Analysis of the evolution of urban three-dimensional morphology: the case of Nanjing city, China

Weifeng Qiao\textsuperscript{a,b}, Yahua Wang\textsuperscript{a,b}, Qingqing Ji\textsuperscript{a}, Yi Hu\textsuperscript{a}, Dazhuan Ge \textsuperscript{a,b} and Min Cao\textsuperscript{a,b}

\textsuperscript{a}School of Geography, Nanjing Normal University, Nanjing, People’s Republic of China; \textsuperscript{b}Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, People’s Republic of China

\section{1. Introduction}

Urban morphology is an external contour of urban space that depicts the overall form of the urban spatial structure and the shape and appearance of the city plane and façade (Chen, 2000). Research on urban spatial morphology can deepen the understanding of urban evolution processes and mechanisms and provide a basis for urban design and land use administration. Based on the three-dimensional model of urban built-up areas in two periods, this paper establishes a quantitative index system for the EUTM and discusses the methods of generating isoline maps for each index. The idea of making integrated partition map of urban three-dimensional morphology is developed according to a multidimensional feature space classification method. A quantitative analysis of the EUTM in Nanjing is carried out by using two types of maps.

An analysis of the evolution of urban three-dimensional morphology (EUTM) can comprehensively explore the processes and mechanisms of urban evolution and provide a basis for urban design and land use administration. Based on the three-dimensional model of urban built-up areas in two periods, this paper establishes a quantitative index system for the EUTM and discusses the methods of generating isoline maps for each index. The idea of making integrated partition map of urban three-dimensional morphology is developed according to a multidimensional feature space classification method. A quantitative analysis of the EUTM in Nanjing is carried out by using two types of maps.

\begin{itemize}
  \itemshape index (Fu, Zhang, \& Peng, 2011; Shang, Zhang, \& Zhou, 2012; Wang, Liu, \& Zhuang, 2005) and compact indexes (Huang, Chen, Hu, \& Li, 2012; Pan \& Han, 2013; Ye \& Zhou, 2013).
  \itemshape index (Fu, Zhang, \& Peng, 2011; Shang, Zhang, \& Zhou, 2012; Wang, Liu, \& Zhuang, 2005) and compact indexes (Huang, Chen, Hu, \& Li, 2012; Pan \& Han, 2013; Ye \& Zhou, 2013).
  \itemshape index (Fu, Zhang, \& Peng, 2011; Shang, Zhang, \& Zhou, 2012; Wang, Liu, \& Zhuang, 2005) and compact indexes (Huang, Chen, Hu, \& Li, 2012; Pan \& Han, 2013; Ye \& Zhou, 2013).
  \itemshape index (Fu, Zhang, \& Peng, 2011; Shang, Zhang, \& Zhou, 2012; Wang, Liu, \& Zhuang, 2005) and compact indexes (Huang, Chen, Hu, \& Li, 2012; Pan \& Han, 2013; Ye \& Zhou, 2013).
  \itemshape index (Fu, Zhang, \& Peng, 2011; Shang, Zhang, \& Zhou, 2012; Wang, Liu, \& Zhuang, 2005) and compact indexes (Huang, Chen, Hu, \& Li, 2012; Pan \& Han, 2013; Ye \& Zhou, 2013).
\end{itemize}
quantitative analysis indexes based on building groups, and making single index isoline maps and integrated partition map of UTM, the three-dimensional characteristics of each land unit can be analysed, and UTM characteristics in different periods and their changing trends are discussed.

