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Spatial morphology analysis of Jinan City based on nighttime light remote sensing data

Zhurong Xing[1], Yougui Feng[2,*], Ruiju Sun[2], Lei Wang[3], Zhaolu Huang[3], Taojie Shi[2], Junzhi Gong[2], Lexian Zhang[2], Jiying Xie[3] and Xuming Ding[2]

1 College of Land Resources and Surveying and Mapping Engineering, Shandong Agriculture and Engineering University, Jinan 250100, China
2 Zhejiang Zhengyuan Geographical Information Co., Ltd, Zhejiang 313200, China
3 Shandong Zhengyuan Aerial Remote Sensing Technology Co., Ltd, Shandong 250102, China

* Correspondence author; E-mail: fengyougui@sdjzu.edu.cn.

Abstract: Economic construction and urbanization can lead to the evolution of urban spatial patterns, Nighttime light remote sensing images can effectively reflect the changes of urban spatial form, provide reference basis for reasonable urban planning and layout. The paper takes Jinan City as the research object, based on two kinds of nighttime light remote sensing images, DMSP-OLS from 2001–2010 and NPP/VIIRS from 2014–2020, as the main data sources, by performing a series of pre-processing operations on the data and using the statistical data comparison method to determine the optimal threshold, the extent of the built-up area of Jinan was extracted. Using indicators such as total nighttime light, urban spatial evolution rate, spatial compactness and elastic expansion coefficient, analyze the evolution of urban spatial form in Jinan. The results of the study showed that: 1) 2001–2020, the total amount of urban nighttime night value in Jinan City is on the rise, the urban area has grown significantly, 2014–2020 is the most rapid period of urban expansion21.78%; 2) The compactness of the built-up area of Jinan gradually decreases during 2001–2020, and the extent of the built-up area gradually becomes larger and spreads outward; 3) The pattern of urban spatial form in Jinan is a combination of group type and scattered type; 4) The expansion of the built-up area of Jinan in each direction shows that the expansion area is the largest in the due east direction, with an expansion area of 151.94 km^2.The westward expansion rate is 1.17 km^2/year; The expansion of the built-up area in the northwest, due north, and due south directions is relatively small due to the limitations of the northern Yellow River and the influence of the southern mountainous areas.

Keywords: nighttime light remote sensing; built-up area; urban spatial morphology

1. Introduction

Nighttime light remote sensing data records the information of surface light intensity, which can directly reflect human activities and provide necessary geographic data for the study of urban spatial morphology and its development [1]. DMSP-OLS and NPP/VIIRS nighttime light data have been widely used for extracting urban built-up areas. As early as 1978, Croft proposed the ability of DMSP/OLS data extraction in urban areas [2]. With the improvement of data and image quality, nighttime light data has become the main means for Chinese and foreign scholars to study urban information.

By using DMSP/OLS nighttime light remote sensing images, Landsat and MODIS data and statistical data from 1992 to 2012, Junfeng Li *et al.* [3] extracted the built-up urban areas of cities above county level in Gansu Province and analyzed the urban spatial changes in Gansu Province over the past 20 years. Tursun Ayi Ruzi et al [4] used DMSP/OLS and NPP/VIIRS data to extract urban built-up areas in Xinjiang by using the optimal threshold method. They combined night light index and urban expansion indicators to study the spatial-temporal evolution of urban expansion.

Tang Min *et al.* summarized the principles, methods, and related specific applications of extracting urban built-up areas through NPP-VIIRS nighttime light remote sensing data in 2017 [5]. Zengzhao Xing *et al.* studied the spatial development pattern of Haikou City in recent 30 years based on DMSP/OLS and NPP/VIIRS nighttime light remote sensing data [6]. Xinyu Li *et al.* utilized GIS technology to extract the spatial information of urbanization in Chengdu from 2013 to 2017 NPP-VIIRS data, and analyzed the spatial expansion of urbanization [7]. Based on the existing research, this paper extracts the spatial form of Jinan City from 2001 to 2020. by using the statistical data comparison method based on DMSP-OLS and NPP/VIIRS nighttime light data, and calculates the total luminous amount, urban spatial evolution rate, spatial compactness, elastic expansion coefficient and other indicators, the characteristics and evolution rules are analyzed.

2. Research area and data

2.1. Overview of the research area

As the capital city of Shandong Province, Jinan is located in the west of the central part of Shandong Province, adjacent to Mount Tai in the south, acrossing the Yellow River in the north, and adjacent to Dezhou, Binzhou, Liaocheng, Zibo, Tai 'an and other places.

