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Research Article

Identification of Urban Functional Area by Using Multisource Geographic Data: A Case Study of Zhengzhou, China

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The rational allocation of functional areas is the foundation for addressing the sustainable development of cities. Efficient and accurate identification methods of urban functional areas are of great significance to the adjustment and testing of urban planning and industrial layout optimization. Firstly, by employing multisource geographic data, an identification method of urban functional areas was developed. A quantitative measurement approach of the urban functional area was then established considering the comprehensive effects of human-land, space-time, and thematic information to present the covering area of ground objects, public awareness, and empirical research. Finally, the Zhengzhou city, which locates in Henan province of central China, was used to test the method. The results show that the developed method is efficient, accurate, and universal and can identify urban functional areas quickly and accurately. We found that the overall distribution of Zhengzhou's functional areas presents a spatial pattern of single and multimixed coordinated development. The city's commercial functional areas and commercial-based mixed functional areas are located in the city's central area. The green square's function area occupies relatively low and is mainly distributed in the city's fringe.

1. Introduction

The urban functional area is a foundation unit in regional planning and developmental policy making, usually indicated by land use and used to reflect social and economic activities [1, 2]. Urban functional areas are independent yet connected, thus combining to form the city as a whole [3, 4]. A reasonable urban spatial structure is the essential condition for high-quality urban development. Accurate identification of urban functional areas and a clear urban spatial structure are of great significance to the proper planning of urban spatial layout and sustainable urban development [5–7]. The identification of urban functional areas is a vital prerequisite for clarifying the spatial arrangement of industries [8, 9], accurately grasping the urban spatial pattern [5, 10], and effectively assessing the status of urban development [10–12]. It can analyze the disadvantages of urban development [13] and provide accurate decision support on issues such as the redistribution of urban public resources [14]. It also provides a crucial supporting role in adjusting the urban functional structure and the rational optimization of industrial layout [8, 15, 16].

Urban functional areas' identification approach is a research hotspot of new urban science [17] and an essential theme in urban complexity research [18, 19]. Previous studies have formed multidimensional classification standards and rules by applying the differences in data sources, research methods, and purposes [20, 21]. Traditional urban functional area identification is mainly based on statistical investigation techniques [22, 23], expert inspection and evaluation, and remote sensing land use extraction [21–24]. These methods have played a significant role in early urban planning and industrial layout [5, 8, 10, 22, 23]. With the advent of the informatization big data era, multisource emerging data such as mobile phone signaling, taxi trajectory, check-in data, and POI (points of interests) have promoted quantitative research urban functional area identification further [25–29].

Generally, the mobile phone signaling data could be used to identify the urban space such as working areas, leisure areas, and residential areas [29, 30]; taxi trajectory data could be applied to divide urban space into daily residential areas, working areas, and other areas [5, 31–33], and the check-in data, including the coordinates of personal activity locations and personal cognition and comments, could be applied to analyze the dynamic characteristics of urban space from a multidimensional perspective [34–39]. Generally, POI data contain precise coordinates and attribute information of geographic entities, which can finely portray urban details and describe urban spatial forms [40–42]. With the increased demand for urban connotation construction and quality improvement, identifying urban functional areas with a single data source can no longer meet the needs of refined urban control and planning. Therefore, there is an urgent need to employ multisource data to push the collaborative research on urban functional area identification. The road network data could be used as a geographic boundary to generate the smallest research unit and establish a comprehensive density index that integrates two weighting factors, general surface area and public awareness. Spatial analysis tools could also be used to construct a quantitative identification method of urban functional areas. Finally, by taking Zhengzhou's core urban area as the tested case, the method is used to reference urban function adjustment and industrial planning.

2. Data Source

2.1. The POI Data. A total of 231,272 POI data in Zhengzhou's urban area were obtained from the Baidu network map (map.baidu.com). A single POI data unit contains name, type, latitude, and longitude [42–44]. According to previous research [44, 45] and also the matching principle of POI and urban industry, referring to the "Urban Land Classification and Planning and Construction Land Standards," the POI data is divided into six major categories and 19 subcategories based on attribute information [46]. Among them, the six major categories include green space and square land (G), administration and public services land (A), residential land (R), street and transportation land (S), commercial and business facilities land (B), and logistics warehouse land (W). Then they are further divided into the following subcategories: commercial facility land (B1), business facilities land (B2), recreation, and sports facilities land (B3), public facilities business outlets land (B4), other commercial service facilities land (B9), second-class residential land (R2), park green land (C1), square green land (C3), urban road land (S1), transportation hub land (S3), traffic station land (S4), other transportation facilities land (S9), administrative office land (A1), cultural transportation land (A2), education and research land (A3), sports land (A4), medical and health land (A5), religious facilities land (A9), and first-class logistics warehousing land (W1).