2. Materials and methods

2.1. Study area

The new century has witnessed the rapid expansion of urban space in Nanjing. Therefore, the study of three-dimensional urban expansion in this period is typical and representative. This paper chooses the Nanjing built-up area as the case area. Nanjing, which is located in the southwest of the Jiangsu Province, is one of the central cities in the Yangtze River Delta. Over the last 30 years of political reform and opening-up, high-rise buildings have trended towards rapid growth. Currently, the number of high-rise buildings in Nanjing ranks 19th out of the world’s major cities and 8th in China. The EUTM in Nanjing has certain typicality and representativeness. In 2012, there were eleven districts and two counties in Nanjing. The research area of this paper includes contiguous built-up areas in municipal districts or non-contiguous built-up areas with important city functions; the study area contains the main city of Nanjing, Dongshan, Xianlin, the Jiangbei vice city, Banqiao, Binjiang, Lukou, Qiaolin, other new cities, peripheral development zones, ports, and airports that have important functions in the city. The study area is approximately 960 km² (Figure 1). The urban three-dimensional models in 2000 and 2012 used in this study are LOD0-level models constructed by high-resolution remote sensing images, large-scale topographic maps and cadastral maps.

2.2. Data source

To study the EUTM of Nanjing, this study primarily uses remote sensing data in 2000 and 2012. TM/ETM+ images, downloaded from the U.S. Geological Survey website (http://www.usgs.gov), are used to extract urban built-up area boundaries. To extract the roof profiles and building heights, high-resolution images are used in this study, including IKONOS and GeoEye-1 images. In addition to remote sensing data, the topographic maps and cadastral maps are also collected for auxiliary analysis and data reference.

2.3. Methods

In this paper, we presented the single index isoline maps and integrated partition maps of UTM based on the three-dimensional model in 2000 and 2012 and then studied the EUTM of Nanjing since the beginning of the new century. Each step in creating the map is described as follows: First, we analysed indexes such as the extreme value, average value, discretization, height difference, composition and structure of urban cities, which could provide a full description of UTM and construct the index system. Then, we determined the grid size by dividing the grid unit in the urban built-up area by that in the urban three-dimensional model, which resulted in several land use units when using a regular grid. Based on the grid unit, we used a partition statistical method to extract single indexes separately and generate the discrete quantization indexes of each land use unit to determine the isoline of each single index with the isoline tracing method. Based on the two periods isoline maps for each index, we analysed the change rule of each index. The discrete quantization results of each index value were taken as the single ‘band’ of the remote sensing image, and the multiband combinations and multidimensional feature space classifications were used to generate two periods-integrated partition map of UTM (Figure 2).

Details of the construction methods of the urban multi-period 3D model and the accuracies of the land use classification and building height extraction were published in an earlier series of articles for this study (Qiao, Liu, Xiang, & Wang, 2015; Qiao, Wang, & Xiang, 2015).

3. Selection of analysis index

To scientifically and accurately analyse the laws of the EUTM, the selection of analysis indexes should follow the scientific principles of integrity, dominance and feasibility. The selection of indicators should be able to analyse the evolution of urban morphology from all angles, and it should be chosen from the perspective of the system. There are many indexes that can be used to describe

Figure 1. Study area.
the UTM, and we should choose representative indicators that allow the quantitative indicators to clearly and intuitively reflect the different periods of UTM.

According to the above principles and combined with the actual situation in Nanjing, this paper defines UTM indicators based on the scale of the building groups. The primary characteristic of the UTM is height. In addition, because the spatial combination methods for different building heights are different, building groups form different three-dimensional morphologies. Therefore, the corresponding index system is constructed based on the characteristics of extreme values, concentrations, and discrepancies in building heights, as well as the difference and structure characteristics of building groups (Table 1).

The standard deviation of height in Table 1 reflects the dispersion degree of building group heights in the grid. Otherness refers to the ratio of the standard deviation in height and the average height of the building group, and it can reflect the degree of vertical variation in building heights in the grid; large otherness values indicate that the degree of vertical variation in building heights is greater. Expansibility represents the ratio of the sum of volumes for all building entities to the total area of the grid, which is similar to the typical concept of plot ratio as it reflects the utilization degree of urban three-dimensional space by urban building group. When the value of expansibility is greater, the degree of use for urban three-dimensional space by building group is greater, which indirectly indicates the land use intensity. Evenness reflects the differences between building entities within each grid. The greater the evenness, the more even and less variable the building entities constituting the building group. Similarity expresses the similar degree of surface-constituting buildings. The greater the similarity, the more uniform the surface; on the contrary, the weaker the similarity, the more complex the surface. The similarity is expressed by the Moran index (Moran’s I).

