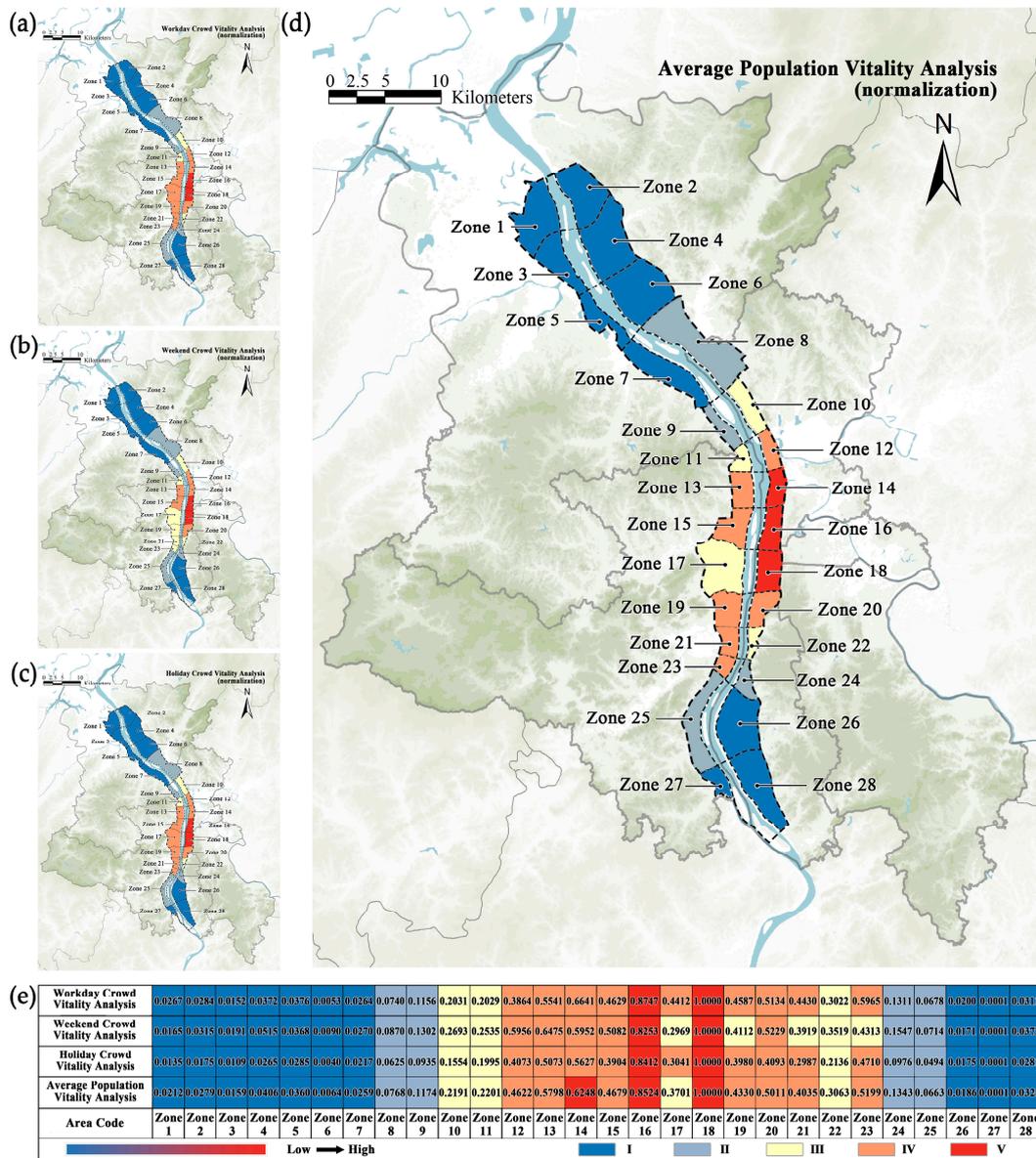


Figure 8. Analysis of average crowd vitality in Xiangjiang River waterfront space: (a) workday crowd vitality analysis; (b) weekend crowd vitality analysis; (c) holiday crowd vitality analysis; (d) analysis of average crowd vitality; and (e) grading of space vitality intensity.

4.4. Mismatch Critical Zone Identification

The openness index and vitality index of Xiangjiang River waterfront space were Z-score normalized, and the waterfront spatial zones were divided into quadrants according to the results of Z-score normalization. The quadrant distribution results (Figure 9a) show that 12 waterfront spatial zones are in the “high openness–high vitality intensity” (Quadrant I), 1 waterfront spatial zone is in the “low openness–high vitality intensity” (Quadrant II), 15 waterfront spatial zones are in the “low openness–low vitality intensity” (Quadrant III), and no waterfront spatial zone meets the characteristics of “high openness–low vitality intensity” (Quadrant IV).