2.2. The Road Network Data. The road network data of streets, county roads, provincial roads, national roads, high-speed road networks, and railways in the core urban area of Zhengzhou City was also obtained from the Baidu network map [47]. Based on the principle of topology analysis, the redundant roads and small roads in the road network data are first eliminated. Then, the road network data are topologically edited. Finally, the road network map of Zhengzhou core urban area is obtained [47, 48]. According to the national four-level highway width standards and the road width data of Zhengzhou City, the highways, provincial highways, national highways, railways, county highways, and streets in the road network were widened by 55 m, 45 m, 45 m, 40 m, 35 m, and 25 m, respectively. The block bounded by road is generated as the smallest unit for functional area identification.

2.3. The Socio-Economic and Field Survey Data. According to research needs, we collected Zhengzhou City's 2018 Statistical Yearbook and Zhengzhou City's Master Plan (2010–2020). We then conducted field investigations on specific urban areas, with distinct areas shown in Table 1. It is expected to be used as auxiliary data for data correction and local inspection in urban functional area identification.

3. Methods

The research methods mainly include three core steps, which are separately named, the calculation of the kernel density index, the calculation of the two-factor weighted kernel density, and the judgment of the functional area type.

3.1. The Calculation of the Kernel Density Index. The kernel density index is mainly proposed based on kernel density estimation [49–53]. By taking each sample point i (x, y) as the center, the kernel function is used to calculate each sample's density contribution to each grid unit's center point within a specified radius (a circle with the bandwidth h as the radius) value. The closer the center point of the grid unit to the sample point, the greater the sample point's density contribution value. The center points of each grid unit's density values are spatially superposed to generate a density map. The kernel density index is calculated as the following formula:

$$f(x, y) = \frac{3}{nh^2\pi} \sum_{i=1}^{n} \left[1 - \frac{(x - x_i)^2 + (y - y_i)^2}{h^2} \right]^2, \qquad (1)$$

where $f(x, y)$ denotes the kernel density index at the spatial location (x, y) and h denotes the search radius (i.e., the bandwidth). Based on the previous work [44, 45], the bandwidth is 700 m; x_i and y_i are the coordinates of the sample point i; n is the number of sample points that are less than or equal to h from location (x, y); x and y are the

Table 1: Table of typical field survey areas.

Functional area	Field investigations
Transportation	Railway station; Zhengzhou West Railway Station
Commercial land	Erqi Square; New Century Farmers Market
Residence	Qingshuiyuan community; Hanfei Jinsha community
Green space	People's Park; Yellow River National Wetland Park
Warehouse	Bonded area logistics center

coordinates of the center point of the grid; $(x - x_i)^2 + (y - y_i)^2$represents the square of the Euclidean distance between the center point of the grid and the sample point i.

3.2. The Calculation of the Two-Factor Weighted Kernel Density. POI data are indicative point data, which have different landmarks in reflecting public awareness, for example, lacking area and volume representation. Therefore, it is necessary to double-check the weight of different POI information types to improve functional partition carriers' accuracy [45, 54]. For example, within a bus station POI point within the spatial scope, there is also shop POI information. However, in the real world, the transportation function information represented by the bus station POI plays a leading role, surpassing the "commercial function" represented by the shop POI. Therefore, the functional positioning of this area should be "transportation function." In this study, the ground feature's general area is used as the first influencing factor that affects the weight of kernel density, and the weight value is differentiated by scoring. Public awareness is used as the second influencing factor. The general area scores of POI subcategories are shown in Table 2, and the public awareness scores of POI subcategories are shown in Table 3. Based on the previous work [44, 45, 50, 51], the general area's weight contribution ratio and public awareness are determined as 50%: 50% [54, 55].