Before selecting a regular grid as the computing unit, the size of the grid should be determined. Because the standard deviation for building height is a

**Table 1.** Data source and description.

| Data                                | Resolutions/scale | Description                           |
|-------------------------------------|-------------------|---------------------------------------|
| Remote sensing images               | TM /ETM+          | 30 m, 15 m                            |
|                                     | IKONOS,           | 4 m, 1 m                              |
|                                     | GeoEye-1          | 1.65 m, 0.41 m                        |
| Topographic map, Cadastral map (2000, 2012) | 1: 500           | Auxiliary analysis                     |

**Figure 2.** Flow chart for generating the single index isoline maps and integrated partition map of UTM.
remarkable index that measures the varying degree in building group heights, and it is easy to calculate, this paper used it as a statistical indicator and counted its mean value at different grid sizes to calculate the decline rate in different grid sizes. Using this test, when grids increased from 100 to 1000 m (at an interval of 100 m), the standard deviation of height began to stabilize at 400 m and changed slightly between 400 and 600 m. Therefore, this paper selected a 500 m grid as the computing unit for analysis.

4. Generation and analysis of isoline maps for each index

After selecting the appropriate indicators and determining the grid size, the indicators were extracted based on the urban three-dimensional model and isoline maps for each index were generated. (See Main Map)

(1) Extraction of the statistical characteristic index of height. The geometric centre of each building in the urban built-up area was extracted, and data of the building point groups were obtained. Applying the partition statistics tool in ArcGIS for the regional analysis, the appropriate statistical functions were selected to extract the statistical characteristic index of height.

(2) Extraction of expansibility. Using the regular grid as the computing unit, several buildings fell into different grids. To ensure the accuracy of the building volume using the computing unit, an overlay analysis should be performed before the statistical analysis to divide same buildings in adjacent grids into different polygons; the volume of each building should be calculated after the division, and building centre points should be extracted to obtain data for building central point groups to calculate the sum of building volumes in the grid with the partition statistics method. The sum of building volumes was divided by the area of the computing unit (i.e. the grid area) to obtain the value of expansibility.

(3) Extraction of evenness. First, the area calculation function in GIS was used to calculate the area occupied by each building; second, the volume of each building was calculated. Finally, the sum of the base area and volumes of all buildings were calculated in each unit; the ratio of the area occupied by each building to total building area was calculated, and the ratio of the volume of each building to the total volume resulted in the overall evenness according to the formula in Table 1.

(4) Extraction of similarity. The urban three-dimensional model was converted into raster data, where the raster data were divided by the computing unit (grid) to calculate the mean and weight of each raster; finally, the similarity of each computing unit (grid) was computed according to the formula in Table 1.

To reveal the trend in spatial change for each index in the built-up area, it is necessary to generate isolines based on the discrete discontinuous indicators. In this paper, the inverse distance weighting method was used to interpolate the grid data, and the isoline tracing method was further used to generate isoline maps.

According to the isoline maps for each index in 2000 and 2012, the urban built-up area in Nanjing could analyse the temporal and spatial characteristic variations in the extreme value, average value, discrete value, value of height difference and structure of urban cities to fully grasp the laws of EUTM. Due to limitations on paper space, this paper only analysed expansibility as an example.

Figure 3 shows trend maps of expansibility with building group in 2000 and 2012, respectively. The meaning of expansibility is similar to that of the building volume ratio, as it reflects the utilization degree of building groups in an urban three-dimensional space. In the process of urbanization, the expansion of the city was multi-directional, while the planar extension and urban internal structure changed constantly. The increase in building volume was the main result of the spatial expansion. As seen from Figure 3, in 2000, the distribution of expansibility values in the main city was centred over Xinjiekou. Regions along Zhongshan Road, Zhongshan South Road, Zhongshan North Road, Zhongshan East Road, and Hanzhong Road were high-value areas, which gradually decreased towards the peripheries of the abovementioned areas. In 2012, the expansibility value in Xinjiekou and the Gulou area increased; high-value regions of expansibility also appeared in the urban expansion area of the vice city, but the distribution was relatively fragmented (not contiguous) due to urban residential areas with high building densities. Development zones in Qixia, Pukou, Yuhua, and Jiangning represented regions with lower expansibility values.