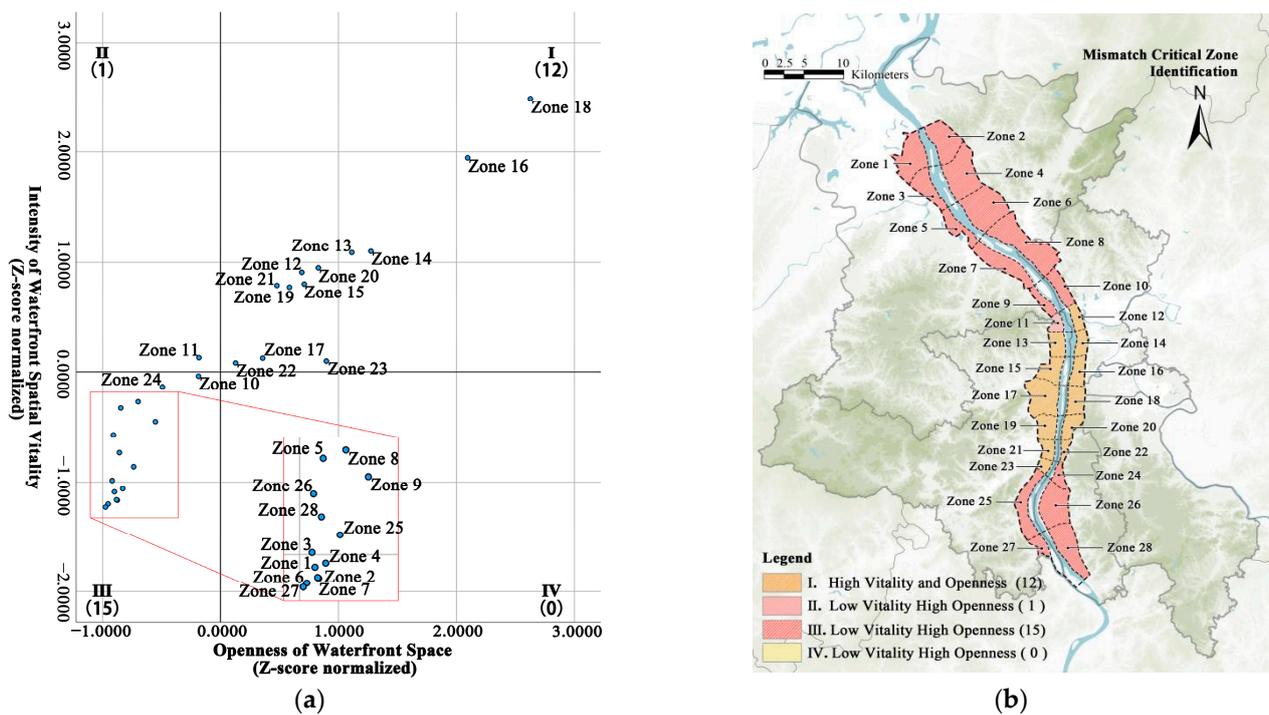


Figure 9. Mismatch critical zone identification: (a) quadrant distribution graph; and (b) mismatch critical zone identification.

To visualize the match between the openness and vitality intensity of each waterfront spatial zone, the results of the quadrant classification were visualized and analyzed (Figure 9b). The results show that the critical area of “low openness–high vitality intensity” imbalance is Zone 11, where the early land use was rural housing and unutilized mountains. Nowadays, a large number of new residential areas are being built by urban expansion, which brings a specific population. However, the supporting facilities in the area are aging and have not been adequately constructed, which will hurt the spatial use of citizens in the area. Such spaces are vital areas that need to be optimized.

