ANALYSIS OF URBAN EXPANSION CHARACTERISTICS OF YANGTZE RIVER DELTA URBAN AGGLOMERATION BASED ON DMSP/OLS NIGHTTIME LIGHT DATA

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KEY WORDS: Urban Agglomeration, Yangtze River Delta, DMSP/OLS, Nighttime Light, Urban Expansion, Expansion Intensity.

ABSTRACT:

Urban agglomeration is the strongest driving force of national economic development. The formation and development of urban agglomeration is an important feature of modern urbanization process, and it is of great significance to study its spatial expansion and development process for regional sustainable development. Based on the DMSP/OLS nighttime light remote sensing data from 2000 to 2010, this paper uses threshold method to extract the urban built-up area of the Yangtze River Delta urban agglomeration. The expansion characteristics of urban built-up area in Yangtze River Delta urban agglomeration are analysed from three aspects: expansion area, expansion intensity and expansion type. The results show that the urban agglomeration in The Yangtze River Delta is experienced a rapid urban built-up area expansion process during the decade. The proportion of urban built-up area increased from 9.95% to 15.46%, the average nighttime light intensity increased from 10.18 to 23.43, and the type of urban built-up area expansion was filling type.

1. INTRODUCTION

The formation and development of urban agglomeration is an important feature of modern urbanization process and an important trend of regional economy and urbanization development. With China's steady and high-quality economic growth, urbanization has entered a new stage, and urban agglomerations have gradually become the main carriers of population and economic activities and supporting the country's economic growth.

Scholars at home and abroad have studied the urban land expansion and development of urban agglomeration from different angles. Stern et al. (1992) believed that nature, social economy and government planning policies for urban land use all played an important role in urban development. Kasper (2001) studied a variety of different types of factors, such as population, technology, economic conditions and politics, and pointed out their influence on urban expansion. Tan et al. (2004) studied the land expansion patterns of some large and medium-sized cities in China in the 1990s, and found that in general, the urban construction land expansion in China was the fastest concentrated in the eastern coastal areas, while the central areas were the slowest. According to Gottmann (2005), the urban expansion type of a single city can be divided into agglomeration type and diffusion type. Fan et al. (2013) and Dang et al. (2022) respectively analysed the spatial expansion characteristics of urban agglomerations in Bohai Rim and Guanzhong Plain by using patch landscape morphological characteristics index. Cui et al. (2022) analysed the spatial characteristics and evolution of land use change in four western urban agglomerations from 1980 to 2018 based on dynamic attitude of land use and land use transfer matrix.

In recent years, remote sensing data of nighttime light have been widely used in related studies of urban expansion to analyse urban spatial structure and evolution rules (Elvidge et al., 2012; Chen et al., 2017). Nighttime light remote sensing is an optical remote sensing technology that can detect the low light level at night and obtain the information that cannot be obtained by daytime remote sensing. Most of the steady light at night comes from artificial light sources in urban areas. Therefore, remote sensing images of nighttime light have been proved to be more intuitive to reflect the differences of human activities at night. It has the advantages of large coverage and easy access and can be widely used in multi-scale long sequence of urban studies (Yu et al., 2021). Lo (2002) first proposed the idea that remote sensing data of nighttime light can be used to identify urban agglomerations, and identified the 10 largest urban agglomerations in Mainland China in 1997 by visual interpretation. Wang et al. (2012) compared and analysed the expansion intensity, expansion type and expansion direction of urban agglomerations by using DMSP/OLS nighttime light remote sensing data of three major urban agglomerations in China. Yu et al. (2014) used DMSP/OLS data to automatic identification of urban agglomerations in China. Taking the Beijing-Tianjin-Hebei urban agglomeration as an example, Wang and Feng (2016) used DMSP/OLS nighttime light remote sensing data to quantitatively reveal the spatial and temporal expansion path and its dynamic mechanism of urban