Through the analysis of the remaining indexes, the unilateral variation in UTM reflected by each indicator was closely related to urban expansion. Old urban areas, the new city area and the core area of the vice city region were high-value areas for the maximum height, average height, standard deviation, otherness and expansibility indexes; these indexes had a downward trend from the abovementioned regions into their peripheries. However, the trends for evenness and similarity were opposite to those of the abovementioned indexes.

5. Generation and analysis of the EUTM-integrated partition map

A single index can reflect only one aspect of the UTM and cannot be used to conduct a comprehensive analysis. To conduct a comprehensive analysis of the UTM,
we must integrate the single indexes and classify the UTM. A comprehensive analysis of the EUTM can be performed based on the classification of the UTM in different periods. The specific concepts for this classification were as follows: the extraction result of a single index value was used as an independent band in the remote sensing image, where the single index value was equivalent to the luminance value of a single-band image; n bands were synthesized to form an n-dimensional feature space. The extracted feature in the n-dimensional feature space was used in the feature extraction algorithm to find a set of new features from the n-dimensional features that could best reflect the class feature and conduct unsupervised classifications based on the new feature space. This result determined the attributes of each category, performed post-processing of the classification and formed the integrated partition map (Figure 4). By comparing the integrated partition map of UTM in different periods, we could comprehensively analyse the laws of EUTM.

Before classification, all bands were standardized to avoid the excessive weighting of individual factors, which would affect the accuracy of the classification results. The standard processing formula is as follows:

$$x_{ij}^\prime = \frac{x_{ij} - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \times 255$$ (1)

In the formula, $x_{ij}$ represents the original data, $x_{ij}^\prime$ represents the standardized data, $x_{\text{min}}$ represents the

![Figure 3. Spatial distribution map of building expansibility in 2000 and 2012.](image)

![Figure 4. The production process of integrated partition map of UTM.](image)
minimum value of the original data, and $x_{\text{max}}$ represents the maximum value of the original data.

Unsupervised classification is an automatic clustering analysis in accordance with the spectral characteristics of an image that determines the comprehensive characteristics of each classification and the attributes for each category after classification. In addition, the several results obtained by unsupervised classification require post-processing (e.g. several crushing pattern spots formed during the classification process). Whether the perspective is from thematic mapping or practical application, it is necessary to eliminate these types of results.

Figure 5 shows the results of the integrated partition of UTM in Nanjing in 2000 and 2012.

Figure 5. Integrated partition map of UTM in Nanjing in 2000 and 2012.

(Note: H – high; S – second highest; M – medium; L – low; A – altitude; I – intensity; E – evenness).

Class IV – low altitude, low intensity and medium evenness zone; Class V – low altitude, low intensity and high evenness zone; Class VI – area of sparse buildings.

The Class I area was comprised of super-high-rise and high-rise building-intensive areas; most of the city’s super-high-rise buildings were concentrated in this area, and indicator values for indexes such as maximum height, average height, and expansibility were the largest, while evenness was the lowest (or lower) in this area. The Class II area was a mixed zone, where high-rise buildings, small high-rise buildings and multi-story buildings occupied a large proportion, and the intensity of land use was less than that of the Class I area, and evenness was greater than that of the Class I area. The Class III area was dominated by multi-story buildings and mixed with a few high-rise and small high-rise buildings, with an evenness greater than those in Class I and Class II areas; the Class IV area was a transition type area, where building heights were low, and evenness was average. The Class V area was mostly comprised of development zones or chemical industrial zones outside of the main city; building
heights were low, and the intensity was low, but the evenness was high. The Class VI area had a scarce number of buildings and was mainly comprised of large green spaces and water surfaces within the city, as well as development zones or university cities outside of the main city, which had just completed road structure construction; however, ground buildings had not yet been built.