4.5. Prioritization of Planning Interventions

Combining the values obtained after normalizing the degree of openness and vitality intensity of the waterfront space, Formula (17) was applied to calculate the priority index. Using the Natural Breaks method, the order of planning interventions for waterfront space zones was divided into five levels, and the higher the level, the higher the priority for planning interventions. The results show (Figure 10) that the priority of the waterfront spatial planning intervention in the middle of Xiangjiang River is high and less fluctuating, and the priority of the waterfront spatial planning intervention in the south of Xiangjiang River and the north of Xiangjiang River is low but more fluctuating. The areas with priority V are Zone 2, Zone 7, and Zone 23. The rapid development of these areas under the guidelines of “Xiangjiang New District Construction”, “Changsha Southward Expansion Strategy”, and “Changsha Great City North Strategy” and the influx of large numbers of people in recent years have led to the overloading of various facilities in the area. Therefore, areas with priority V need to be urgently prioritized for remediation and renewal to meet the needs of citizens’ activities. Priority IV areas include 13, 14, 16–18, and 27 Zones, mainly concentrated in the middle of the Xiangjiang River. This area has a high degree of spatial openness. However, the high volume of public activity exceeds the area’s capacity to accommodate spatial activities, resulting in a mildly unbalanced state. This area needs to be improved and optimized appropriately. The openness and vitality of the waterfront space zones of Grade I–Grade III are appropriate and can carry the activity demands of the citizens in the area.

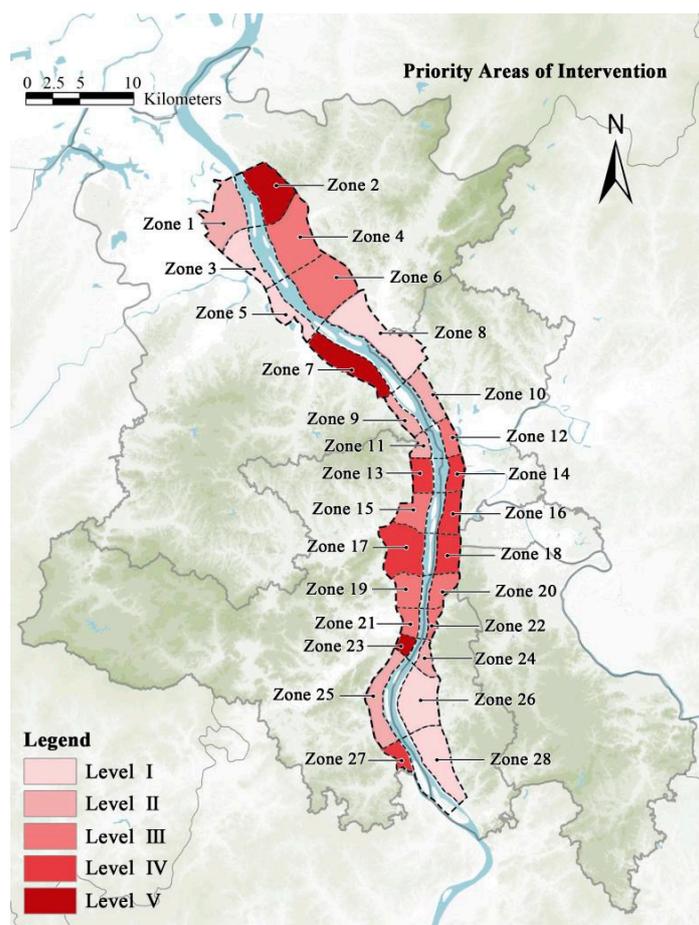


Figure 10. Prioritization of planning interventions.

5. Discussion

Existing research results on urban waterfront space mainly focus on analyzing the relationship between spatial components and spatial vitality, determining the factors hindering waterfront space vitality enhancement, and proposing targeted optimization measures [10,23,33]. From the perspective of the public's use of waterfront space, this study complements the spatial components affecting the public's use of waterfront space concerning the relevant index system, forming a system of evaluation indices of the openness of waterfront space, which can scientifically quantify the degree of openness of waterfront space. At the same time, by comparing the analysis results of waterfront space openness and vitality intensity, the planning intervention sequence of each waterfront space zone can be clarified to form a systematic and orderly waterfront space optimization strategy, not only for the improvement of a particular spatial component. In addition, this paper overcomes the disadvantage whereby the grid analysis method [2,24] cannot reflect the overall construction level of the zone and takes the urban arterial road as the dividing line, divides the study area into several study zones, and unifies the waterfront spatial components in the zone as a whole for quantitative analysis. The research results show the following:

(1) The overall openness of the Xiangjiang River waterfront space shows the structure of the "core-edge". The overall openness of the central part of the Xiang River is high and fluctuates less. The openness of the northern and southern parts of the Xiang River is low and fluctuates wildly. The construction of waterfront space in the middle part of Xiangjiang River has a long history and significant capital investment, so the overall degree of openness is high. The southern and northern Xiangjiang Rivers are limited by the disadvantages of the location and short development time, so the overall degree of openness is low.