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agglomeration by adopting expansion intensity index, spatial correlation model and multidimensional driving force analysis model. Jia et al. (2017) used DMSP-OLS nighttime light remote sensing data to study the expansion mode of major urban agglomerations in mainland China, and found that the expansion level of medium or small urban agglomerations was usually higher than that of large urban agglomerations, while the expansion speed of large urban agglomerations showed a downward trend. Lu et al. (2018) analysed the expansion characteristics of urban agglomerations from the perspectives of expansion rate, expansion spatial pattern and expansion evaluation based on DMSP/OLS night light remote sensing data. Peng et al. (2020) used threshold method and spatial gravity model to apply DMSP/OLS data to long-term series urban agglomeration range identification. At present, DMSP/OLS nighttime light data extraction methods of urban built up areas mainly include mutation detection method (He et al., 2006), empirical threshold method (Imhoff et al., 1997), comparison method based on statistical data (Elvidge et al., 1997) and spatial comparison method based on remote sensing data.

Based on DMSP/OLS nighttime light image data and GlobeLand30 land cover data, this paper extracted the urban built-up area of China's Yangtze River Delta urban agglomerations in 2000, 2002, 2004, 2006, 2008 and 2010, and then analyzed the characteristics of urban expansion in this period in order to provide support for the sustainable development of urban agglomeration in China.

2. STUDY AREA AND DATA

2.1 Study Area

The Yangtze River Delta region (28.04°N-33.41°N, 118.33°E-122.43°E) includes the southeast of Jiangsu Province, the northeast of Zhejiang Province and Shanghai, with Shanghai as the centre and Shanghai, Nanjing and Hangzhou as the main body (Wang, 2009), as shown in Figure 1. It is one of the urban agglomerations with the highest urbanization level and fastest development speed in China. The Urban agglomerations in Yangtze River Delta are mainly composed of 16 cities, namely Nanjing, Wuxi, Changzhou, Suzhou, Zhenjiang, Taizhou, Yangzhou, Nantong of Jiangsu Province, and Hangzhou, Jiaxing, Shaoxing, Huzhou, Taizhou, Ningbo and Zhoushan of Zhejiang Province (Zhu and Li, 2015).

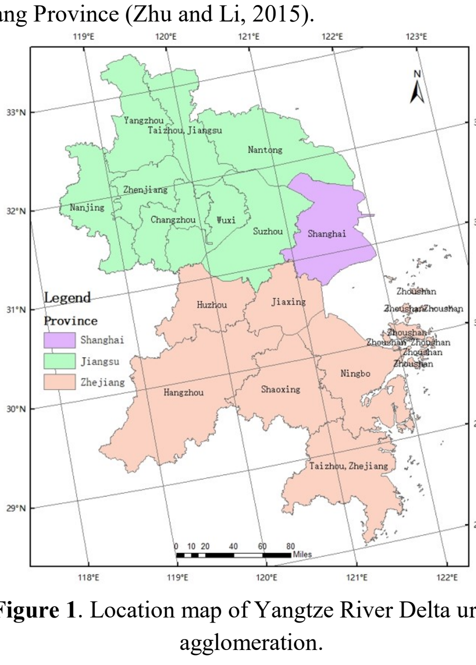

Figure 1. Location map of Yangtze River Delta urban agglomeration.

The Yangtze River Delta urban agglomeration is one of the most rapid and developed urban agglomeration in China, as well as one of the six major urban belts in the world. By 2010, the population of urban agglomerations in the Yangtze River Delta only accounted for 3.05% of the national population, while the total GDP accounted for 10.9% of the national total. The urbanization rate increased from 26.68% in 2000 to 50.22% in 2010.

