

Research Article

Measurement of Urban Expansion and Spatial Correlation of Central Yunnan Urban Agglomeration Using Nighttime Light Data

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The Central Yunnan Urban Agglomeration (CYUA) is an important zone of western development in China. The clarification of the spatial structure and changing trends in CYUA could help promote the coordinated development of the CYUA and enhance the overall competitiveness of the region. Based on data from the Yunnan Statistical Yearbook and the nighttime light data, this paper extracts the urban built-up area of the CYUA and analyzes the urban expansion and urban spatial connection intensity of the CYUA from 2000 to 2018 by using the urban gravity center model and the gravity model. The results show the following: (1) From 2000 to 2018, the urban built-up area of the CYUA expanded rapidly, and the urban built-up area increased by 369.35%, with Kunming accounting for 45.41% of the increased area. Kunming was the main contributor to the increase in the urban built-up area in the CYUA. From 2000 to 2018, the urban built-up areas of the CYUA were scattered in various mountain basins. (2) Overall, the urban gravity center of the CYUA has moved to Kunming, and the distance of the urban gravity center has increased since 2005, indicating that urban expansion has accelerated since 2005. (3) The development of the CYUA is extremely unbalanced. The urban spatial connection intensity between Kunming city, Yuxi city, and Qujing city, and Yi Autonomous Prefecture of Chuxiong is relatively strong, while the urban spatial connection intensity among cities other than Kunming is weak. Overall, the CYUA is characterized by stellar radiation with Kunming city as the core and Yuxi city as the secondary core.

1. Introduction

Urban agglomerations refer to relatively complete urban "aggregations" composed of multiple cities with different properties, types, and scales within a specific geographic area [1]. Urban agglomerations are the most dynamic and potential core areas in the China's future economic development pattern. Urban agglomerations are key and optimized development zones in China's main functional zoning and serve the roles of strategic support points, growth poles, and core nodes in China's productivity layout [2]. During the process of urban agglomeration development, there are problems of uncoordinated and unbalanced development among cities, and substantial differences in economic development exist among cities [3]. Therefore, analyzing the

expansion process of urban agglomerations and the spatial connection of urban agglomerations and revealing the temporal and spatial changes in urban agglomeration development are of great significance for the optimization of urban layouts and the coordinated development of regions.

It is impossible for any city to exist in isolation. To ensure the normal operation of production and life, the exchange of material, energy, and information among cities is constantly carried out. This exchange is called spatial interaction [4]. This spatial connection combines spatially separated cities into an urban system with a certain structure and function [5]. The connection between regions and cities not only drives the formation of a regional space but also promotes the evolution of regions and urban functions [6]. Current research concerning urban spatial connections mainly focuses on model construction and application. The models mainly include social network analysis models [7-9], urban flow models [10, 11], and gravity models [12-14]. Among these models, the gravity model is widely used in studies investigating urban spatial connection due to its simple structure and stronger adaptability [15]. The city mass is the core of constructing the gravity model, which is usually expressed by the population and gross domestic product (GDP). For example, Fan et al. constructed a gravity model based on the population and GDP, revealed the spatial pattern of the urban system in the Huaihe River Basin, and analyzed the urban network structure through entropy theory [16, 17]. Sun et al. used a gravity model to evaluate the spatial connections of China's eight urban agglomerations [18]. Xiong et al. used this model to analyze the urban spatial structure of the Changsha-Zhuzhou-Xiangtan Urban Agglomeration and the Dongting Lake Urban Agglomeration [19]. Many similar studies investigated different urban agglomerations [20-22], and these studies laid a good foundation for revealing urban spatial connections. Although the city mass expressed by the population and GDP is widely used, there are still some shortcomings. Urban spatial connection mainly refers to the connection between urban areas. However, population and GDP data are social statistical data based on administrative boundaries, including towns and rural areas. Because the urban population and GDP cannot be obtained from social statistical data, it is impossible to objectively and accurately express the city mass, leading to a certain error in urban spatial connections [23]. Therefore, the accurate acquisition of the urban quality is very important for the measurement of urban spatial connections.

Compared with social statistical data, nighttime light data can realize the monitoring of urban development in a long-term sequence on a large scale. Additionally, such data are widely used in spatial data mining in the socioeconomic field [24]. Existing research results show that the population, economy, electricity consumption, and urbanization level exhibit significant correlations with nighttime light data. Nighttime light data can be used to estimate the population [25-27], GDP [28-30], electricity consumption [31-33], and level of urbanization [34-36]. Nighttime light data cover various types of city-related information and can comprehensively reflect the development level of a city. The urban built-up area can be extracted based on nighttime light data, and the total light intensity within the built-up area is used as the city mass, which can accurately reflect the spatial connection between cities. The city mass expressed by nighttime light data is more objective and accurate than the city mass expressed by social statistical data. Therefore, the obtained urban spatial connection intensity is also more accurate.

The long-term sequence of nighttime light data can be used to analyze the spatiotemporal change in urban spatial connections. Meanwhile, nighttime light data have the unique ability to reflect human social activities and can reflect the spatial structure of a city [37], which can be used to not only analyze the temporal and spatial changes in urban spatial connections but also the process of urban expansion. An area with DN values of nighttime light data can reflect the center of a city, and an area with lower DN values reflects an edge area of a city. The gravity model based on nighttime light data can accurately express the spatial connection among cities but lacks the expression of the direction of urban expansion. To further explore the direction of urban expansion, the traditional gravity center model was modified by using DN values as weights to obtain a weighted gravity center model. Tracking the position change in the weighted gravity center model can reflect the change direction of the intensity of urban expansion.

As one of the 19 urban agglomerations in China, the Central Yunnan Urban Agglomeration (CYUA) is an important strategic center of the "One Belt and One Road", the Yangtze River Economic Belt, the Bangladesh-China-India-Myanmar Economic Corridor, and the China-Indochina Economic Corridor. The CYUA is a core support area facing the radial center of South Asia and Southeast Asia. In recent years, the CYUA has entered a stage of rapid development, but there have been problems of unbalanced and uncoordinated development within the urban agglomeration. How to address the coordinated social and economic development of the CYUA has become an important issue facing municipal governments in China. To explore the development of the CYUA, we used the dichotomy method to extract the built-up areas in the CYUA based on nighttime light data. The intensity of the lights in the built-up area expressed the city mass. A gravity model was constructed to explore the intensity of the urban spatial connections among the cities in the CYUA and analyze the changing trends from 2000 to 2018. Meanwhile, the weighted gravity center model was used to analyze the urban expansion direction of the CYUA from 2000 to 2018.