There are ten districts and two counties in Jinan City. This paper mainly extracts the urban built-up area of Jinan City, which refers to the non-agricultural production and construction areas that have been requisitioned and actually developed within the administrative area of the city, including urban construction land with public facilities in the urban and suburban areas [8]. Laiwu and Gangcheng District were merged into Jinan City in 2019, with its predecessor being Laiwu City. In order to comprehensively analyze the built-up area situation of Jinan City and consider factors such as practicality and policy impact, Laiwu City before 2019 was included in the research area.

2.2. Data source and data preprocessing

2.2.1 Data source

(1) Nighttime light remote sensing data: The nighttime light remote sensing data used in this paper mainly fall into two categories. One is the global night light data obtained by OLS sensor carried by the US Defense Meteorological Satellite DMSP, with DN value range from 0 to 63. The other is the VIIRS data carried by the American polar-orbiting satellite NPP, with specific parameters shown in Table 1.

Table 1. Basic information of data source.

Observation platform	Sensors	Spatial resolution/m	Time	Remarks
DMSP	OLS	2700	2001、2005、2010 2006	Stable lighting data Radiometric calibration data
NPP	VIIRS	750	2014、2020	Stable lighting data

(2) Statistical data: sourced from the Statistical Yearbook of Shandong Province from 2001 to 2020 [9], mainly used to obtain the economic, social, and urban built-up area of the research area.

(3) Administrative division vector data: Administrative division data of Jinan City, which is sourced from the National Basic Geographic Information Center [10].

2.2.2. Data Preprocessing

The data processing process is shown in Figure 1, where the images are preprocessed with projection transformation, correction, clipping, *etc.* The two types of data are subjected to continuity correction to eliminate abnormal fluctuations of the DN values between different years [11].

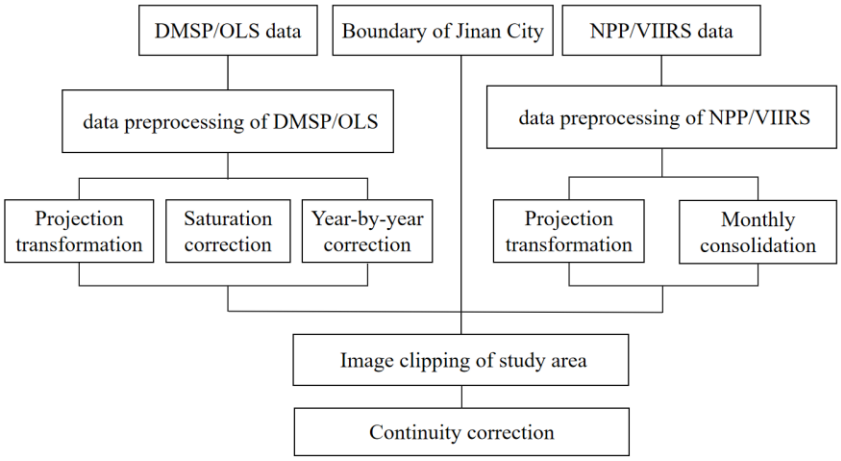

Figure 1. Preprocessing of night light remote sensing data.

3. Urban built-up area extraction

3.1. Totl nighttime lighting

The sum of DN values of all lights in the study area, namely the total amount of lights SL, which can reflect the characteristics of regional lighting and the development status of urbanization, population and industry. The growth rate of city lighting can reflect the rate of city lighting growth [12].

The formulas for the total amount of lighting and the growth rate of city lighting are shown as follows:

$$SL = \sum_{i=1}^{n} x_i \quad (1)$$

$$r = \frac{SL_j - SL_i}{SL_i} \quad (2)$$

In the formula: x_i is the light value of the i pixel; SL_i and SL_j are The total amount of light in the beginning and end years respectively.

Using ArcGIS to extract the total amount of nighttime lighting in 2001, 2005, 2010, 2014, and 2020, which is the sum of all lighting DN values in Jinan City, as shown in Table 2.

Table 2. The total amount and growth rate of lighting in Jinan City.

Years	Total amount of lighting	Rate of growth
2001	213552	
2005	251782	17.9%
2010	291561	15.79%
2014	321597	10.30%
2020	391649	21.78%

It can be seen from the table that the total amount of lighting in Jinan City is increasing year by year, indicating that the urban area is in continuous expansion, and the growth rate from 2014 to 2020 is the largest 21.78%.