Therefore, the weighted kernel density index value is calculated as follows:

$$\widehat{f}_k(x, y) = a_k f_k(x, y) + b_k f_k(x, y), \tag{2}$$

where $\widehat{f}_k(x, y)$ denotes the weighted kernel density index value of type k POI subcategory at the location (x, y), $f_k(x, y)$ is the kernel density index of type k POI subcategory at the location (x, y), a_k is the general area score of type k POI subcategory, and b_k denotes the public awareness score of type k POI subcategory, $k = 1, 2, \ldots, 19$.

3.3. The Judgment of the Functional Area Type. For the urban functional area units divided by irregular grids, the category ratio formulas (3)–(5) were constructed to determine the functional area's nature according to the kernel density index value:

$$D_k = \frac{d_k}{S} \times 100\%, \tag{3}$$

$$d_k = \widehat{f}_k(x, y), \tag{4}$$

$$S = \sum_{k=1}^{19} \widehat{f}_k(x, y), \tag{5}$$

where D_k represents the percentage of the kernel density index value of the k type of POI subcategories, $k = 1, 2, \ldots, 19$; d_k represents the kernel density index value of the k POI subcategories; S represents the sum of the kernel density of all POI subcategories in the study area. According to the formula, if $D_k \geq 50\%$ in a unit, this unit is a single functional area. If $D_k < 50\%$ $(k = 1, 2, \ldots, 19)$ in a unit, this unit is a diverse functional area, which depends on the first two determined land types; if there is no kernel density value, the area is no data area.

4. Case Study

4.1. Brief Introduction of Zhengzhou. Zhengzhou is the capital city of Henan Province, which is located in north-central China (112°42′E-114°14′E, 34°16′N-34°58′N), and plays an essential role in economic development. Located in central China, the regional transportation hub location, Zhengzhou is also the political, economic, and cultural center of Henan Province [56]. It is also a "double-cross" center in China's ordinary railway and high-speed road network [57]. Moreover, Zhengzhou is one of the critical cities under the Belt and Road Initiative; for example, Zhengzhou Airport is known as the Air Silk Road center. It is also an international comprehensive transportation hub [58, 59]. Zhengzhou's core urban area covers an area of 1100 km^2. As of the end of 2018, Zhengzhou's population has reached 10 million, and its GDP has exceeded 1 trillion yuan. There are 8 districts and zones in Zhengzhou consisting of Zhongyuan District, Erqi District, Guancheng Hui District, Jinshui District, Huiji District, Zhengdong New District, Economic Development Zone, and High-tech Zone (Figure 1).

4.2. Results. There are 18 types of functional districts identified in Zhengzhou, consisting of 1,745 plots (Figure 2). The functional district plots have a relatively uniform area in the center of the city. As the functional plots move away from the center of the city, their area gradually increases with distance. There are six types of single functional areas: transportation land, utilities land, commercial land, residence land, warehouse land, and green space, with 597 blocks and a total area of 396.15 km^2, accounting for 39.06%. There are 12 types of mixed functional areas, named as follows: transportation-utilities land, transportation-commercial land, transportation-residence land, transportation-warehouse land, transportation-green space land, utilities-commercial land, utilities-residence land, utilities-green space land, residence-commercial land, residence-warehouse land, commercial-warehouse land, and green space-warehouse land, which consist a total of 1148

Table 2: General area score of POI subcategories.

Area (m^2)	1–500	500–1000	1000–3000	3000–5000
Subcategories	B1, B2, B3, B4, B9, A1	S1, R2, S3, S4, S9, A2, A4	A3, A5, A9,	W1, C1, C3
Score	0.1	0.2	0.6	1

Table 3: Public awareness scores of POI subcategories.

Subcategory	Score	Subcategory	Score	Subcategory	Score	Subcategory	Score
A1	0.3550	A2, A3	0.6706	A4	0.5010	A5	0.5069
A9	0.8245	B1	0.5562	B2	0.3057	B3	0.5562
B4, B9	0.0100	C1, C3	0.6548	R2	0.0100	W1	0.3057
S1	0.0100	S3, S4, S9	1.0000	—	—	—	—