2. Study Area

The CYUA is one of 19 urban agglomerations in China. It is located in east of central Yunnan Province between 100°45'-104°48′E and 23°20′-27°02′N. The land area is 114600 km², accounting for 29% of the total area of Yunnan Province. The CYUA consists of the cities of Kunming, Qujing, and Yuxi, Yi Autonomous Prefecture of Chuxiong and Hani-Yi Autonomous Prefecture of Honghe as shown in Figure 1. The terrain is high in the north and low in the south. The elevation of most areas is between 1500 and 2800 m. The terrain is dominated by mountains and mountain basins. Nearly 1/2 of the intermontane plain in Yunnan Province is concentrated in the CYUA. The CYUA is rich in land resources with large reserves of mineral resources, a high economic value, and extremely rich resources. Since the reform and opening up, the population of Yunnan Province has increased from 30.915 million in 1978 to 48.295 million in 2018. In 2018, the population of the CYUA accounted for 47.38% of the total population in Yunnan Province. The total GDP of Yunnan Province increased from 6.905 billion yuan in 1978 to 1788.112 billion yuan in 2018. In 2018; the total GDP of the CYUA accounted for 63.37% of the GDP of Yunnan Province [38]. The CYUA is a core area of Yunnan and occupies an important position in the economic and social development of the province.



FIGURE 1: Location of the study area. (a) Kunming city. (b) Quijing city. (c) Yuxi city. (d) Yi Autonomous Prefecture of Chuxiong. (e) Hani-Yi Autonomous Prefecture of Honghe.

3. Materials and Methods

3.1. Data Source. The data used in this paper include Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) nighttime light data, National Polar-Orbiting Partnership/Visible-Infrared Imaging Radiometer Suite (NPP/VIIRS) nighttime light data, and data from the Yunnan Statistical Yearbook. The DMSP/OLS image data constitute a nonradiometric nightlight image data set (Version 4), and the image times are 2000 (F142000, F152000), 2005 (F152005, F162005), and 2010 (F182010). The NPP/VIIRS image data are nighttime light images from December 2015 to December 2018. The DMSP/OLS nighttime light data and NPP/ VIIRS nighttime light data were all provided by the National Geophysical Data Center of the National Oceanic and Atmospheric Administration. In addition, the National Geophysical Data Center released 8 radiancecalibrated nighttime light images. This paper selects nightlight images from the F16 satellite radiance calibration in 2007 as the corrected reference image. The urban built-up area of the CYUA was derived from the Yunnan Statistical Yearbook (2000–2018). The Yunnan Statistical Yearbook was downloaded from the Yunnan Provincial Economic and Social Development Statistical Database.

3.2. Nighttime Light Data Processing. The spatial resolution of the nonradiometric DMSP/OLS nighttime light data is 30 arc seconds (approximately 1 km); the image pixel value represents the average light intensity, and its value ranges between 0 and 63. The NPP/VIIRS nightlight image is a monthly composite product with a spatial resolution of 15"

arc seconds (approximately 0.43 km). The digital number (DN) value represents the light intensity, and the unit is $nW \cdot cm^{-2} \cdot sr^{-1}$. The DMSP/OLS image and NPP/VIIRS image are all in the WGS-84 coordinate systems. To unify the spatial resolution, the DMSP/OLS image and NPP/VIIRS image are projected as Albers projection and resampled to 1 km resolution.

3.2.1. DMSP/OLS Image Correction. The DMSP/OLS nightlight images were not subjected to radiometric calibration and are affected by differences in the detection capabilities of different sensors, and discontinuities exists between images for many years. Furthermore, saturation of the DN values may occur in urban centers with high urbanization [24]. The DN value of nightlight images is used as a key index for the extraction of urban built-up areas. The elimination of DN value errors can improve the accuracy of the extraction of urban built-up areas. Based on previous studies, Cao et al. compared the correction accuracy of an exponential model, linear model, logarithmic model, quadratic polynomial model, and power function model and found that the power function model had the highest accuracy in China [39]. Following the correction method proposed by Cao et al. [39], Hegang city in Heilongjiang Province was selected as a stable target area. From 1992 to 2012, Hegang city has been in a relatively stable development process, and the change in nightlight intensity is relatively stable. Based on this method, the data were mutually corrected and corrected for saturation. The F16 satellite radiometric calibration image in 2006 was used as the reference image. According to equation (1), the F16 satellite radiation calibration image in Hegang city in 2006 was fitted with the images from other years to obtain regression coefficients a and b. The result is shown in Figure 2. After the regression coefficients were obtained, the coefficients were used to complete the data correction in the study area.

$$DN_{v} = a \cdot DN_{x}^{b}, \tag{1}$$

where DN_x is the DN value of the pixel to be corrected, DN_y is the DN value of the pixel of the reference image, and a and b are the fitting parameters.

After the mutual correction, differences still exist between the DMSP/OLS nightlight images obtained by different sensors in the same year. Mutual correction can resolve this difference only to a certain extent and cannot completely eliminate the difference. To make full use of the images and solve this problem, we use equation (2) to fuse the images acquired by different sensors in the same year.

$$DN_i = \frac{\left(DN_i^a + DN_i^b\right)}{2},\tag{2}$$

where DN_i^a and DN_i^b are two images from the same year, and DN_i is the fused image.

After the DMSP/OLS nightlight image is corrected by the two steps mentioned above, image discontinuities still exist between the images for many years, which are manifested as fluctuations in the *DN* values of the pixel at the same position over the years. Therefore, the long-term sequence of nightlight images requires continuous image correction for many years. According to the law of urban development, the bright pixels whose images were urban patches in the previous year will not disappear in the next year [40]. Therefore, the *DN* value of a pixel at the same position should meet the following requirements: the pixel *DN* value of the image of the next year should be greater than or equal to the pixel *DN* value of the image from the previous year. Based on this requirement, the nighttime light data were calibrated for many years. The formula is as follows:

$$DN_{(n,i)} = \begin{cases} 0, & DN_{(n+1,i)} > 0, \\ DN_{(n-1,i)}, & DN_{(n+1,i)} > 0 \text{ and } DN_{(n-1,i)} > DN_{(n,i)}, \\ DN_{(n,i)}, & \text{others,} \end{cases}$$
(3)

where $DN_{(n-1,i)}$, $DN_{(n,i)}$, and $DN_{(n+1,i)}$ are the images in the n-1 year, n year, and n + 1 year, respectively.

3.2.2. NPP/VIIRS Image Correction. Compared with the DMSP/OLS sensor, the NPP/VIIRS sensor has a high light detection ability and spatial resolution. NPP/VIIRS images have background noise problems. To remove the background noise in the NPP/VIIRS images, according to the research results reported by Ma et al. [41], noise processing is performed with $nW \cdot cm^{-2} \cdot sr^{-1}$ as the threshold.