3.2. Built-up area extraction

By using the statistical data comparison method to extract urban built-up areas, combined with the Jinan Statistical Yearbook over the years, the area of the research year was obtained as shown in Table 3.

Table 3. Historical statistical data of Jinan City.

Jinan (including Laiwu City)	2020	2014	2010	2005	2001
Built-up area（km^2）	839	487	405	293	203

By combining statistical data and using ArcGIS to reclassify the corrected night light remote sensing data, the optimal threshold range is determined. Based on this, the calculation area of each DN value range is calculated to make the urban area close to the statistical data. Finally, the corresponding relationship is obtained in Table 4.

Table 4. The built-up area with the best threshold.

Years	2020	2014	2010	2005	2001
best threshold	96	113	125	139	150
Extraction area(km^2)	830.41	485.37	408.33	295.92	195.49

According to the optimal threshold, the urban area map of each year is extracted, as shown in Figure 2.

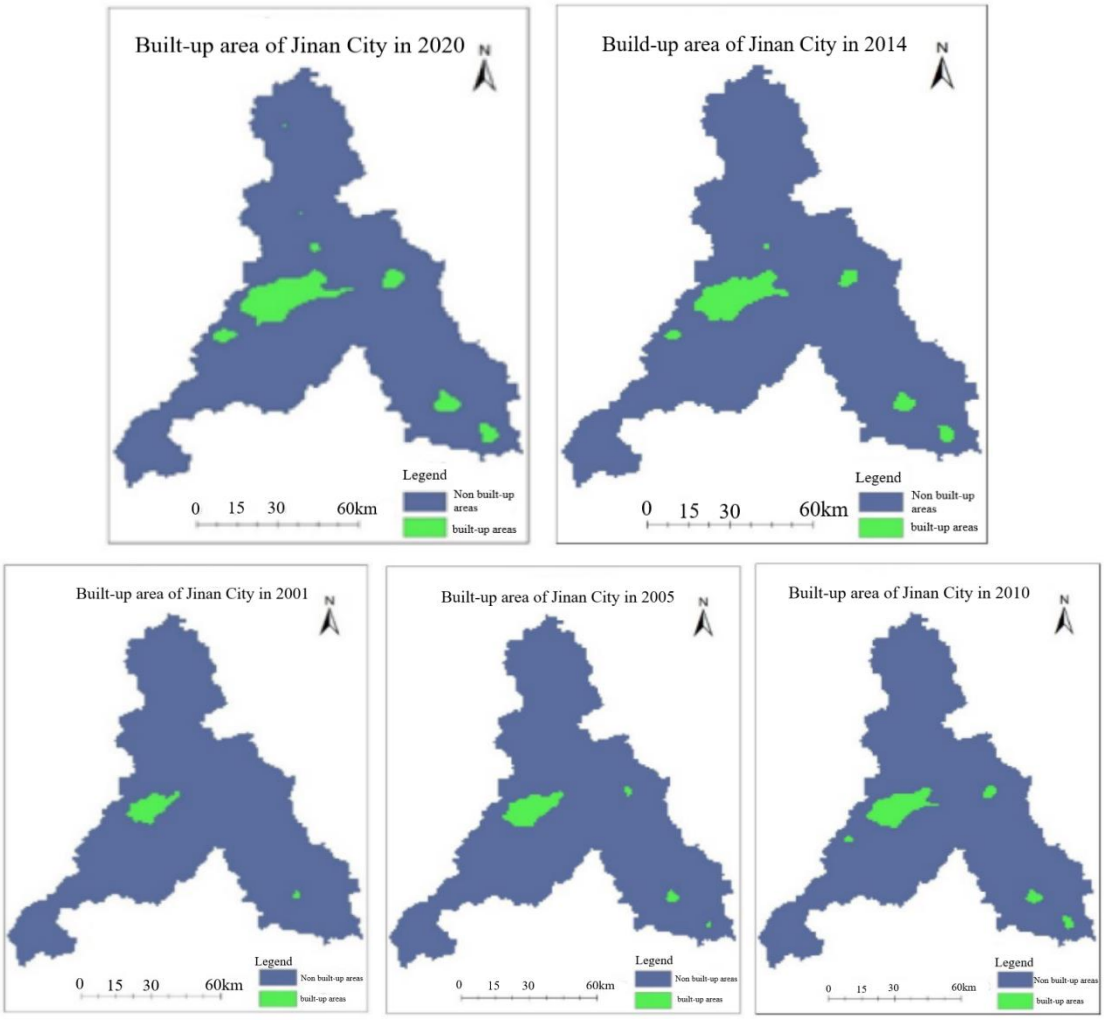

Figure 2. Urban areas in Jinan during different years.