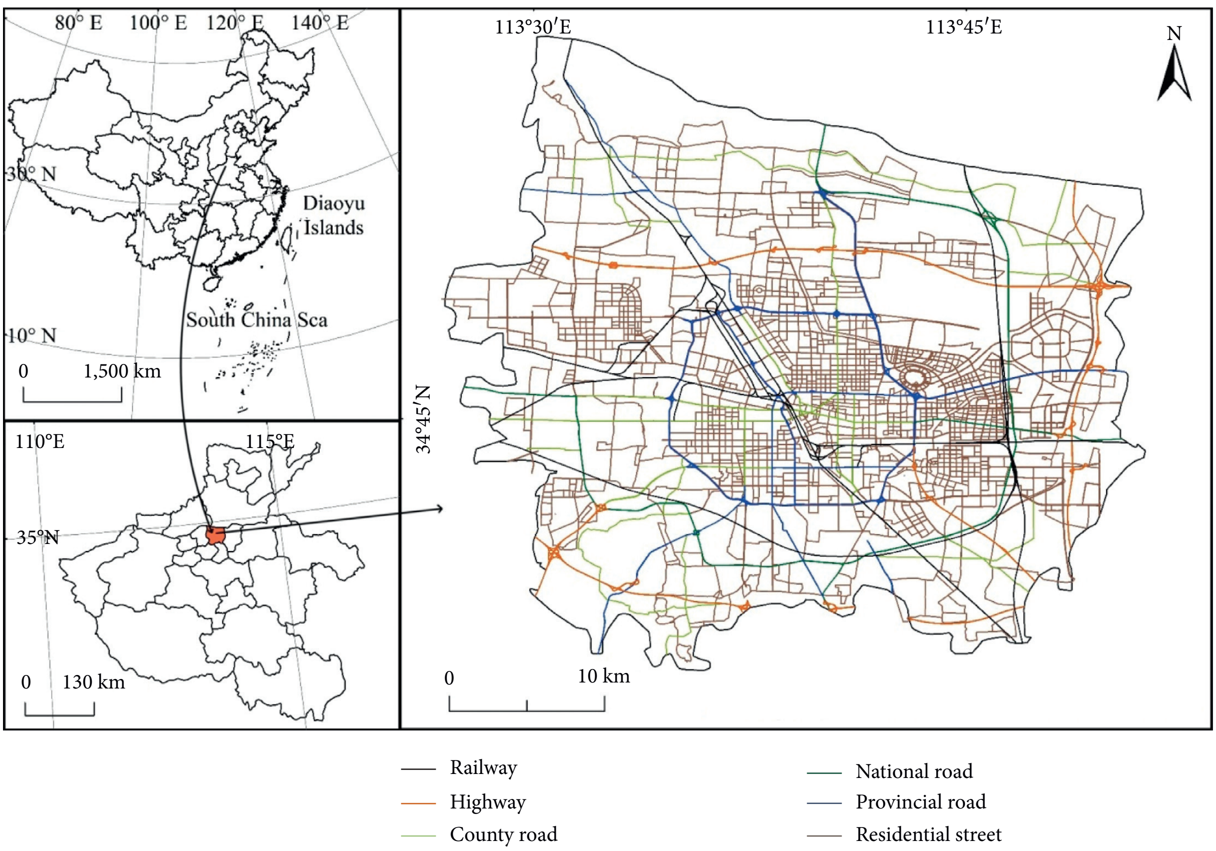

Figure 1: Location of the study area.

blocks and with a total area of 618.03 km^2, accounting for 60.94%. Detailed statistics are shown in Table 4.

The types of land used as a single functional area are mainly transportation land and commercial land (Figure 3). Transportation land mainly consists of roads, bus stops, high-speed railway stations, and other traffic stations. Its distribution characteristics are related to the urban road network, mainly the suburbs and highways. The results show that the number of traffic land is 330, with an area of 260.19 km^2, accounting for 25.66% of the city's total functional area, consistent with Zhengzhou's location in the central and western nodes and the advantages of a comprehensive transportation hub. Commercial land presents the characteristics of "central concentration," with the integrated square (Erqi Square) and the railway station as the core. The characteristics of commercial space radiate layer by layer outwards. Residence land, green space, square land, utility land, and warehouse land are generally distributed in blocks along the traffic line, mostly distributed in mixed functional areas and few single functional areas. Because of the small area occupied by green land, square land, and utility land, they are generally classified as other land or mixed land.