3.3. Urban Built-Up Area Extraction. The methods used to extract the urban built-up areas can be divided into the following two categories: image classification methods and threshold extraction methods. The threshold methods include the empirical threshold method [42], mutation detection method [43], and dichotomy method [44]. Among these methods, the dichotomy method is the most widely used method. The dichotomy method compares the urban built-up area extracted from nighttime light data with statistical data and obtains the best extraction threshold through iteration. This method is simple to calculate and has a strong scientific basis [45]. Based on this method, this paper uses the urban built-up area from the Yunnan Statistical Yearbook and Google Earth images in 2000-2018 as auxiliary data, uses the dichotomy method to obtain the optimal extraction threshold for urban built-up areas in different years, and extracts the urban built-up area based on the threshold. The error in the urban built-up area extraction results is expressed by the following equation:

$$R = \left| \frac{S_{ex} - S_t}{S_{ex}} \right|,\tag{4}$$

where *R* is the relative error, S_{ex} is the extracted area of the urban built-up area, and S_t is the statistical area of the urban built-up area.



FIGURE 2: Intercalibration model coefficients of each image (*Y* axis represents the DN values of the radiometric calibration image. *X* axis represents the DN values of the nonradiometric calibration image).

3.4. Gravity Center Model. The gravity center model is an important indicator used to describe the spatial distribution of geographic objects and can clearly and objectively reflect the trajectory of the changes in regional geographic objects in time and space [46]. In this paper, the weighted urban gravity center model is obtained by using the nightlight value as the weight (equation (5)), and the changes in the gravity center represent directional changes in the intensity of urban expansion.

$$X_g = \frac{\left(\sum_{i=1}^n w_i \cdot x_i\right)}{\left(\sum_{i=1}^n w_i\right)},$$

$$Y_g = \frac{\left(\sum_{i=1}^n w_i \cdot y_i\right)}{\left(\sum_{i=1}^n w_i\right)},$$
(5)

where X_g and Y_g are the coordinates of the urban center of gravity, x_i and y_i are the coordinates of the i-th pixel, and w_i is the weight.

3.5. Gravity Model. The gravity model is commonly used to study urban spatial connections. The model is constructed based on the distance attenuation principle and the universal gravitation equation. Its expression is as follows [47]:

$$T_{ij} = K \frac{P_i \cdot P_j}{d_{ij}^b}.$$
 (6)

 T_{ii} is the gravitational force between city *i* and city *j*; *K* is the gravitational coefficient with a value of 1; P_i and P_i are the mass of city *i* and *j*, respectively; d_{ii} is the distance between city *i* and city *j*; *b* is the distance attenuation coefficient. The city mass is the sum of the lighting values within the built-up area of the city. The distance between two cities should generally consider space and time, such as the traffic distance between the two cities and the freight time between the two cities. However, in studies involving a long time series, we cannot obtain these distances in the CYUA because these distances may be different by year, and in some years, these distances cannot be obtained by the query. Therefore, this paper selects the Euclidean distance to present d_{ii} to control the factor of distance. The distance between city *i* and city *j* is the same every year. We only explore the influence of urban expansion on the spatial connection intensity of the cities in the CYUA. The value of b can reflect the decay speed of gravity with increasing distance. According to the results reported by Gu and Pang, when the value of b is set to 2, the spatial connection of the urban system at the provincial scales can be approximately revealed [48]. The CYUA includes the major cities of Yunnan Province, which is close to the provincial scale, and finally, the value of b is determined to be 2.

The urban spatial connection intensity calculated using the DMSP/OLS and NPP/VIIRS nighttime light data cannot be directly compared. To compare the spatial connection intensities between cities over the years, the T_{ij} results were normalized to eliminate the difference between the two datasets. R_i represents the total gravitational value between the current city and other cities in the urban agglomeration as follows:

$$R_{i} = \sum_{i=1}^{n} T_{ij}.$$
 (7)

4. Results

4.1. Changes in the Urban Built-Up Area of the CYUA. Based on nightlight images, the urban built-up areas of the CYUA over the past 18 years were extracted. By comparing with the urban built-up area in the Yunnan Statistical Yearbook, the results show that the overall error in the extraction results of the CYUA is small, and the extracted areas were close to the statistical areas as shown in Table 1. As shown in Figure 3, the urban built-up area of the CYUA increased by 166 km² from 2000 to 2005. From 2005 to 2010, the urban built-up area of the CYUA increased by 385 km². From 2010 to 2015, the urban built-up area of the CYUA increased by 225 km², and the urban built-up area of the CYUA increased by 140 km² from 2015 to 2018. Overall, the expansion of urban built-up areas accelerated after 2005. During the study period, the built-up area of the CYUA increased by 916 km² from 2000 to 2018, and Kunming city increased by 416 km², accounting for 45.41% of the total increase, followed by Qujing city, which increased by 188 km², accounting for 20.52% of the total increase. Yuxi city increased by 58 km², accounting for 6.33% of the total increase. The Yi Autonomous Prefecture of Chuxiong increased by 81 km², accounting for 8.84% of the total increase. The Hani-Yi Autonomous Prefecture of Honghe increased by 173 km², accounting for 18.89% of the total increase as shown in Table 2. Among the above five cities, Kunming city had the fastest rate of expansion in urban built-up areas and is the center of the development of the CYUA.

4.2. Spatial and Temporal Changes in the Urban Pattern of the CYUA. From the perspective of spatial distribution, the urban built-up areas of the CYUA are generally scattered, partially concentrated, and characterized by the scattered distribution of cities with Kunming as the core. As shown in Figure 4, the urban built-up areas in Kunming were mainly distributed in Wuhua District, Panlong District, Guandu District, and Anning city, and the built-up areas expanded in a ring shape over the urban area before 2005. After 2005, the urban built-up areas were mainly distributed in Guandu

District and Chenggong District. Overall, the urban built-up areas of Kunming city in 2018 were mainly distributed in Wuhua District, Panlong District, Guandu District, Chenggong District, Anning city, and Jinning District, with Dianchi Lake as the center with a concentrated distribution along the bank of Dianchi Lake. Before 2005, the urban builtup area of Qujing city was mainly distributed in Qilin District and expanded in a ring shape along the urban area. After 2005, the urban built-up area expansion was accelerated, and the expansion areas were mainly distributed in Xuanwei city, Malong District, Luliang County, Luoping County, Huize County, and Fuyuan County. In 2018, the urban built-up area of Qujing city was mainly distributed in various districts and counties, and the distribution was relatively fragmented. Qilin District was the center of Qujing's development. Before 2005, the urban built-up area of Yuxi city was mainly distributed in Hongta District, which expanded in a ring shape surrounding the urban area. After 2005, the expansion areas were mainly distributed in Tonghai County, Chengjiang County, Xinping County, and Yuanjiang County, and the expansion speeds of various counties were accelerated. Among them, Hongta District exhibited the largest expansion area and expanded outward in a ring shape. Before 2005, the urban built-up areas of Hani-Yi Autonomous Prefecture of Honghe were mainly distributed in Mengzi city, Gejiu city, and Kaiyuan city and expanded outward in a ring shape. After 2005, Mile city, Jianshui County, and Luxi County began to expand outward in a ring shape. Before 2010, the urban built-up area of Yi Autonomous Prefecture of Chuxiong was mainly in Chuxiong city and expanded outward in a ring shape. After 2010, the expansion areas were mainly distributed in Nanhua County, Lufeng County, Mouding County, Yuanmou County, Dayao County, and Shuangbai County. Chuxiong city exhibited the largest urban area and the fastest expansion rate.