2.2 Data

2.2.1 DMSP/OLS Nighttime Light Remote Sensing Data: In this paper, DMSP/OLS stabilized average intensity data of nighttime light in 2000, 2002, 2004, 2006, 2008 and 2010 were used. The data were free downloaded from the national geographic information centre web site (https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html). The data resolution is 30". The Digital Number (DN) range is of 0 ~ 63. The data can detect nighttime lights in towns, and distinguish them from dark rural areas. The advantage of DMSP/OLS data lies in that it does not require high spatial resolution. Although the amount of data is small, it can accurately distinguish urban and non-urban areas and reflect human activity information related to lighting. After correction and denoising, the data were resampled to a spatial resolution of 1km. The vector data of the Yangtze River Delta urban agglomeration were used to clip the data of the six periods to obtain the data of the study area.

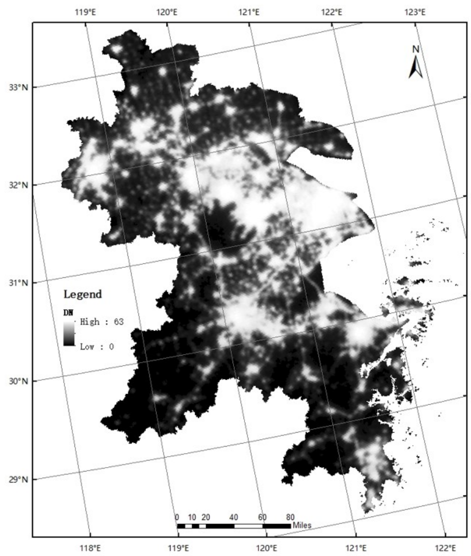

Figure 2. DMSP/OLS nighttime light data in 2020.

2.2.2 GlobeLand30 data: GlobeLand30 data from the Yangtze River Delta region in 2000 and 2010 are used in this paper. The data can be downloaded from the website http://www.globeland30.org. The data is the global land cover data at 30m spatial resolution, including 10 land cover types, such as cropland, forest, grassland, shrub land, wetland, water body, artificial surface, bareland, glacier and permanent snow (Chen et al., 2015). The classified image data used in the study included the TM5, ETM+ multispectral images of the Us Landsat and the multispectral images of the Chinese Environmental Disaster Mitigation Satellite (HJ-1). According to the accuracy assessment of the third-party, the overall accuracy of GlobeLand30-2010 is 83.5%, artificial surface accuracy is 86.97% (Chen et al., 2015; Zhang et al., 2016). The urban built-up area of the Yangtze River Delta urban agglomeration used in this study is obtained by artificial surface data in GlobeLand30 data. The land cover in 2010a of the Yangtze River Delta urban agglomeration is as shown in Figure 3.

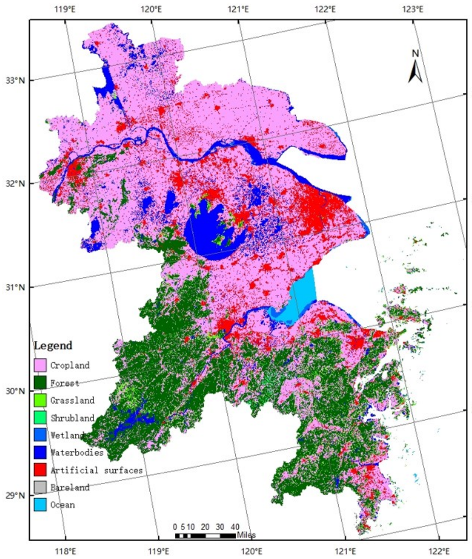

Figure 3. GlobLand30-2010a of the Yangtze River Delta urban agglomeration.

3. METHODS

3.1 Threshold Method

This paper mainly uses the spatial comparison method based on remote sensing data. First, a more accurate boundary of urban built-up area was extracted based on the high precision remote sensing data. Then, DMSP/OLS nighttime light data were used to select different thresholds to calculate the results and compare them with the urban built-up area extracted. When the relative error was the smallest, the corresponding threshold was the best threshold. This method can provide relatively accurate urban built-up area data when the existing accurate data is insufficient. Moreover, this method is convenient and fast, with low data acquisition cost and moderate accuracy, which is suitable for urban agglomeration built-up area analysis.

