J. Geogr. Sci. 2020, 30(4): 583-600
DOI: https://doi.org/10.1007/s11442-020-1744-5

Spatial characteristics and driving forces of the morphological evolution of East Lake, Wuhan

CHEN Kunlun[1,2,3], LIU Xiaoqiong[1], CHEN Xi[2], GUO Yuqi[3], *DONG Yin[4]

1. School of Environmental Studies, China University of Geosciences, Wuhan 430074, China;
2. Department of Geography, University of Cincinnati, Cincinnati, OH 45221, USA;
3. School of Physical Education, China University of Geosciences, Wuhan 430074, China;
4. School of Public Administration, China University of Geosciences, Wuhan 430074, China

Abstract: The shapes of the urban lakes in Wuhan city have been strongly influenced by the rapid industrialization and urbanization experienced in recent decades. Based on topographic maps and remote sensing images, the temporal and spatial changes of East Lake, Wuhan city, over the past two decades were analyzed. The landscape shape index (LSI) and centroid method were applied to analyze the evolution of lake morphology and its causes. Several key results were obtained. (1) The surface area of East Lake decreased sharply by 2.13 km^2 from 1995 to 2005, and slightly by 1.00 km^2 from 2005 to 2015. The shoreline length of East Lake displayed a continuous trend of decline during the study period: The length reduced by 21.89 km from 1995 to 2005, and by 0.67 km from 2005 to 2015. The LSI values, 7.04 (1995), 6.46 (2005), and 6.28 (2015), displayed an accelerated downward trend, indicating a reduction of complexity in East Lake and the intensification of manual interventions in the water body. (2) The changes to East Lake displayed a clear temporal and spatial heterogeneity. The centroid of East Lake moved northeast from 1995 to 2005 and southeast from 2005 to 2015. (3) The reduction in the area of East Lake was mainly affected by human activities. A lake area of about 4.8 km^2 was converted to other land uses during 1995–2005, most of which was unused land, whereas from 2005 to 2015, 0.43 km^2 of the lake area was converted into built-up land, and 0.25 km^2 was converted into other land uses. The reduction in area was caused by infrastructure construction by the government, the development of the real estate industry, illegal construction by villagers, and the development of scenic spots for tourism. The driving forces of this reduction included Wuhan's growing population, and the rapid development of the economy and urbanization between 1995 and 2015, which has resulted in a large demand for land. Finally, a formation mechanism model was constructed by analyzing the causes of East Lake's morphological evolution.

Keywords: morphological changes; shape of water body; urban expansion; East Lake; formation mechanism model

Received: 2019-04-25 **Accepted:** 2019-12-29

Foundation: National Natural Science Foundation of China, No.71974070, No.41501593; Social Sciences Foundation of Ministry of Education of China, No.19YJCZH068; Scientific Research Project of Hubei Provincial Natural Resources Department, No.ZRZY2019KY08

Author: Chen Kunlun (1982–), Professor, specialized in urban geography and urban planning. E-mail: ckl_2001@163.com

*Corresponding author: Dong Yin, E-mail: dongy_simlab@163.com

1 Introduction

Rapid industrialization and urbanization have promoted China's fast economic growth and sustained social prosperity in the past three decades, which caused a large amount of consumption of resources and environment. Meanwhile, the problem of resources and environment in the context of global change has become a common one faced by all countries around the world. How to correctly handle the relationship between economic development and ecological environment has also become the focus of academic and international political attention (Jin *et al*., 2017; Tsai *et al*., 2018; Zhang *et al*., 2018; Jin *et al*., 2019; Li *et al*., 2019). Urban expansion has generated economic developments along urban waterfronts, but this has also led to the shrinkage of the original wetland, which plays an important role in regulating climate, purifying wastewater, and preserving biodiversity (Cuffney *et al*., 2010; Li *et al*., 2018; Sahana *et al*., 2018). As one of the most important features of the urban water environment, urban lakes experience many environmental problems (Niu *et al*., 2015; Zeng *et al*., 2013; Li *et al*., 2013). The dynamic conflicts between the changes in water bodies and urbanization have led to significant changes in riparian environments, with the interpretation of these changes often being complex (Zou *et al*., 2017).

Early studies of lake morphology mainly focused on the morphological characteristics of different lakes and the relationship between lakes and their areas (Ji *et al*., 2013; Jiang *et al*., 2017). In studies of lake morphology, there has been a comprehensive evaluation of the health status of certain lakes (Chi *et al*., 2018; Jiang *et al*., 2009; Li *et al*., 2018). Studies have shown that lakes largely determine the physical and chemical distribution of water and aquatic organisms, which reflects the evolution of lakes, water quality changes, and hydrodynamic characteristics (Huang *et al*., 2012; Dai *et al*., 2018). Since the 21st century, researchers have applied fractal theory to studies of the morphological characteristics of lakes using remote sensing (RS) and geographic information system (GIS) technology, with the main focus on the validation of the shoreline development coefficient, the effectiveness of the fractal dimension, and the relationship between the crushing degree of the lakeshore and the fractal dimension (Zeng *et al*., 2013; Peters *et al*., 2014; Shaikh *et al*., 2010). Most of these studies have focused on the morphological evolution and fractal characteristics of lakes during land use changes, including the use of landscape ecology and the development of tourism (Cui *et al*., 2013; Wang *et al*., 2019; Dai *et al*., 2015).