The distribution pattern of urban built-up areas in the CYUA was mainly affected by topographical factors. The CYUA contains mostly mountains, and natural disasters, such as earthquakes and landslides, are prone to occur [49]. Building cities on mountain basins can reduce the impact of natural disasters and is also conducive to the development of cities. The scattered mountain basins lead to the scattered distribution of the CYUA. Under the dual influence of the Western Development Strategy and the City Planning Law of China, central Yunnan mainly develops small and medium-sized cities, rendering the distribution of built-up areas more fragmented [50]. Overall, the spatial distribution pattern of the built-up areas of the CYUA has Kunming city as the center, and Qujing city, Yuxi city, Yi Autonomous Prefecture of Chuxiong, and Hani-Yi Autonomous Prefecture of Honghe are scattered surrounding Kunming city. The urban built-up area of Kunming city mainly shows oneway sprawling expansion with a central city as the center. Yuxi city, Qujing city, Hani-Yi Autonomous Prefecture of Honghe, and Yi Autonomous Prefecture of Chuxiong show sprawling expansion with a central city as the center, but the central cities are accompanied by multiple satellite cities.



TABLE 1: Error in the extraction of the urban built-up areas of the CYUA.

FIGURE 3: Urban built-up area changes in the CYUA during 2000 to 2018.

TABLE 2: Percentage of the urban built-up area of the CYUA from 2000 to 2018.

City	2000		2018		2000-2018	
	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)
Kunming city	149	60.08	565	48.54	416	45.41
Qujing city	25	10.08	213	18.30	188	20.52
Yuxi city	18	7.26	76	6.53	58	6.33
Hani-Yi Autonomous Prefecture of Honghe	32	12.90	205	17.61	173	18.89
Yi Autonomous Prefecture of Chuxiong	24	9.68	105	9.02	81	8.84

4.3. Changes in the Urban Gravity Center of the CYUA. The trajectory of the urban gravity center can reflect the directional changes in the intensity of urban expansion, and the standard deviation ellipse can reveal the moving trend of the urban center of gravity. As shown in Figure 5, the trajectory of the urban gravity center of Kunming city is characterized by a "southeast-east-south" movement. After 2005, the moving distance of the urban gravity center gradually increased, with the longest moving distance of the urban gravity center of 6.15 km in 2010-2015. The urban gravity center is located at the junction of Xishan District and Pandong District and is moving in the southeast direction. The trajectory of the urban gravity center of Qujing city is characterized by a "northeast-southeast" movement. The distance of the urban gravity center was the longest in 2005-2010 with a value of 11.60 km. The urban gravity center is located at the junction of Qilin District and Zhanyi District and is moving in the northeast direction. The trajectory of the urban gravity center of Yuxi city is

characterized by a "southwest" movement. The moving distance of the urban gravity center was the longest in 2010-2015, with a value of 30.06 km. The urban gravity center is located at the junction of Hongta District and Eshan County and is moving in the southwest direction. The trajectory of the urban gravity center of the Yi Autonomous Prefecture of Chuxiong is characterized by a "northeast to southwest" movement. The longest movement distance of the urban gravity center was 12.55 m from 2010 to 2015. The urban gravity center of the Yi Autonomous Prefecture of Chuxiong is located in Chuxiong city and is moving in the northeast direction. The urban gravity center of the Hani-Yi Autonomous Prefecture of Honghe is characterized by a "northeast-southeast" movement, with the longest movement distance of the urban gravity center in 2000-2005, with a value of 26.06 km. The urban gravity center of the Hani-Yi Autonomous Prefecture of Honghe is located in Kaiyuan city and is moving in the northeast direction. Overall, the urban gravity center of the CYUA is concentrated in



FIGURE 4: The spatial distribution of the urban built-up area of the CYUA. (a) Kunming city; (b) Qujing city; (c) Yuxi city; (d) Yi Autonomous Prefecture of Chuxiong; (e) Hani-Yi Autonomous Prefecture of Honghe.

Kunming city, indicating that Kunming city is the development core of the CYUA and occupies an important economic position.

4.4. Changes in the Urban Spatial Connection of the CYUA. The analysis results of the gravity model show that the spatial distribution characteristics of the urban spatial connection intensity of the CYUA present the following characteristics: among the cities in the CYUA in 2000, "Kunming-Yuxi" has the strongest urban spatial connection intensity, followed by "Kunming-Qujing," "Kunming-Yi Autonomous Prefecture of Chuxiong," and "Kunming-Hani-Yi Autonomous Prefecture of Honghe". In 2005, "Kunming-Yuxi" exhibited the strongest spatial connection, followed by "Kunming-Qujing," "Kunming-Hani-Yi Autonomous Prefecture of Honghe," and "Kunming-Yi Autonomous Prefecture of Chuxiong". Compared with the spatial connection intensity in 2000, the spatial connection of "Kunming- Hani-Yi Autonomous Prefecture of Honghe," "Kunming-Yi Autonomous Prefecture of Chuxiong," and "Yuxi-Qujing" gradually strengthened, while the other changes were small. In 2010, "Kunming-Yuxi" had the strongest spatial connection, followed by "Kunming-Qujing," "Kunming- Hani-Yi Autonomous Prefecture of Honghe," and "Kunming-Yi Autonomous Prefecture of Chuxiong". The "Kunming-Qujing" spatial connection gradually strengthened. In 2015, the urban spatial connection intensity was basically



FIGURE 5: The spatial distribution of urban gravity center of the CYUA. (a) Kunming city. (b) Qujing city. (c) Yuxi city. (d) Yi Autonomous Prefecture of Chuxiong. (e) Hani-Yi Autonomous Prefecture of Hongle.

consistent with that in 2010. In 2018, the urban spatial connection intensity was the strongest in "Kunming-Yuxi," followed by "Kunming-Qujing" and "Kunming-Yi Autonomous Prefecture of Chuxiong" as shown in Table 3. Overall, the urban spatial connection intensity radiates outward with Kunming as the core and Yuxi as the secondary core. Except for Kunming city and Yuxi city, the urban spatial connection intensity among the cities is weak.