The mixed functional area is a crucial context of urban complexity and is a concrete manifestation of the social-economic-environmental interaction (Figure 4) [60, 61]. As the city's scale becomes more extensive, the mixed complexity becomes more prominent [62]. Zhengzhou has a wealth of

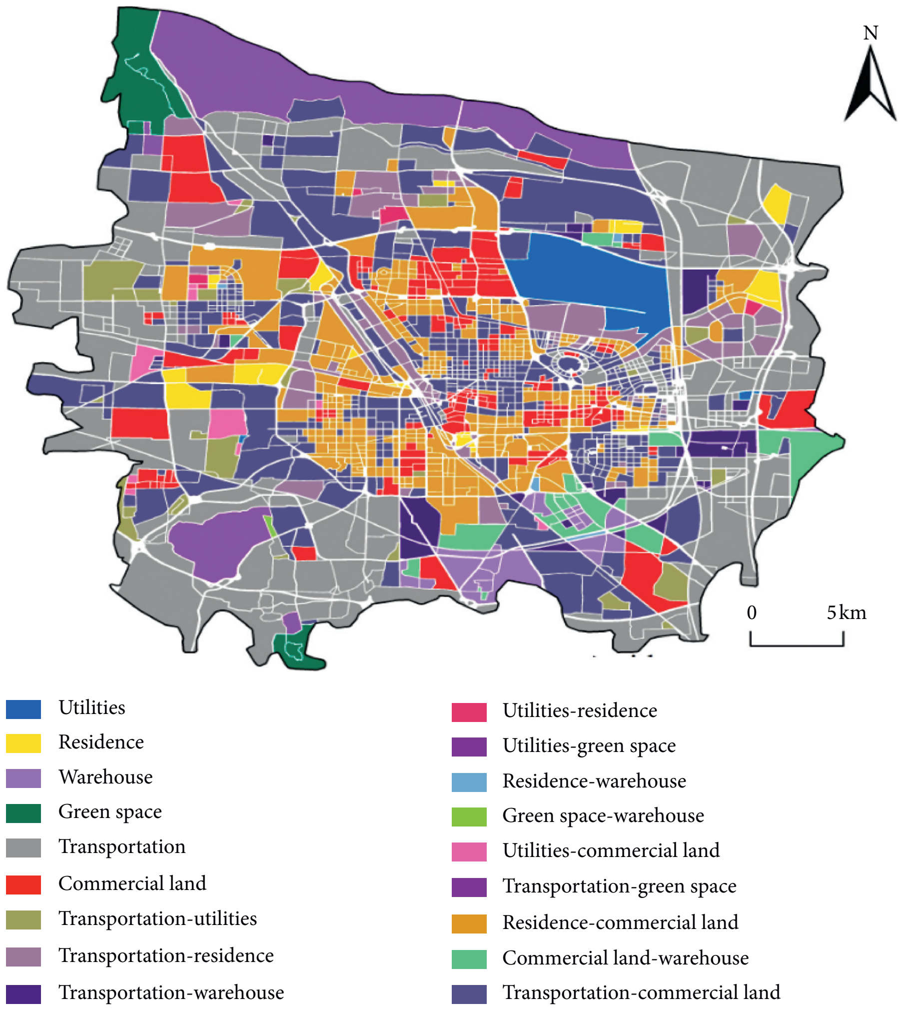

Figure 2: Functional area map of Zhengzhou.

Table 4: Statistical table of functional area.

Functional area	Plots	Area (km^2)
Transportation	330	260.19
Utilities	4	26.61
Commercial land	204	61.36
Residence	24	13.41
Warehouse	30	15.15
Green space	5	19.43
Transportation-utilities	31	21.1
Transportation-commercial	532	345.23
Transportation-residence	103	46.39
Transportation-warehouse	27	17.68
Transportation-green space	7	67.86
Utilities-commercial land	10	5.56
Utilities-residence	5	2.2
Utilities-green space	1	0.17
Residence-commercial land	401	90.61
Residence-warehouse	4	0.76
Commercial-warehouse	26	20.17
Green space-warehouse	1	0.3

mixed-function zones, of which the transportation-commercial and residential-commercial mixed-function zones occupy immense proportions, accounting for 34.04% and 8.93% of the area. Transportation-commercial land is mainly reflected in the distribution of commerce and the road network, forming a typical area of transportation-commercial land, among which the core commercial gathering area is represented by the railway station-large square (Erqi Square) axis. Residential-commercial land is mainly concentrated in the central area of the city. Residential and commercial are inseparable, forming the characteristics of an urban residential and commercial complex. Other transportation-warehouse lands, residential-warehouse land, green-warehouse land, and utilities-green land are relatively few, and they are mainly distributed in the edge of the city. From the perspective of the urban spatial pattern, the urban functional area presents a “multicenter” coordinated spatial pattern, indicating that basic functions such as commerce and residence have made necessary divisions on the city’s overall level and made appropriate measures on the local