By comparing the two maps and analysing the EUTM, the circle distribution phenomenon from the integrated partition in 2000 was obvious; however, in 2012, the circle distribution phenomenon was not obvious, and each partition showed an interspersed layout structure. As is shown in Table 2, the area of each partition had significantly increased from 2000 to 2012, with the area of Class I increasing from 545.04 hm$^2$ in 2000–5094.52 hm$^2$ in 2012 (8.35 times greater). In 2012, in addition to the Purple Mountain, Xuanwu Lake, Da Jiaochang and the Mufu Mountains, the remaining regions in the main city had all been covered by partitions from Class I to Class III. In 2012, the Class VI area increased greatly in the periphery of the built-up area; there were many development zones where the framework has been pulled, but ground buildings had not yet been built. When analysing the distribution change for Class I in the main city in 2000, the Class I area was concentrated in the south-north narrow region centred over Xinjiekou, where the UTM exhibited an obvious single-centre pattern; in 2012, the Class I area significantly expanded northward along the Zhongyang Road and the Zhongshan North Road, and a new Class I area formed along the Jiangdong North Road and the Jiangdong Middle Road, where the main city formed a double-centre pattern in the Xinjiekou-Gulou and Hexi areas (Table 3).

### Table 2. The selected indexes of UTM.

| Index                                      | Formula                           | Definition of the parameters in the formula | Indicator meaning |
|--------------------------------------------|-----------------------------------|--------------------------------------------|-------------------|
| Statistical characteristic index           |                                   |                                            |                   |
| of height for building groups in the grid  |                                   |                                            |                   |
| Maximum height                            | $\max (H_i)$                      | $H_i$ represents the height of each building in the grid |                   |
| Average height                            | $\frac{1}{n} \sum H_i$           | $n$ represents the number of buildings in the grid |                   |
| Standard deviation                         | $\sqrt{\frac{1}{n} \sum (H_i - \bar{H})^2}$ | $\bar{H}$ represents the average height of the buildings in the grid |                   |
| Otherness                                  | $\frac{\sigma^2}{\bar{H}}$       | $\sigma$ represents the standard deviation of the buildings in the grid |                   |
| Spatial composition and structural         |                                   |                                            |                   |
| characteristic index of building groups    |                                   |                                            |                   |
| in the grid                                |                                   |                                            |                   |
| Expansibility                              | $\frac{\sum_{i=1}^n V_i}{S}$      | $V_i$ represents the volume of each building in the grid, and $S$ represents the area of the evaluation unit | Composition       |
| Evenness                                   | $1 - \frac{\sum_{i=1}^n |A_i - V_i|}{S}$ | $A_i$ represents the ratio of the floor area for each building to the floor area for all buildings in the grid, and $V_i$ represents the ratio of the volume of each building to the volume of all buildings in the grid |                   |
| Similarity                                 | $\frac{n \times \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - x_m) (x_j - x_m)}{\sum_{i=1}^n \sum_{j=1}^n w_{ij} x_i x_j}$ | $x_i$ and $x_j$ represent the values at positions $i$ and $j$, respectively; $x_m$ represents the average values of all $i$ and $j$ position values, $n$ represents the total number of points, and $w_{ij}$ represents the weight given for each grid measurement unit | Structure         |

### Table 3. Partition areas of UTM. (Unit: hm$^2$)

| Year | Class I area | Class II area | Class III area | Class IV area | Class V area | Class VI area |
|------|--------------|---------------|----------------|---------------|--------------|---------------|
| 2000 | 545.04       | 2788.55       | 7802.93        | 10,307.52     | 8811.39      | 5154.57       |
| 2012 | 5094.52      | 12,463.70     | 18,306.81      | 14,863.37     | 25,925.87    | 19,353.73     |

### 6. Conclusions

Studying the EUTM can deepen our understanding of the processes and mechanisms of urban evolution from multiple perspectives and provide a basis for urban design and land use administration. Based on the single index isoline maps and integrated partition map of UTM in two periods, this paper analysed the EUTM in Nanjing. The conclusions are as follows:

1. This paper established a quantitative analysis index system for the UTM based on a regular grid and studied the method of making the EUTM analysis maps. Using height statistical characteristics, spatial compositions and structural characteristics of building groups within the grid, we selected quantitative indexes, such as the maximum height, average height, standard deviation, otherness, expansibility, evenness and similarity in urban structures, to study the UTM. By using the partition statistics method in GIS, discrete index values of each grid were generated. The inverse distance weighting (IDW) method was used for interpolation, and the single index isoline maps were generated with the isoline tracing method. Comparing the isoline maps for each
index in two periods, we could analyse the temporal and spatial evolution laws of UTM. To perform a comprehensive analysis of the EUTM, we used the idea of multiband remote sensing classifications for reference and used the extracted result of each index as a single-band in the remote sensing image to combine each single-band and perform the classification based on the multidimensional feature space, and generated the integrated partition map of UTM. Finally, we performed a comparative analysis on the comprehensive characteristics based on the maps in two periods. The methods used in this paper can quantitatively analyse UTM and can describe morphological evolution more accurately, which is also applicable for studies of other cities.

(2) The analysis of EUTM in the built-up area of Nanjing based on a single index was shown. The characteristics of EUTM reflected by a single index were closely related to the three-dimensional expansion of various regions in the city. The old urban area, the core area of the new city and the vice city were high-value zones for indexes such as maximum height, average height, standard deviation, otherness and expansibility, which had decreasing trends from the abovementioned regions into their corresponding peripheries. Evenness and similarity increased gradually from the main city to its periphery.

(3) An analysis of the integrated partition change based on multi-indexes showed that the circle distribution phenomenon of the integrated partition in 2000 was obvious; however, in 2012, the circle distribution phenomenon was not obvious, and each partition showed an interspersed layout structure. The area of each partition had significantly increased over 12 years. The UTM of the central city changed from a single pattern in Xinjiekou to a double-centre pattern in the Xinjiekou-Gulou and Hexi areas. Three-dimensional morphology of the central city changed from a single-centre pattern in Xinjiekou to a double-centre pattern in the Xinjiekou-Gulou and Hexi areas.

This paper provides a useful attempt to study the methods and cases of the EUTM. The study is based on a regular grid; the segmentation method usually lacks consideration on the internal self-organization of the research object during index extraction and even splits the internal connection of an urban uniform unit, which makes it difficult to explain the reasons for grid differences. Therefore, additional works will attempt to use irregular grids, such as land use type, to extract the index of building groups and generate corresponding analysis maps.

Software
ESRI ArcGIS 10.0 was utilized in the spatial analysis, statistical analysis, and mapping of all spatial datasets.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This study was supported by the National Natural Science Foundation of China [grant numbers 41871178, 41671385, 41371172], the Special Financial Grant and General Financial Grant from the China Postdoctoral Science Foundation [grant numbers 2015T80127 and 2014M561040].