The temporal and spatial changes in the total gravitational value of the cities in the CYUA were analyzed, and the spatial radiation differences among the cities were revealed. Based on the calculation results of the gravity model, the temporal and spatial characteristics of the gravity value of each city were analyzed. The results showed that from 2000 to 2018, the urban spatial connection intensity of the cities in the CYUA increased to different degrees, but the growth rate of each city was quite different. Among them, Kunming city had the largest increase, followed by Qujing city and Yi Autonomous Prefecture of Chuxiong, and the other cities had small increases. Kunming city increased from 1.31 in 2000 to 2.14 in 2018. Qujing city increased from 0.22 in 2000 to 0.73 in 2018. The Yi Autonomous Prefecture of Chuxiong increased from 0.08 in 2000 to 0.44 in 2018 as shown in Table 4. The urban spatial correlation intensity of Yuxi city and Hani-Yi Autonomous Prefecture of Honghe exhibited limited changes and remained relatively stable. Although the growth rate of Yuxi city was relatively small from 2000 to 2018, Yuxi city's urban radiation capacity was second only to Kunming city. The main reason for this result is that Yuxi city has a better location advantage than Qujing city, Hani-

City	2000	2005	2010	2015	2018
Kunming city-Yuxi city	1.00	1.00	1.00	1.00	1.00
Kunming city-Qujing city	0.21	0.17	0.24	0.39	0.66
Kunming city-Hani-Yi Autonomous Prefecture of Honghe	0.03	0.10	0.13	0.10	0.10
Kunming city-Yi Autonomous Prefecture of Chuxiong	0.07	0.08	0.09	0.19	0.37
Hani-Yi Autonomous Prefecture of Honghe- Yuxi city	0.01	0.03	0.05	0.03	0.02
Qujing city-Yuxi city	0.01	0.01	0.02	0.03	0.03
Yi Autonomous Prefecture of Chuxiong-Yuxi city	0.01	0.01	0.02	0.03	0.05
Hani-Yi Autonomous Prefecture of Honghe-Qujing city	0.00	0.00	0.01	0.01	0.01
Yi Autonomous Prefecture of Chuxiong-Hani-Yi Autonomous Prefecture of Honghe	0.00	0.00	0.00	0.00	0.00
Yi Autonomous Prefecture of Chuxiong-Qujing city	0.00	0.00	0.00	0.01	0.03

TABLE 3: The intensity change of spatial connection among cities in CYUA from 2000 to 2018.

TABLE 4: The urban spatial connection intensity from 2000 to 2018.

Urban spatial connection intensity	2000	2005	2010	2015	2018
Kunming city	1.31	1.35	1.46	1.68	2.14
Qujing city	0.22	0.18	0.26	0.43	0.73
Yuxi city	1.02	1.06	1.09	1.09	1.10
Hani-Yi Autonomous Prefecture of Honghe	0.04	0.13	0.19	0.14	0.13
Yi Autonomous Prefecture of Chuxiong	0.08	0.10	0.11	0.23	0.44

Yi Autonomous Prefecture of Honghe and Yi Autonomous Prefecture of Chuxiong. Yuxi city is close to Kunming city and has a close connection with Kunming city. From the perspective of the entire research period, the urban spatial connection intensity of the CYUA is unbalanced. With the acceleration of economic development, the gap also widened. These results indicate that Kunming city is the center, and the other cities surround Kunming city. Kunming's role as the core growth pole of the CYUA is also more prominent. As the development core of the CYUA, Kunming city plays a significant role in promoting urban agglomerations, and this role radiates to the periphery with Yuxi city as the secondary core.

The spatiotemporal analysis of the urban spatial connection intensity of the CYUA from 2000 to 2018 shows that the CYUA presents a circular structure with Kunming city as the core as shown in Figure 6. As the core area of the CYUA, with the acceleration of economic development, Kunming's core position has become more prominent, and its ability to radiate to surrounding cities has further enhanced. Kunming is in the central city position and has an obvious promoting effect on the economy of the CYUA. In 2018, the total GDP of Kunming city accounted for 45.95% of the total GDP of the CYUA. Yuxi city, Qujing city, Yi Autonomous Prefecture of Chuxiong, and Hani-Yi Autonomous Prefecture of Honghe are the secondary development centers of the CYUA. Compared with the spatial radiation capacity of Kunming city, there are obvious gaps in the radiation capacities of these other areas. Kunming city has the strongest spatial radiation capacity, followed by Yuxi city, and these cities initially formed a "Kunming-Yuxi" dual-core spatial structure. The "CYUA Planning Revision (2009-2030)" noted that the CYUA will form a "one pole and three core" spatial structure, namely, Kunming city will serve as the core, and Yuxi city, Qujing city, and Yi Autonomous Prefecture of Chuxiong will serve as the secondary cores.

Furthermore, a "Kunming-Yuxi" dual core will be formed to improve the comprehensive radiation capacity. In this paper, the urban spatial connection intensity changes of the CYUA are consistent with the planning results.

5. Discussion

5.1. Changing Trend of the Urban Gravity Center of the CYUA. The movement of an urban gravity center can reflect the direction of urban expansion. Wang et al. analyzed the urban expansion characteristics of the Beijing-Tianjin-Hebei urban agglomeration based on the urban gravity center model [51]. Li et al. used the urban gravity center model to analyze the changes and development of the construction land of the Changsha-Zhuzhou-Xiangtan Urban Agglomeration [52]. The urban gravity center in the above study refers to the geometric center of the urban area, which is not accurate enough. A region with a high DN value of nighttime light data can reflect the core region of a city, and the region with a low DN value is a core edge region of a city. A weighted urban gravity center model that uses the nightlight DN value as the weight is more objective. The change in the trajectory of the weighted urban center gravity can reflect the directional changes in the intensity of urban expansion. This paper uses a weighted urban gravity center model to analyze the urban expansion of the CYUA. The results show that the overall urban gravity center of the CYUA is concentrated near the urban region of Kunming city, indicating that Kunming city is the development center of the CYUA. To reveal the trend of urban expansion in various cities, the city is used as a unit to analyze the movement characteristics of the urban center gravity of the CYUA. Compared with the overall urban center gravity of the CYUA, the urban gravity center of each city can reflect the development trend of each city. The movement trajectory of Kunming's urban gravity center is the same as the expansion direction of Kunming's



FIGURE 6: The spatial correlation intensity of the CYUA. (a) 2000. (b) 2005. (c) 2010. (d) 2015. (e) 2018.

urban areas as revealed by superimposing the urban gravity center with the urban built-up area, indicating that the weighted urban gravity center model can reveal the direction and trend of urban expansion. In four cities (Yuxi city, Qujing city, Hani-Yi Autonomous Prefecture of Honghe, and Yi Autonomous Prefecture of Chuxiong) other than Kunming, the urban gravity center is located near the central urban area of the city, and the movement direction of the urban gravity center is affected by the counties under the jurisdiction of the city. The main reason for this difference is that the urban built-up areas are relatively scattered, especially in the Hani-Yi Autonomous Prefecture of Honghe. When the urban gravity center in the Hani-Yi Autonomous Prefecture of Honghe moves in a certain direction, it indicates that the expansion of the counties of the Hani-Yi Autonomous Prefecture of Honghe is greater than the expansion of the central urban of the Hani-Yi Autonomous Prefecture of Honghe. Kunming's urban gravity center differs from the situations in the other cities because Kunming's urban area is concentrated.