3.2 Area Proportion Index of Urban Built-up Area

The area proportion index of urban built-up area is used for quantitative analysis of urban built-up area. It refers to the proportion of a city's urban built-up area to the entire urban administrative area. The higher the proportion of urban built-up area, the higher the level of urbanization. The formula is as follows:

$$C = S_t / S_0 \tag{1}$$

In Equation 1, C is the proportion index of urban land area in this region; S_t stands for urban built-up area; S_0 represents the administrative division land.

3.3 Spatial Expansion Intensity and Average Light Intensity of Urban Built-up Area

The spatial expansion intensity and average light intensity of urban built-up area were used to analyze the expansion intensity of urban built-up area. The spatial expansion intensity of urban built-up area refers to the percentage of the urban built-up area expansion in the region within a certain time interval to the area of the entire urban administrative division. The formula is as follows:

$$M_{t\sim t+m} = [\,(U_{t+m} - U_t) / m\,] / S_0 \tag{2}$$

In Equation 2, $M_{t\sim t+m}$ represents the average annual expansion intensity of urban built-up area; U_{t+m} and U_t represent the urban built-up area in t+m and t years respectively. And m represents the year difference; S_0 represents the total area of the region.

DMSP/OLS images were used to calculate the total light index of each region. Pixel radiation value of each grid unit multiplied by the number of grids in the region, and then divided by the area of the region to obtain the average light intensity of each region. It was used as the reference of urbanization degree. The formula is as follows:

$$ANLI = \sum^{n}_{i=1} * DN_i / S_0 \tag{3}$$

In Equation 3, ANLI refers to the average light intensity of the region; DN_i represents the pixel radiation value of each grid cell in the region. n represents the number of grids; S_0 represents the total area of the region.

3.4 Convex Hull Method

The convex hull method is adopted to analyze the expansion types of urban built-up area. Firstly, all urban built-up areas within the scope of urban agglomeration should be constructed with convex hulls, that is, the minimum convex multilateral of all urban built-up areas within the region. Then, the expanded area is judged to determine whether it is within the convex hull. If the number of pixels of the expanded area in the convex hull is larger than that outside the convex hull, the expansion type of the city is considered as filling type; otherwise, it is an extension type.

4. RESULTS AND ANALYSIS

4.1 The Light Threshold of Urban Built-up Area

Based on the existing GlobeLand30 data of each city in the Yangtze River Delta in 2000a, the urban built-up area was obtained by spatial statistical analysis. Then, the urban built-up area data in DMSP/OLS nighttime light data in 2000 were extracted with the threshold value from 20 to 40. Compared with the urban built-up area obtained by GlobeLand30 data analysis, the relative error was calculated. When the threshold value is equal to 20, the relative error is as high as 82.14%. When the threshold value is 34, the relative error is only -0.74%. In conclusion, when the threshold value is equal to 34, Urban area extracted from nighttime light data is closest to that from GlobeLand30-2000a, so the optimal threshold should be 34, as shown in Figure 4.

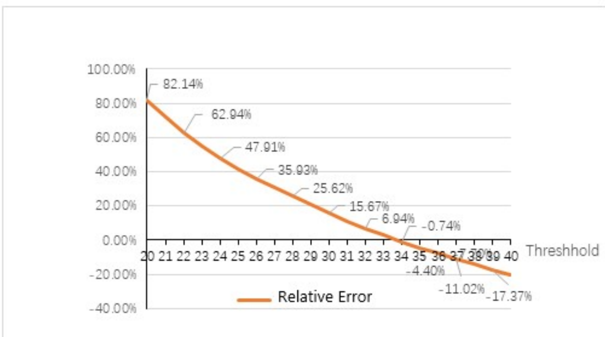

Figure 4. Determination of lighting threshold.