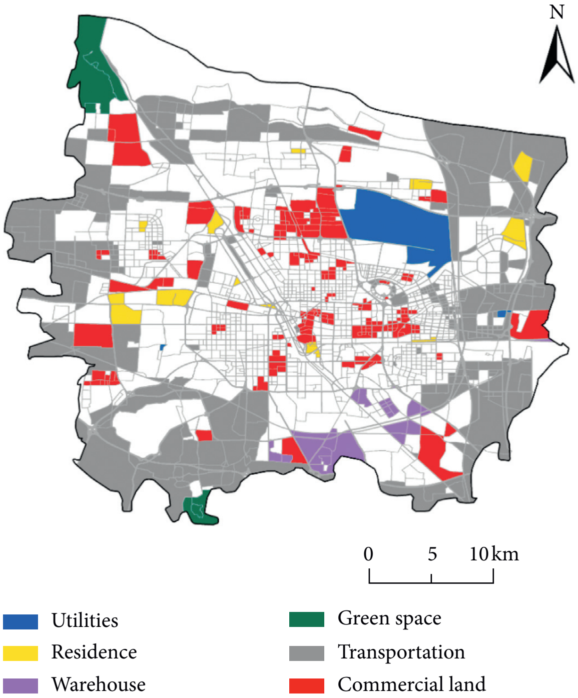

Figure 3: The single functional area map of Zhengzhou.

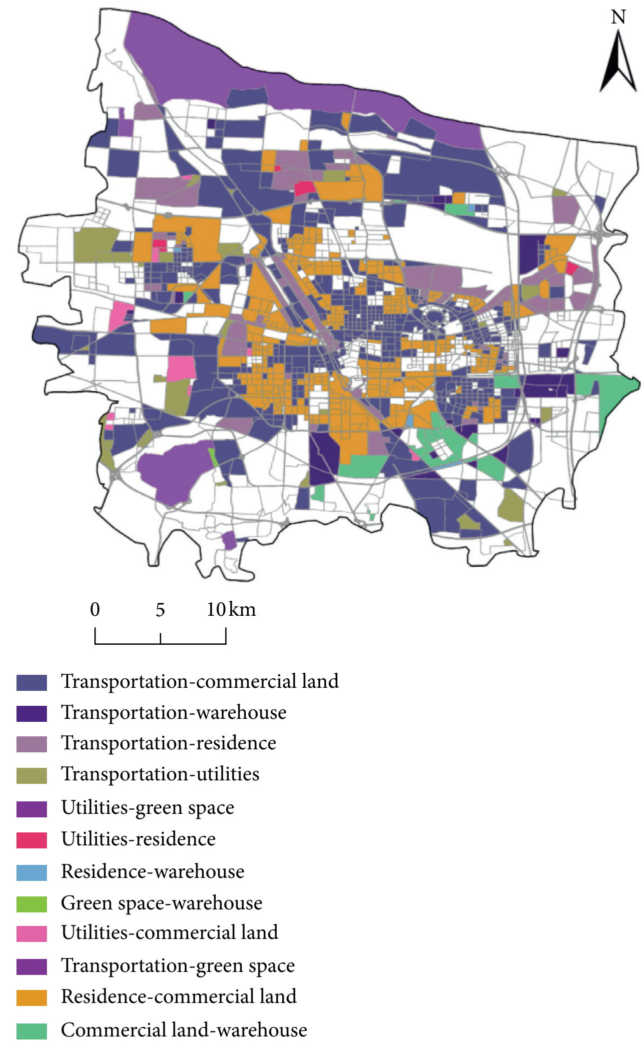

Figure 4: The mixed functional area map of Zhengzhou.

scale. Integration can give full play to the maximum benefits of mixed functional areas and is conducive to optimizing and regulating urban space [63]. Rational allocation of urban functional areas is the requirement of current efficient urban operation. With the intensive development of land use, the mixing degree of urban functional areas is becoming more complicated. The city embodies higher social and economic benefits, presents more vigorous urban vitality, and further promotes the city's highly intensive and sustainable development.