To compare the difference between the weighted urban gravity center and the unweighted urban gravity center, the weighted urban gravity center and the unweighted urban gravity center were superimposed and analyzed. The results show that the differences in the position of the weighted urban gravity center and the unweighted urban gravity center of Kunming city are relatively small, and the

overall trend is consistent. However, the weighted urban gravity center and unweighted urban gravity center in the Hani-Yi Autonomous Prefecture of Honghe are quite different, and the overall trend is not consistent as shown in Figure 7. The main reason for this difference is that the urban areas of Kunming are concentrated, while the urban areas of Hani-Yi Autonomous Prefecture of Honghe are scattered. Bai et al.'s research concerning the urban expansion in Chongqing revealed that urban patches that are too fragmented can affect the calculation results of the urban gravity center [40]. Huang et al. compared the nighttime light gravity center and economic gravity center in Henan Province and found that the nighttime light gravity center could better reflect the development direction of the city [53]. The above analysis revealed that the urban gravity center with nightlights as the weight can more objectively reflect the direction of urban expansion than other methods.

5.2. Changing Trend of the Urban Spatial Connection Intensity of the CYUA. The objective expression of city mass in the gravity model can accurately reflect the changes in the urban spatial connection intensity. The city mass is usually expressed by the population and GDP. As the embodiment of the comprehensive strength of a city, the population and GDP cannot objectively express the urban quality [12].



FIGURE 7: The difference between the weighted urban center of gravity and unweighted urban center of gravity. (a) Kunming city. (b) Hang-Yi Autonomous Prefecture of Hongle.

Nighttime light data cover various types of information related to the city, which can be used as a comprehensive expression of the city mass. This paper uses the total light intensity within the built-up area to express the city mass and calculates the urban spatial connection intensity of the CYUA from 2000 to 2018. The results show that the urban spatial connection characteristics of the CYUA are characterized by Kunming city as the core and Yuxi city as the secondary core, radiating to the periphery. The strongest urban spatial connection intensity is observed in "Kunming-Yuxi", followed by "Kunming-Qujing," "Kunming-Yi Autonomous Prefecture of Chuxiong" and "Kunming-Hani-Yi Autonomous Prefecture of Honghe". This result is consistent with the results reported by Dong et al. [54] and Wang et al. [55]. Dong et al. used the urban population and GDP to express the city mass. Based on the gravity model, these authors analyzed the urban spatial connections of Kunming city, Qujing city, Yuxi city, and Yi Autonomous Prefecture of Chuxiong from 2004 to 2013 and found that Kunming city has the strongest urban spatial radiation intensity, followed by Yuxi city, Qujing city, and Yi Autonomous Prefecture of Chuxiong. The gap among Yuxi city, Qujing city, and Kunming city gradually decreased [54]. Wang et al. studied the spatial structure efficiency of the CYUA, and the results showed that the CYUA is centered in Kunming city and surrounded by Yuxi city, Qujing city, and Yi Autonomous Prefecture of Chuxiong [55]. The research results in this paper are consistent with the results of existing research investigating the urban spatial connection of the CYUA, indicating that the total light intensity within built-up areas can be used as the city mass in the gravity model to calculate

the urban spatial connection intensity and that the method is reliable.

We normalized the previous research results calculated by social statistical data of the CYUA. Then, the comparison of the urban spatial connection intensity calculated by nighttime light data with the urban spatial connection intensity calculated by social statistics data revealed that the urban spatial connection intensity calculated by nighttime light data is generally consistent with the urban spatial connection intensity calculated by social statistics data, but there is a certain degree of internal differences. Yin et al. built a comprehensive evaluation model of urban spatial connections based on social statistical data to evaluate the urban spatial connection intensity of the CYUA. The results showed that the urban spatial connection intensity of Kunming city in 2005 was 2.69 times that of Qujing city and 1.63 times that of Yuxi city [56]. In 2010, Kunming's urban spatial connection intensity was 2.27 times that of Qujing city and 1.58 times that of Yuxi city. The results of the urban spatial connection intensity calculated by nighttime light data in this paper show that the urban spatial connection intensity of Kunming city in 2005 was 7.5 times that of Qujing city and 1.27 times that of Yuxi city. In 2010, Kunming's urban spatial connection intensity was 5.6 times that of Qujing city and 1.34 times that of Yuxi city. Overall, the results of this paper are consistent with the research by Yin et al., but there are internal differences. The main reason for these differences is that the urban spatial connection intensity calculated by social statistical data is greatly affected by the GDP. Qujing's primary industry (agriculture) accounted for 20% and 18% of its GDP in 2005 and 2010, respectively. However, Kunming city and Yuxi city accounted for relatively small proportions of the total GDP. In general, the spatial interconnection between cities mainly affects urban built-up areas, while social statistical data cover the entire administrative unit, including urban areas and villages. In this paper, the urban spatial connection intensity is calculated by the total light intensity within the built-up area, which reduces the influence of the countryside on the calculation results, and the calculation results can better reflect the difference across cities within an urban agglomeration.

6. Conclusions

Based on the DMSP/OLS and NPP/VIIRS nighttime light data from 2000, 2005, 2010, 2015, and 2018, the dichotomy method is used to extract the urban built-up areas of the CYUA by combining the urban gravity center model and the gravity model and researching the expansion characteristics of urban built-up areas and urban spatial connections of the CYUA from 2000 to 2018. The results show the following: (1) From 2000 to 2018, the CYUA always adopted Kunming city as the development core, and Kunming city was the main source of the increase in the built-up area of the CYUA. (2) From 2000 to 2018, the built-up area of the CYUA increased by 916 km², and Kunming city increased by 416 km², accounting for 45.41% of the increased area. The second source was Qujing city, which accounted for 20.52% of the increased area. Yuxi city, Hani-Yi Autonomous Prefecture of Honghe, and Yi Autonomous Prefecture of Chuxiong have similar proportions. (3) The cities of the CYUA are scattered among the mountain basins. Urban expansion is manifested mainly in the characteristics of circular expansion along urban areas. Among them, Kunming shows the characteristics of unidirectional expansion in the southeast direction. (4) Since 2005, the moving distance of the urban gravity center of the cities in the CYUA has increased, indicating that the rate of urban expansion has accelerated. (5) The measurement results of the spatial connections among the cities in CYUA from 2000 to 2018 show that the CYUA is centered over Kunming city. The urban spatial connection intensity between Kunming city and the other cities is the strongest. Except for Kunming, the urban spatial connection intensity among the cities is weak. Overall, the urban spatial connection intensity of the CYUA is characterized by stellar radiation with Kunming city as the core and Yuxi city as the secondary core.