In order to further verify the reliability of the data, we extracted the area of urban built-up area of each city in the Yangtze River Delta urban agglomeration in 2000 from the nighttime light data and evaluated the corresponding accuracy by comparing with the area of urban built-up area from GlobeLand30 in 2000a. It can be seen from Table 1 that the relative error of each region is not large when the threshold value is 34. The largest error was less than 15 percent, and the relative error was within 5 percent in most areas. It can be concluded that the urban area data obtained by the spatial comparison method based on DMSP/OLS nighttime light data is very close to the data extracted from accurate remote sensing images. Therefore, we can extract more accurate and effective urban built-up area by determining the threshold value of DMSP/OLS nighttime light data.

City	Area from GlobeLand30-2000a (km²)	Extraction Area (km²)	Relative Error (%)
Yangzhou	362.96	316.98	-14.51
Taizhou, Jiangsu	576.16	518.01	-11.22
Nantong	316.61	320.63	1.25
Nanjing	679.78	676.65	-0.46
Zhenjiang	281.06	262.48	-7.08
Suzhou	883.17	852.75	-3.57
Changzhou	343.73	358.11	4.02
Wuxi	557.82	518.54	-7.58
Shanghai	1600.77	1779.09	10.02
Zhoushan	236.49	211.34	-11.90
Huzhou	453.99	421.34	-7.75
Jiaxing	382.68	363.15	-5.38
Ningbo	1263.01	1288.21	1.96
Hangzhou	1274.73	1298.42	1.82
Shaoxing	684.45	672.37	-1.80
Taizhou, Zhejiang	1168.49	1115.89	-4.71

Table 1. Relative error of urban built-up area in each city in Yangtze River Delta urban agglomeration.

4.2 The Area Cange of Urban Built-up Area

On the whole, as shown in Figure 5, the area proportion index of urban built-up area in the Yangtze River Delta Urban agglomeration shows an increasing trend. The rise was getting bigger and bigger. In 2000a, the proportion of urban built-up area in the Yangtze River Delta urban agglomeration was only 9.95%. After 10 years of development, the proportion reached 15.46%, with an increase of more than 50%. This shows that under the planning and guidance of national policies, the land area expansion of urban agglomeration in the Yangtze River Delta is in an orderly and stable growth stage.

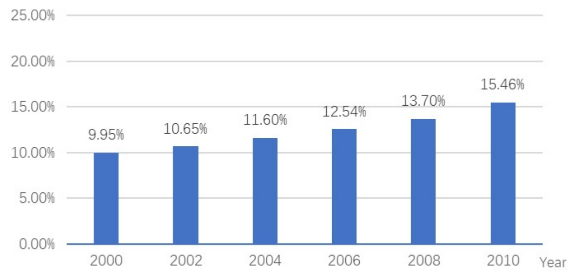

Figure 5. Urban land area index of Yangtze River Delta.

From the perspective of urban agglomeration expansion speed, as shown in Figure 6, the annual average expansion rate of built-up area of urban agglomeration in Yangtze River Delta was also accelerating, increasing from 3.54% in 2002 to 6.43% in 2010, showing a steady and progressive growth rate.

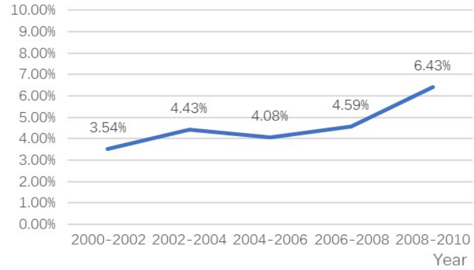

Figure 6. Urban built-up area expansion speed index in Yangtze River Delta urban agglomeration.

From the perspective of specific cities, as shown in Table 2, after 10 years of development, Shanghai, as one of the metropolises with the highest level of urbanization and internationalization in China, was far ahead of the rest, with its urban built-up area proportion reaching 43.6%. Wuxi ranked second with 19.15% and Suzhou third with 15.94%. Shaoxing city had the lowest urban built-up area index at 6.61%. The expansion scale of urban built-up areas in Jiangsu province was generally higher than that in Zhejiang province. In general, each city had maintained a relatively stable rate of expansion.