4. Analysis of the evolution of urban spatial form

4.1. Growth rate of Urban area

In order to calculate the growth rate of urban area more accurately, the annual growth rate of the area is calculated based on the built-up area of each stage, combined with formula (3).

$$E_i = \frac{S_b - S_a}{N \cdot S_a} (i = 1,2,3\ldots) \quad (3)$$

In the formula: E_i is the annual growth rate of phase I, S_a and S_b represent the urban area of the beginning year and the end year of i Phase respectively, N represents the number of years included in i Phase [13].

The annual growth rate of Jinan city is shown in Table 5.

Table 5. Growth rate of built up areas in different stages.

Stages	Annual growth rate
The first stage	10.27%
The second stage	7.60%
The third stage	4.72%
The fourth stage	11.85%

As can be seen from the table, the urban area of Jinan has been growing from 2001 to 2020. In the fourth stage from 2014 to 2020, Jinan has the fastest urban development and significant regional expansion; In the first stage, the growth was second from 2001 to 2005, and in the second and third stage, the growth was similar.

4.2. Elastic coefficient of expansion

The coefficient of expansion elasticity is the ratio of area growth rate and population growth rate in a period of time, and is an index to determine the expansion intensity of built-up area. According to the research of China Urban Planning and Design Institute, the optimal value of this coefficient is 1.12, if it is higher than 1.12, it indicates that the land use efficiency in the built-area will decrease. Below 1.12, problems such as traffic congestion, inadequate urban infrastructure, and poor comfort will become prominent [14].

The formula for calculating the elasticity coefficient of urban expansion is as follows:

$$B = \frac{(S_n - S_0)/S_0}{(R_n - R_0)/R_0} \quad (4)$$

In the formula: B is the elastic coefficient of expansion, Sn is the built-up area at the end of the stage, S0 is the built-up area at the beginning of the stage, Rn is population at the end of the stage, R0 is population at the beginning of the stage. Table 6 shows the calculation of the elasticity coefficient of built-up area expansion in different stages of Jinan city.

Among the four stages, the maximum expansion elasticity coefficient between 2014 and 2020 in the fourth stage is 0.8, indicating that the expansion intensity of this stage is the

largest. The expansion elasticity coefficients of the four stages are all less than 1.12, indicating that there are problems such as traffic congestion in the built-up areas of Jinan City, which will make people feel that the infrastructure is tight and the comfort level is poor.

Table 6. Expansion elasticity coefficient.

Stages	Area growth rate	Population growth rate	Expansion elasticity coefficient
The first stage	0.51	0.73	0.70
The second stage	0.38	1.45	0.26
The third stage	0.19	1.22	0.15
The fourth stage	0.71	0.89	0.80

4.3. Morphological analysis of built-up areas in Jinan City

Zhang Nannan *et al.* divided the main patterns of built-up area morphology into concentrated block type, belt type, radiation type, cluster type, constellation type and scattered type [14]. Through the nighttime light images of Jinan City（as shown in Figure 3 ）, it can be seen that the city center is cluster type and the surrounding areas are scatter type.

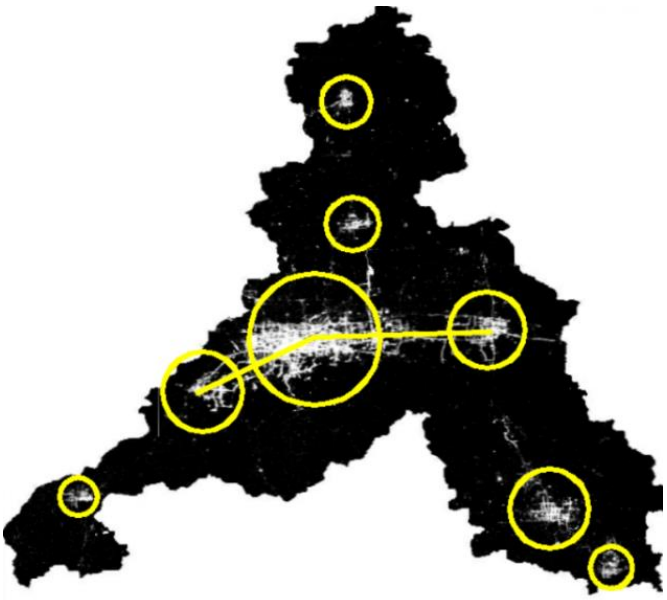

Figure 3. Morphology of built-up areas in Jinan City.