Data Availability

All data generated or analyzed during this study are included within this manuscript and are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- S. Yao, Y. Zhu, and Z. Chen, *The Urban Agglomerations of China*, University of Science and Technology of China Press, Hefei, China, 2001.
- [2] C. Fang and X. Guan, "Comprehensive measurement and spatial distinction of input-output efficiency of urban agglomerations in China," *Acta Geographica Sinica*, vol. 66, no. 8, pp. 1011–1022, 2011.
- [3] H. Liu, Y. Pei, and W. Jia, "Spatial differences and spillover effects of economic development of urban agglomerations in China," *Finance and Trade Research*, vol. 28, no. 11, pp. 1–12, 2017.
- [4] H. Wang, C. Miao, L. Ru, and C. Cui, "The spatial framework and change of Chinese provincial region economic links," *Economic Geography*, vol. 32, no. 7, pp. 18–23, 2012.
- [5] J. Han and J. Liu, "Urban spatial interaction analysis Using inter-city transport big data: a case study of the Yangtze river delta urban agglomeration of China," *Sustainability*, vol. 10, no. 12, p. 4459, 2018.
- [6] K. Liu and Y. Shen, "Review of research on regional spatial interaction at home and abroad," *World Regional Studies*, vol. 23, no. 1, pp. 73–83, 2014.
- [7] Q. Sun, F. Tang, and Y. Tang, "An economic tie networkstructure analysis of urban agglomeration in the middle reaches of Changjiang River based on SNA," *Journal of Geographical Sciences*, vol. 25, no. 6, pp. 739–755, 2015.
- [8] M. Qiao, Y. Wang, S. Wu, A. Luo, S. Ruan, and Y. Gu, "Finegrained subjective partitioning of urban space Using human interactions from social media data," *IEEE Access*, vol. 7, pp. 52085–52094, 2019.
- [9] R. Zhu, D. Lin, Y. Wang et al., "Social sensing of the imbalance of urban and regional development in China through the population migration network around Spring Festival," *Sustainability*, vol. 12, no. 8, p. 3457, 2020.
- [10] D. Zhu, J. Sun, and L. Lu, "Spatial-temporal evolution of Hefei economic circle's spatial correlation," *Scientia Geographica Sinica*, vol. 37, no. 5, pp. 738–747, 2017.
- [11] C. Xia, A. Zhang, H. Wang, B. Zhang, and Y. Zhang, "Bidirectional urban flows in rapidly urbanizing metropolitan areas and their macro and micro impacts on urban growth: a case study of the Yangtze River middle reaches megalopolis, China," *Land Use Policy*, vol. 82, pp. 158–168, 2019.
- [12] R. Han, H. Cao, and Z. Liu, "Studying the urban hierarchical pattern and spatial structure of China using a synthesized gravity model," *Science China Earth Sciences*, vol. 61, no. 12, pp. 1818–1831, 2018.
- [13] E. Li, M. Lu, and Y. Chen, "Analysis of China's importance in "Belt and Road initiative" trade based on a gravity model," *Sustainability*, vol. 12, no. 17, p. 6808, 2020.
- [14] J. Felipe and U. Kumar, "The role of trade facilitation in central Asia," *Eastern European Economics*, vol. 50, no. 4, pp. 5–20, 2012.
- [15] Y. Yu, Q. Han, W. Tang, Y. Yuan, and Y. Tong, "Exploration of the industrial spatial linkages in urban agglomerations: a case of urban agglomeration in the middle reaches of the Yangtze river, China," *Sustainability*, vol. 10, no. 5, p. 1469, 2018.

- [16] Y. Fan, S. Zhang, Z. He et al., "Spatial pattern and evolution of urban system based on gravity model and whole network analysis in the Huaihe River Basin of China," *Discrete Dynamics in Nature and Society*, vol. 2018, Article ID 3698071, 2018.
- [17] Y. Fan, R. Guo, Z. He et al., "Spatio-temporal pattern of the urban system network in the Huaihe River Basin based on entropy theory," *Entropy*, vol. 21, no. 1, p. 20, 2019.
- [18] Q. Sun, S. Wang, K. Zhang et al., "Spatial pattern of urban system based on gravity model and whole network analysis in eight urban agglomerations of China," *Mathematical Problems in Engineering*, vol. 2019, Article ID 6509726, 18 pages, 2019.
- [19] Y. Xiong, Y. Xu, W. Sun, J. Yin, and K. Hou, "A case study of changsha-zhuzhou-xiangtan urban agglomeration and dongting lake urban agglomeration," *Scientia Geographica Sinica*, vol. 39, no. 10, pp. 1561–1569, 2019.
- [20] Z. Zhao, J. Wang, and J. Feng, "Research on the spatial correlation of central cities in Beijing-Tianjin-Hebei urban agglomeration," *Economic Geography*, vol. 37, no. 6, pp. 60–66+75, 2017.
- [21] S. He, C. Tang, and G. Zhou, "Research on spatial interaction of the urban agglomeration in the middle reaches of the yangtze river," *Economic Geography*, vol. 34, no. 4, pp. 46–53, 2014.
- [22] Y. Sun, D. Jiang, C. Liu et al., "City spatial patterns in Jiangxi province based on gravity model," *Journal of Subtropical Resources and Environment*, vol. 11, no. 2, pp. 76–83, 2016.
- [23] X. Chen, J. Peng, Y. Liu, Y. Chen, and T. Li, "Measuring spatial expansion and correlations of cities in Beijing-Tianjin-Hebei urban agglomeration using DMSP/OLS nighttime light data," *Geographical Research*, vol. 37, no. 5, pp. 898–909, 2018.
- [24] N. Levin, C. C. M. Kyba, Q. Zhang et al., "Remote sensing of night lights: a review and an outlook for the future," *Remote Sensing of Environment*, vol. 237, Article ID 111443, 2020.
- [25] S. Yu, Z. Zhang, and F. Liu, "Monitoring population evolution in China using time-series DMSP/OLS nightlight imagery," *Remote Sensing*, vol. 10, no. 2, p. 194, 2018.
- [26] P. Kumar, H. Sajjad, P. K. Joshi et al., "Modeling the luminous intensity of Beijing, China using DMSP-OLS night-time lights series data for estimating population density," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 109, pp. 31–39, 2019.
- [27] X. Li and W. Zhou, "Dasymetric mapping of urban population in China based on radiance corrected DMSP-OLS nighttime light and land cover data," *Science of The Total Environment*, vol. 643, pp. 1248–1256, 2018.
- [28] Z. Cao, Z. Wu, Y. Kuang, N. Huang, and M. Wang, "Coupling an intercalibration of radiance-calibrated nighttime light images and land use/cover data for modeling and analyzing the distribution of GDP in Guangdong, China," *Sustain-ability*, vol. 8, no. 2, p. 108, 2016.
- [29] Z. Dai, Y. Hu, and G. Zhao, "The suitability of different nighttime light data for GDP estimation at different spatial scales and regional levels," *Sustainability*, vol. 9, no. 2, p. 305, 2017.
- [30] P. Zhang, S. Liu, and J. Du, "A map spectrum-based spatiotemporal clustering method for GDP variation pattern analysis using nighttime light images of the Wuhan Urban Agglomeration," *ISPRS International Journal of Geo-Information*, vol. 6, no. 6, p. 160, 2017.
- [31] C. He, Q. Ma, Z. Liu, and Q. Zhang, "Modeling the spatiotemporal dynamics of electric power consumption in Mainland China using saturation-corrected DMSP/OLS

nighttime stable light data," *International Journal of Digital Earth*, vol. 7, no. 12, pp. 993–1014, 2014.