Year / City	2000 (%)	2002 (%)	2004 (%)	2006 (%)	2008 (%)	2010 (%)
Shanghai	28.31	29.25	33.96	37.95	41.66	43.61
Wuxi	11.91	14.49	16.09	16.03	18.44	19.15
Suzhou	10.04	12.11	12.10	13.35	14.17	15.94
Jiaxing	7.79	8.09	9.26	10.65	12.29	13.60
Changzhou	7.68	9.75	11.54	12.19	12.95	13.33
Nanjing	10.06	10.57	11.03	11.44	12.30	12.51
Taizhou, Jiangsu	9.77	10.43	10.96	11.22	11.68	12.09
Ningbo	6.66	9.73	11.49	10.41	11.44	11.48
Zhenjiang	7.22	7.94	8.56	8.70	8.92	9.45
Hangzhou	5.54	6.64	6.68	7.25	7.60	8.32
Nantong	3.48	4.07	4.32	5.27	6.91	8.30
Zhoushan	4.20	5.66	6.22	6.46	6.87	7.42
Yangzhou	5.11	5.42	6.09	6.79	6.87	7.02
Taizhou, Zhejiang	5.48	5.70	5.52	6.25	6.93	6.94
Huzhou	4.61	4.65	4.17	5.10	5.53	6.63
Shaoxing	4.37	5.03	5.64	5.70	5.88	6.61

Table 2. Urban land area index of each city.

4.3 Expansion intensity analysis of urban built-up area in Yangtze River Delta

The overall expansion intensity of the urban agglomeration in the Yangtze River Delta was calculated according to the annual average spatial expansion intensity index of the urban agglomeration, as shown in Figure 7. It can be seen that the spatial expansion intensity of the whole urban built-up area in the Yangtze River Delta urban agglomeration was in a stable and fluctuating state. It was in the range of 0.3%-0.5% during

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the 10 years, reaching its peak between 2002 and 2006 and its lowest period between 2006 and 2008.

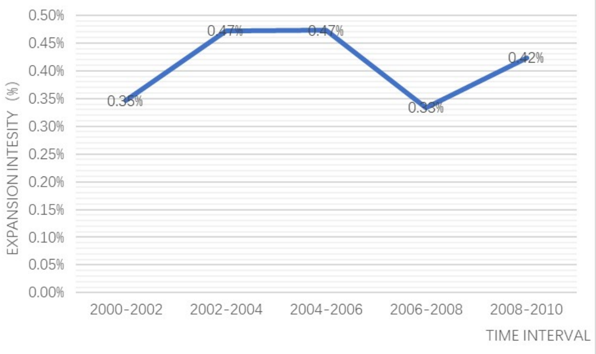

Figure 7. Expansion intensity of built-up areas in the Yangtze River Delta urban agglomeration.

The urban average light intensity was used to analyse the specific urban expansion intensity of each city in the Yangtze River Delta. It could be seen from Table 3 that Shanghai still has the highest average light intensity, rising from 34.17 in 2000 to 53.01. It is worth noting that Suzhou, ranked second, has the largest increase in average light intensity over the past 10 years, with a total increase of 26.75, which reflects the strong momentum of Suzhou's urban expansion from the side. Compared with Table 2, we found that urban expansion speed and expansion intensity had the same law. Shanghai, Suzhou, Wuxi, Changzhou and Jiaxing were the top five cities in terms of expansion speed and intensity. And on the whole, the urbanization development degree of Jiangsu was higher than that of Zhejiang.