In the subsequent construction of the low openness area, according to the analysis of the indicators, the spatial components that need to be optimized can be identified. For example, Zone 2 has better spatial construction and functional facilities, but, due to the poor quality of the transportation system and ecological quality, it results in the openness of the region for the I level. Therefore, Zone 2 needs to focus on improving the quality of transportation facilities and ecological quality in the subsequent construction process.

(2) The vitality intensity of the Xiangjiang River waterfront space shows a prominent spatial distribution characteristic of “high in the middle and low at the north and south”, and the openness of the east bank of Xiangjiang River is better than that of the west bank of Xiangjiang River as a whole. Furthermore, the overall vitality intensity of the Xiangjiang River waterfront space is high, and there are 14 waterfront space zones with openness at the III–V level. In addition, the central part of the Xiangjiang River has obvious location advantages and abundant resources, which can attract and accommodate many citizens for various activities, and the overall vitality intensity is very high.

(3) It was found that, although 16 waterfront spatial zones had a “low openness”, 15 of them also had a low vitality intensity. In addition, all the waterfront zones with the “high vitality intensity” attribute also have a high openness. The openness of most of the waterfront spatial zones is relatively harmonized with the intensity of vitality. Only Zone 11, which has a severe imbalance of “low openness–high vitality intensity”, is a crucial waterfront spatial zone that needs to be optimized.

(4) The study delineates five priority levels for planning interventions. Priority V includes Zones 2, 7, and 23, which are located in the southern and northern parts of the Xiangjiang River; these zones attract a large number of citizens, but the overall spatial quality of the construction does not meet the needs of the citizens, so they need to be prioritized for comprehensive planning interventions. Priority IV includes Zones 13, 14, 16–18, and 27, mainly concentrated in the middle of Xiangjiang River. Priority IV zones have a higher overall spatial quality but also have many citizens’ activities and need to focus on optimizing the weak spatial elements. Priority III zones include Zones 4, 6, 12, 15, and 19–22, which are mainly located in the northern and central parts of the Xiangjiang River; the degree of openness and the intensity of vitality of Priority III zones differ somewhat; and Priority III zones have a high potential for development and need to take appropriate improvement measures. Priority I and II zones are mainly located in the south and north of Xiangjiang River, and the degree of openness and vitality intensity of these zones are in a balanced state, which can be considered for planning improvement in the long term.

This paper also has limitations that deserve further research. First, a certain percentage of users, such as some older people, children, and people who do not use apps, are not included in the crowd vitality data obtained in this paper using the Baidu WiseEye data platform. Second, the diversity of vitality can be analyzed more deeply, such as the composition of activity subjects (different types of people, e.g., tourists, residents, etc.) versus the different types of activities. In addition, the attractiveness of water bodies for citizen activities in land space should be the focus of subsequent research.

6. Conclusions

In this paper, we use multi-source information data to quantitatively analyze the matching relationship between the degree of openness and the intensity of vitality of waterfront spaces in Changsha City’s Xiangjiang River waterfront space as an example. Given the availability of Baidu data, the method can also be used to assess waterfront spaces in other Chinese cities. In addition, this study proposes and validates the feasibility of waterfront space intervention prioritization based on the prioritization index method. The results show the following: (1) The simulation results of the openness and vitality of the Xiangjiang River waterfront space have a high similarity in spatial distribution, showing the spatial distribution characteristics of “high in the middle and low at the north and south” and the east bank of the Xiangjiang River is better than the west bank of the Xiangjiang River as a whole, and there are only a few mismatches. (2) The openness and vitality intensity of the

Xiangjiang River waterfront space has three states: “high openness–high vitality intensity”, “low openness–high vitality intensity”, and “low openness–low vitality intensity”. One waterfront space zone is in a severe imbalance of “low openness–high vitality intensity”. (3) The 28 waterfront spatial zones in the study area were categorized into five planning intervention priority levels. Among them, three waterfront space zones belong to priority V, which need to be prioritized for improvement and updating. Five waterfront space zones belong to the IV priority area, mainly concentrated in the middle of Xiangjiang River, which needs to be improved and optimized appropriately. The findings are significant and can provide policymakers and managers with comprehensive information on waterfront space construction to accurately identify and prioritize areas for improvement. The findings can provide urban planners with direct reference examples of waterfront space optimization for sustainable waterfront space development.

Under the new trend of open-source data, there will be more access to open data, and the quantification methods of indicators for social attributes, emotional dimensions, and other human-oriented attributes will become more and more perfect, which is a potential direction for future research on the analysis of urban public space. The subsequent research can explore more multi-dimensional waterfront space evaluation indices and construct more accurate and applicable spatial quantification methods using information technology such as “Internet+” and big data to guide the sustainable development of waterfront space further.

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