- [32] T. Hu and X. Huang, "A novel locally adaptive method for modeling the spatiotemporal dynamics of global electric power consumption based on DMSP-OLS nighttime stable light data," *Applied Energy*, vol. 240, pp. 778–792, 2019.
- [33] K. Shi, B. Yu, C. Huang, J. Wu, and X. Sun, "Exploring spatiotemporal patterns of electric power consumption in countries along the Belt and Road," *Energy*, vol. 150, pp. 847–859, 2018.
- [34] K. Yi, H. Tani, Q. Li et al., "Mapping and evaluating the urbanization process in Northeast China using DMSP/OLS nighttime light data," *Sensors*, vol. 14, no. 2, pp. 3207–3226, 2014.
- [35] B. Wu, B. Yu, S. Yao, Q. Wu, Z. Chen, and J. Wu, "A surface network based method for studying urban hierarchies by night time light remote sensing data," *International Journal of Geographical Information Science*, vol. 33, no. 7, pp. 1377– 1398, 2019.
- [36] Y. Zhong, A. Lin, Z. Zhou, and F. Chen, "Spatial pattern evolution and optimization of urban system in the Yangtze River Economic Belt, China, based on DMSP-OLS night light data," *Sustainability*, vol. 10, no. 10, p. 3782, 2018.
- [37] Z. Chen, B. Yu, W. Song et al., "A new approach for detecting urban centers and their spatial structure with nighttime light remote sensing," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 55, no. 11, pp. 6305–6319, 2017.
- [38] Statistical Bureau of Yunnan Province, *Yunnan Statistical Yearbook*, China Statistics Press, Beijing, China, 2019.
- [39] Z. Cao, Z. Wu, Y. Kuang, and N. Huang, "Correction of DMSP/OLS night-time light images and its application in China," *Journal of Geo-Information Science*, vol. 17, no. 9, pp. 1092–1102, 2015.
- [40] H. Bai, M. Ma, R. Yan, K. Liu, and C. Jun, "Evaluation of urban expansion in Chongqing City based on the nighttime light data," *Remote Sensing Technology and Application*, vol. 34, no. 1, pp. 216–224, 2019.
- [41] T. Ma, C. Zhou, T. Pei, S. Haynie, and J. Fan, "Responses of Suomi-NPP VIIRS-derived nighttime lights to socioeconomic activity in China's cities," *Remote Sensing Letters*, vol. 5, no. 2, pp. 165–174, 2014.
- [42] P. Sutton, "Modeling population density with night-time satellite imagery and GIS," *Computers, Environment and Urban Systems*, vol. 21, no. 3-4, pp. 227–244, 1997.
- [43] M. L. Imhoff, W. T. Lawrence, and C. D. Elvidge, "A technique for using composite DMSP/OLS "city lights" satellite data to map urban area," *Remote Sensing of Environment*, vol. 61, no. 3, pp. 361–370, 1997.
- [44] R. Yang, H. Luo, S. Zhou et al., "Restoring and analyzing the space forming process of Chengdu-Chongqing Urban Agglomeration by using DMSP/OLS night-time light data," *Journal of Geo-Information Science*, vol. 19, no. 5, pp. 653–661, 2017.
- [45] C. He, J. Li, J. Chen et al., "The urbanization model and process in bohai sea surrounding area in the 1990s by using DMSP/OLS data," *Acta Geographica Sinica*, vol. 60, no. 3, pp. 409–417, 2005.
- [46] M. Wang, "Analysis the change of urban internal spatial structure based on the shift of city gravity in Dalian city," *Territory & Natural Resources Study*, vol. 4, no. 1, pp. 1–3, 2015.
- [47] Z. Liu, R. Mu, S. Hu, M. Li, and L. Wang, "The method and application of graphic recognition of the social network

structure of urban agglomeration," Wireless Personal Communications, vol. 103, no. 1, pp. 447-480, 2018.

- [48] C. Gu and H. Pang, "Study on spatial relations of Chinese urban system: gravity model approach," *Geographical Re*search, vol. 27, no. 1, pp. 1–12, 2008.
- [49] Y. Chen, W. Xie, and X. Xu, "Changes of population, built-up land, and cropland exposure to natural hazards in China from 1995 to 2015," *International Journal of Disaster Risk Science*, vol. 10, no. 4, pp. 557–572, 2019.
- [50] Q. Huang, S. Meng, C. He, Y. Dou, and Q. Zhang, "Rapid urban land expansion in earthquake-prone areas of China," *International Journal of Disaster Risk Science*, vol. 10, no. 1, pp. 43–56, 2019.
- [51] H. Wang, B. Zhang, Y. Liu et al., "Urban expansion patterns and their driving forces based on the center of gravity-GTWR model: a case study of the Beijing-Tianjin-Hebei urban agglomeration," *Journal of Geographical Sciences*, vol. 30, no. 2, pp. 297–318, 2020.
- [52] Z. Li, W. Jiang, W. Wang, X. Lei, and Y. Deng, "Exploring spatial-temporal change and gravity center movement of construction land in the Chang-Zhu-Tan urban agglomeration," *Journal of Geographical Sciences*, vol. 29, no. 8, pp. 1363–1380, 2019.
- [53] X. Huang, J. Zhao, Q. Meng, J. Hao, and Z. Sun, "Study on urban expansion and gravity evolution in rapid urbanization areas based on nighttime light data—taking Henan Province as an example," *World Regional Studies*, vol. 28, no. 1, pp. 79–89, 2019.
- [54] S. Dong and J. Yin, "Study on the temporal evolution of spatial connection among cities of Dianzhong Urban Agglomeration in Recent 10 Years," *Modern Urban Research*, vol. 4, pp. 75–79, 2015.
- [55] D. Wang and L. Niu, "Optimization of spatial structure benefits of yunnan central urban agglomeration based on GIS," Yunnan Geographic Environment Research, vol. 26, no. 5, pp. 15–20, 2014.
- [56] J. Yin, S. Dong, and H. Chen, "Temporal evolution of spatial connection among cities of Dianzhong Urban Agglomeration from 2004 to 2013," *Areal Research and Development*, vol. 34, no. 1, pp. 65–70, 2015.