Year / City	2000 (%)	2002 (%)	2004 (%)	2006 (%)	2008 (%)	2010 (%)
Shanghai	34.17	37.67	40.63	43.64	46.41	53.01
Suzhou	13.66	19.13	24.25	27.61	32.50	40.40
Wuxi	14.42	19.39	23.26	25.95	31.44	39.30
Jiaxing	11.48	14.06	15.45	18.86	22.36	30.52
Changzhou	10.46	13.18	16.17	18.05	23.32	28.87
Zhenjiang	10.01	12.78	13.85	14.49	18.69	26.73
Nanjing	12.02	14.59	15.92	16.68	20.09	25.88
Ningbo	9.79	13.43	13.98	15.03	17.27	24.10
Zhoushan	7.75	10.78	11.04	12.95	15.64	23.88
Taizhou, Jiangsu	9.07	10.26	10.60	12.09	15.03	20.52
Nantong	8.12	9.39	9.99	11.61	14.86	20.44
Yangzhou	8.47	9.58	10.25	11.49	13.75	19.08
Huzhou	7.22	9.57	10.00	10.49	12.38	16.96
Shaoxing	6.64	7.83	9.12	9.57	11.25	15.61
Taizhou, Zhejiang	6.35	7.50	7.83	8.19	10.12	13.14
Hangzhou	5.62	6.80	7.57	7.98	9.57	12.02

Table 3. Average light intensity table of each city.

4.4 Analysis of urban expansion types of urban built-up areas in Yangtze River Delta

In order to analyse the classification characteristics of the Yangtze River Delta urban agglomeration, Shanghai, the most representative city in China, was taken as an example. Its type of urban expansion quantitatively analysed, as shown in Figure 8. Through calculation and analysis, the urban pixels in Shanghai increased by 1357 in total, among which 925 were in the convex hull. The proportion of pixels in the convex hull was larger than that outside the convex hull. Therefore, the urban expansion type of Shanghai from 2000 to 2010 is filling type. By the same method, it can be concluded that the urban expansion type of the whole Yangtze River Delta urban agglomeration was also filled type.

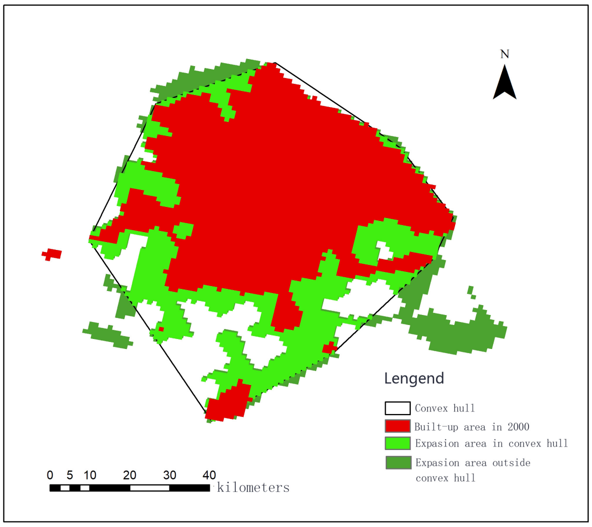

Figure 8. Urban built-up area expansion in Shanghai from 2000a to 2010a.

5. CONCLUSION

In this paper, the DMSP/OLS nighttime light data threshold of the Yangtze River Delta urban agglomeration was determined to be 34 by taking advantage of the strong contrast between urban nighttime light intensity and non-urban dark background and comparative analysis with GlobeLand30 land cover data. Through segmentation of threshold, the urban built-up areas of the Yangtze River Delta urban agglomeration in 2000, 2002, 2004, 2006, 2008 and 2010 were extracted.

Then, this paper analysed the characteristics of urban built-up area expansion in Yangtze River Delta from three aspects of urban built-up area, such as expansion area, expansion intensity and expansion type. In terms of area, the Yangtze River Delta urban agglomerations experienced a rapid process of urban built-up area expansion from 2000 to 2010. From the perspective of intensity, the intensity of urban built-up area expansion in the region was large, and the average light intensity was in the stage of rapid growth. From the perspective of types, the expansion types of cities in Yangtze River Delta urban agglomeration were all filling types. With Shanghai as the core, the urban built-up areas of Suzhou, Wuxi and Changzhou were gradually joined together. The synergistic development between Shanghai and cities in central Jiangsu and Zhejiang was relatively lower.

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