ORCID
Dazhuan Ge http://orcid.org/0000-0001-8995-6540

References
Batty, M., & Longly, P. A. (1988). The morphology of urban land use. Environment and Planning B: Planning and Design, 15, 461–488.
Chen, X. L. (2000). Knowledge of urban planning: Urban economy, geography, society, ecology and environment. Beijing: China Building Industry Press.
Chen, Y. G., & Liu, J. S. (2001). An index of equilibrium of urban land-use structure and information dimension of urban form. Geographical Research, 20(2), 146–152.
Chu, J. L. (2007). Quantitative analysis on urban spatial morphology. Nanjing: Southeast University Press.
Feng, J. (2003). Spatial-temporal evolution of urban morphology and land Use structure in Hangzhou. Acta Geographica Sinica, 58(3), 343–353.
Fu, L. H., Zhang, Y., & Peng, S. H. (2011). The index system construction of land use ecological risk assessment in landscape scale perspective. Journal of Natural Science of Hunan Normal University, 34(2), 89–94.
Ge, S. S. (2009). Study on urban three-dimensional morphology based on urban DEM: A case study of Nanjing old city. Nanjing: Nanjing Normal University.
Huang, X. Y., Chen, A. L., Hu, X. M., Li, Y. C., & Hu, B. (2012). On urban spatial expansion and analysis of driving forces in Chongqing city. Journal of Chongqing Normal University (Natural Science), 29(4), 41–46.
Jiang, S. G., & Zhou, Y. X. (2006). The fractal urban form of Beijing and its practical significance. Geographical Research, 25(2), 204–212.
Kuang, W. H. (2011). Simulating dynamic urban expansion at regional scale in Beijing-Tianjin-Tangshan metropolitan area. Journal of Geographical Sciences, 21(2), 317–330.
Li, F. X., Li, M. C., Liu, Y. X., Liang, J., & Chen, Z. J. (2007). Urban growth in Nanjing since 1949. Journal of Natural Resources, 22(4), 524–535.
Li, J. (2005). Fractal dimension of urban spatial morphology and its application. Engineering Journal of Wuhan University, 38(3), 99–103.
Li, X. M., Zhang, C. H., Zhou, L. Y., & Yang, J. (2005). Response of urban Man-made Landscape to urbanization: The case of Dalian. Geographical Research, 24(5), 785–793.
Luo, G. S., Sun, W., Li, G., Ji, Y., & Wang, Y. M. (2008). Construction of three-dimensional model of Guangzhou city. *Tropical Geography, 28*(6), 523–528.

Malczewski, J. (2004). GIS-based land-use suitability analysis: A critical overview. *Progress in Planning, 62*(1), 3–65.

Pan, J. H., & Han, W. C. (2013). Spatial-temporal changes of urban morphology of Provincial Capital cities or above in China. *Journal of Nature Resource, 28*(3), 470–480.

Qiao, W. F., Liu, Y. S., Wang, Y. H., & Xiang, L. Z. (2015). Three-dimensional urban gravity Center calculation method and empirical research: A case study of Nanjing. *Journal of Geo-Information Science, 17*(3), 268–273.

Qiao, W. F., Liu, Y. S., Xiang, L. Z., & Wang, Y. H. (2015). Research on Extracting building height rapidly based on high-resolution remote sensing images without parameters. *Geo-Information Science, 17*(8), 995–1000.

Qiao, W. F., Wang, Y. H., & Xiang, L. Z. (2015). Hierarchical extraction of land use information based on knowledge and rule. *Resources and Environment in the Yangtze Basin, 24*(7), 1079–1083.

Shang, Z. Y., Zhang, X. L., & Zhou, X. Z. (2012). Study on urban spatial expansion and external morphology evolution, based on RS/GIS: A case of Huai’an city. *Economic Geography, 32*(8), 64–70.

Shen, G. (2002). Fractal dimension and fractal growth of urbanized areas. *International Journal of Geographical Information Science, 16*(5), 419–437.

Wan, S. C. (2007). *Analysis of urban spatial morphology*. Beijing: Science Press.

Wang, S. J., Wang, R. J., Wang, Y. C., & Liu, C. Y. (2012). Analyzing Daqing’s urban spatial form evolution: Basing on the technology of RS and GIS. *Economic Geography, 32*(6), 67–73.

Wang, X. Y., Liu, J. Y., & Zhuang, D. F. (2005). Spatial-temporal changes of urban spatial morphology in China. *Acta Geographica Sinica, 60*(3), 392–400.

Yao, S. M., & Chen, S. (1998). The trend of urban spatial evolution in the Changjiang River delta. *Acta Geographica Sinica, 53*(S1), 1–10.

Ye, C. D., & Zhou, C. S. (2013). Urban morphology evolution of Chinese metropolitans. *Geography and Geo-Information Science, 29*(3), 70–75.

Zhang, Z. Q., Jia, D. X., Deng, S. H., & Jin, X. F. (2013). Quantitative research of urban spatial morphology: A case study of the main urban zone of Chongqing. *Journal of Geo-Information Science, 15*(2), 297–306.

Zhao, C. S. (2007). *Urban spatial structure and morphology*. Beijing: Science Press.

Zhu, S. J., & Zheng, B. H. (2010). Construction over all space, image in Changsha based on high-rise buildings layout. *Areal Research and Development, 29*(2), 72–75.