4.3. Results' Verification. The survey area and Baidu network map were then applied to verify the results. Through the city's actual investigation and comparing some urban functional area identification results with the Baidu network map, the accuracy of the identification results can be verified. (1) Inspection result of the Qingshuiyuan community (Figure 5(a)): the recognition result shows that area *a* is residential land. By comparing with the Baidu map, we can conclude that Hongyuan, Renzhuang community, Qingshuiyuan, and Xiushuiyuan villas in the area *a* are residential areas. Therefore, this area is residential land, and the functional area's recognition result is more accurate. (2) Inspection results of Hanfei Jinsha Community (residential-commercial mixed functional area) (Figure 5(b)): from the recognition result map, it can be concluded that area *b* is residential-commercial land. By comparing with the Baidu map, it can be concluded that Hanfei Jinsha Community in area *b* is a residential area, and there are Century Hualian, Lixin Moxibustion Living Museum, and other Commercial facilities surrounding areas. Therefore, this area belongs to residential-commercial land, and the recognition result of the functional area is more accurate. (3) Inspection results of AntaiJiayuan and Hengsheng Mansion (residential-commercial land) (Figure 5(c)): from the recognition results, it can be found that area ***c*** is residential-commercial land. Comparing with the Baidu map, we concluded that the residential land in area *c* is AntaiJiayuan and Hengshengfudi, and Chenghui Fresh Bai Orchard and New Century Farmers Market in the surrounding area; Antai Community Supermarket and Old Sichuan Restaurant, and another commercial land. Therefore, this area is residential-commercial land, and the identification result of the functional area is more accurate. (4) Zhengzhou West Railway Station (traffic-commercial land) inspection results (Figure 5(d)): from the recognition results, it can be concluded that area *d* is for transportation-commercial land. According to the Baidu map and actual survey, it can be known that Zhengzhou Railway Station West Square in area *d* is used for transportation, while China Construction Bank and Zhengzhou Central Business District are commercial lands. Therefore, this area is a transportation-commercial land, and the identification result of the inspection function area is more accurate.