The independent main body of the cluster type is called the "central area", which is the most prosperous urban area in Jinan City, running from east to west across the central part of Jinan City.

The central area connects Zhangqiu district in the east and Changqing district in the west, forming a cluster urban area in the center of Jinan. While the southeast, southwest, and north are distributed in a triangle, which is a scattered pattern.

4.4. The morphology evolution of built-up areas in Jinan City

Using sector analysis method, the geometric center of the built-up area is determined as the origin, and the built-up area is divided into eight regions according to the direction, namely, North, east, south, West, Northwest, northeast, southeast and southwest. The built-up areas in 2001 and 2020 were extracted and superimposed, and the area and proportion of built-up areas increased or decreased were calculated, and then the spatial variation differences of built-up areas were analyzed.

The more the built-up area increases, the larger the proportion, and the stronger the expansion of the built-up area in this direction, which proves that this direction is the main expansion direction of the built-up area. Table 7 shows the area, proportion, area change and expansion rate of the built-up area in each direction of Jinan city center from 2001 to 2018.

Table 7. Expansion directions of built-up areas.

The built-up area	**Direnction**	**Due north**	**Due east**	**Due south**	**Due west**	**Northwest**	**Northeast**	**Southeast**	**Southwest**	**Total**
area（km^2）	2001	34.75	36.42	31.18	62.90	36.09	67.24	11.73	57.16	337.47
	2020	38.84	188.36	42.60	86.34	38.12	76.53	18.76	67.47	557.02
Proportion	2001	0.12	4.17	0.37	0.38	0.06	0.14	0.60	0.18	0.63
(%)	2018	0.11	0.81	0.27	0.27	0.05	0.12	0.37	0.15	0.39
Area change (km^2)	2001–2020	4.09	151.94	11.42	23.44	2.03	9.29	7.03	10.31	211.55
Expansion rate(km^2/year)	2001–2020	0.20	7.59	0.57	1.17	0.10	0.46	0.35	0.52	10.58

From the table we can see that, in the past 20 years, the built-up area of Jinan City has expanded the most in the direction of due east, with an expansion area of 151.94 square kilometers, followed by westward expansion. This is consistent from the pattern of "east expansion, west expansion, south control, north span and central sparsity" in Jinan City in 2003, when a main axis of Jingshi Road running through the main city from Zhangqiu to Changqing was built. It has promoted that the rapid development of the region along the line. The built-up areas in the other seven directions have expanded to varying degrees. The expansion of the built-up areas in the northwest and due north directions is relatively small, mainly due to the limitations of the Yellow River in the north, which makes it difficult to expand, and the slow development towards the south due to mountainous limitations.

5. Conclusion

The expansion of built-up areas is the main characteristic of urbanization process. In this paper, DMSP/OLS and NPP/VIIRS data were used to determine the optimal threshold based on statistical method, extracted the built-up area of Jinan city, analyzed the urban spatial form and its development changes in the past 20 years, the urban regional expansion and the urban

expansion rate, and analyzed the influencing factors of urban expansion in Jinan city. The research conclusion: The built-up area of Jinan City continues to grow with the fastest growth from 2014 to 2020. The expansion intensity indicates that the city has unreasonable situation such as traffic congestion, inadequate infrastructure and living comfort. The overall spatial pattern of Jinan city is a combination of cluster and scattered types; The urban space of Jinan city is constantly expanding outward, mainly in the east and west directions, and mainly in the east direction, with a relatively fast outward expansion rate.

In this paper, statistical data are used to determine the optimal threshold value to extract urban spatial form. The threshold method has certain limitations in the universality of data. In the next step, more efficient and accurate methods will be considered to extract urban space, and the main factors causing urban expansion will be further considered to provide decisions for rational planning of urban layout.

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Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Writing—original draft preparation, Zhurong Xing; writing—Review and Editing, Yougui Feng; data processing, Lei Wang and Zhaolu Huang; drawing production, Taojie Shi and Junzhi Gong; accuracy verification, Lexian Zhang and Jiying Xie; data analysis, Xuanding Ding and Ruiju Sun. All authors have read and agreed to the published version of the manuscript.

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