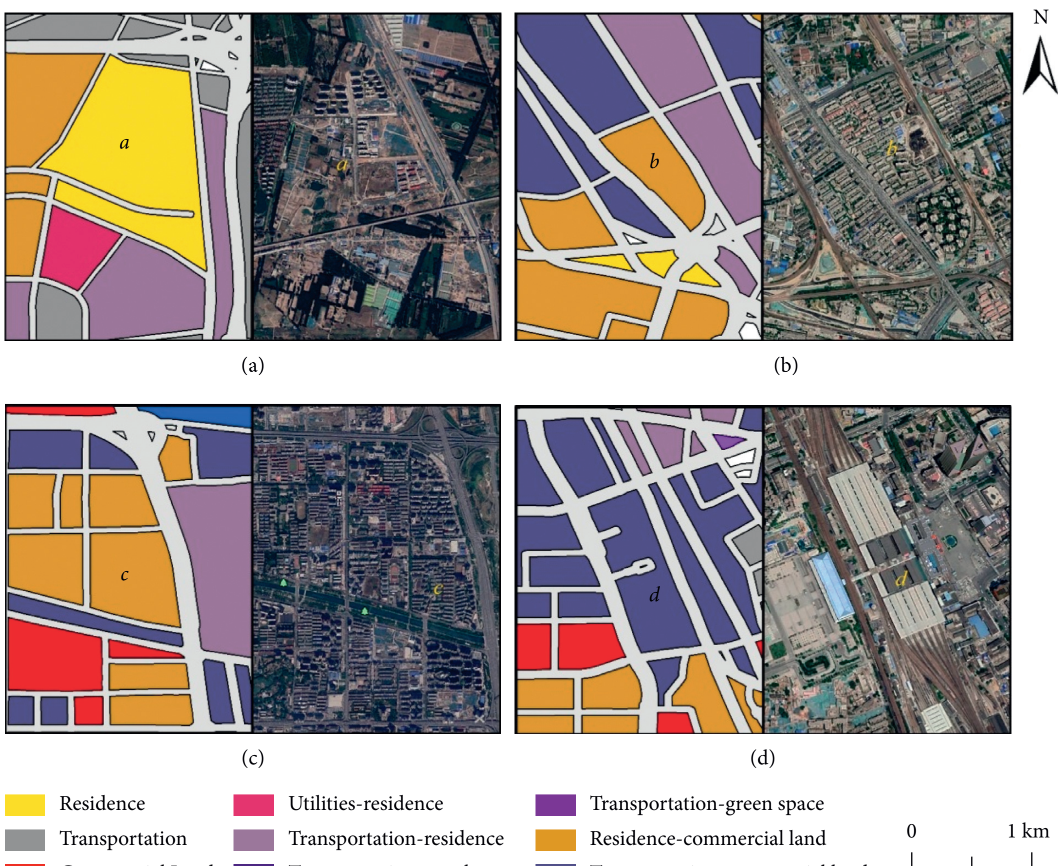

FIGURE 5: Result validation map. (a) The Qingshui Housing Estate. (b) The Hanfei Jinsha Housing Estate. (c) The Hensheng Community. (d) Zhengzhou Railway Station West Square.

5. Discussion

Remote sensing images [24], mobile phone signaling [29, 30], and other data also have good performance in identifying urban functional areas. Still, due to time efficiency and data volume, the description of urban functional areas is not completed in time. Due to the characteristics of the full sample of POI data [28], current research mainly focuses on the four types of functional elements of residence, office, business, and leisure in the city [3, 64], which does not reflect the actual situation of the urban industry category. This study fully considers the actual characteristics of urban functions and redivides POI data into 6 major categories and 19 subcategories, which can effectively express urban mixed functional areas' characteristics. By using multilevel roads to construct blocks as the basic unit of urban functional area division, this approach avoids grid size determination and the impact of road segmentation, which effectively preserves the integrity of the urban functional area at the block scale [29, 31].

Expert survey methods and remote sensing classification methods have high accuracy in identifying urban single functional areas [21–24]. Still, there are uncertainties in the identification of urban mixed functional areas. With the rapid development of cities, the proportion of urban mixed functional areas is getting higher and higher; thus, traditional methods can no longer meet urban functional area identification needs. Therefore, in this study, the two influencing factors of public awareness and block area were introduced, and the advantages of multisource data were used to construct a quantitative identification method of urban functional areas based on the comprehensive kernel density index. This method is based on the core density value for weighting and superposition, which solves the shortcomings of the POI point data in identifying the urban functional area without geographical entity area and influence range. It was verified in Zhengzhou City, and the identification result of the urban functional area is closer to reality. It has high recognition accuracy and can be realized programmatically, which has high practical value for the rapid recognition of modern urban functional areas.

Zhengzhou City is dominated by mixed functional zones, especially with distinctive features such as transportation, logistics, commerce, and residence. The core urban functional zones are small but more complex and densely clustered, which is in line with the previous research on land use evolution mechanisms [65]; the single logistics function area is large, mainly distributed in the urban fringe. These characteristics are related to Zhengzhou's vigorous development of free trade ports, cross-border e-commerce platforms, and China Railway logistics hubs [58]. With the country's support, it has become an important node city in the "One Belt One Road" initiative and strives to build a transportation and logistics hub in Europe and Asia. It will soon become an international commercial metropolis. These cities' large-scale growth has led to a large amount of urban green space reduction [57], which indirectly verifies the feature of less urban green space that we found in identifying functional areas.

6. Conclusions

In this paper, a method for rapid identification of urban functional districts was developed by integrating the POI data, the road network data, the social statistics data, and the field survey data, in the meanwhile, using the density comprehensive weighted index method. The results show the city's mixed complexity as an international comprehensive transportation hub, highlighting the current large-scale city's characteristics of mixed functional areas. We also found that under the rapid urbanization of Zhengzhou, there are severe deficiencies in the management of functional areas, and there is a problem with uneven development of urban connotation, which cannot meet the current needs of livable urban construction. On the one hand, the results imply that it must give full play to its regional advantages to build an international transportation hub; on the other hand, it should strengthen the codevelopment of urban green land. The further study could focus on the driving mechanism of changes in urban functional areas by enhancing the data from multiple periods to obtain historical development trends and provide data support and policy support for the reconfiguration of urban block-scale industrial resources.

Data Availability

The dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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