Previous studies of lake morphology have produced useful results, mainly focusing on the dynamic changes in area and the morphology of the shoreline. The evaluation and analysis of lake morphological evolution and its application in various fields has been studied in depth, with a diverse range of results. The premise of any evaluation is based on the need for an in-depth understanding of the reasons for change, but research on the factors controlling the changes of lake morphology is relatively rare. Increasingly, researchers are simply trying to describe the factors responsible for the changes in lake morphology without adequate theoretical support and with a lack of detailed analysis. Thus, due to the existing research gap in this area, this study analyzed the temporal and spatial changes of the urban water body of East Lake and the factors influencing these changes over the past two decades, using topographic maps and RS images as basic data.

China's spatial development strategy has experienced many rounds of "coastal openness", "western development", and "the rising strategy in central regions" in recent decades. It has

focused on economic construction and social development from the perspective of spatial cascade development. In 2014, the "Yangtze River Economic Belt Strategy" became a major national strategy, which redefined China's spatial development strategy. While pursuing spatial and economic development, there has been an emphasis on the comprehensive regional development model that enables a deep spatial integration from the perspective of river basins. The pursuit of regionally coordinated development highlights the importance of resources and the environment. The Yangtze River Basin is an important economic zone, with the area supporting China's social and economic sustainable development and regionally balanced growth, both in terms of its spatial location and resource environment (Jin *et al*., 2018; 2019). The Yangtze River Economic Belt Strategy emphasizes the need to develop the Yangtze River Economic Belt into an "influential inland economic zone with global influence, a coordinated development zone of East-West interaction and cooperation, an opening-up zone that is open to the outside world along the Yangtze River, and a demonstration zone for the construction of an ecological civilization." There is also a need to "effectively protect and utilize Yangtze River water resources, strictly control Yangtze River water pollution, properly handle the relationship between rivers and lakes, strengthen the comprehensive management of the river basin environment, strengthen the ecological protection and restoration along the Yangtze River, and promote the orderly development of the Yangtze River coastline." Yangtze River water resources protection and water pollution control are the key tasks of the Yangtze River Economic Belt Strategy. As one of the core cities in the Yangtze River Economic Belt, Wuhan is an important area for the green development of the Yangtze River Economic Belt.

Wuhan is a metropolis characterized by water due to it containing stretches of the Yangtze and Hanshui rivers as well as many other lake resources. Lake environmental protection has always been an important issue, which has attracted great attention from both the academic community and the government. In recent years, with the continuous expansion of urban built-up land, the lake water system in the central urban area has been eroded and the lake area has seriously declined. It is the region of the Yangtze River Valley that has experienced the most obvious dynamic changes. As a result, the area of urban lakes has strikingly decreased (Wu *et al*., 2011; Deng *et al*., 2017) and water quality has deteriorated significantly (Tang *et al*., 2009; Jiang *et al*., 2013). Wuhan has established several targeted measures to ensure river basin management and protection. The current development strategy of the Yangtze River Economic Belt has been transformed from "big development" to "big protection". Therefore, protecting the water resources and controlling water pollution in the Yangtze River Economic Belt will be the most significant mission for the future development of the Yangtze River Economic Belt. There have been several studies of the relationship between urbanization and wetland change in Wuhan (Wang *et al*., 2008; Du *et al*., 2010; Xu *et al*., 2010; Yang *et al*., 2015). These researches generally pay more attention to two aspects: one is the natural change process of wetland under the background of urbanization, and the other is the impact of the natural change process of wetland on cities. Both lack the analysis of human driving force of wetland change. Moreover, similar research in China of this field is more inclined to be involved by the macroscopic perspective, lacking the deep analysis from the microscopic perspective. As the largest urban lake in China, East Lake has profoundly affected human activities in the process of urban development (Yang *et al*., 2011; Chen *et al*., 2015; Ding *et al*., 2015; Han *et al*., 2015). Studies of East Lake will enable a

better understanding of the environmental changes in key cities under the background of Yangtze River protection. An investigation of the influence of human factors on urban environmental change under the background of rapid urbanization can provide theoretical guidance for the future development of Wuhan and even the Yangtze River Economic Belt. However, in the last two decades, few studies have focused on the evolution of East Lake. Therefore, this paper interprets the human dynamics and mechanism of urban lake environmental change from the perspective of human factors, which can make up for some gaps in the current research in this field. Meanwhile, it puts Wuhan urban lake environmental change in the context of Yangtze River protection, by conducting this research from the perspective of microcosmic and urban level can also complement other domestic macroscopic perspective research. The objective of this study was therefore to determine East Lake's evolution from 1995 to 2005 and then to 2015 in the rapidly urbanized area of central China, using multi-temporal Landsat Thermal Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images.

2 Methods

2.1 Study area

Wuhan (113°41′–115°05′E, 29°59′–31°22′N) is the core city of central China with an area of 8596 km^2. It is an important transportation hub in China and is the largest industrial city and economic center in the Yangtze River Economic Belt. Wuhan city covers a built-up area of 460 km^2 and has a population of about 10.77 million.

East Lake (114°20′57′–114°27′42″E, 30°30″56″–30°36′4″N) is located on the south bank of the Yangtze River, covering an area of 33 km^2, which is six times the area of West Lake in Hangzhou. As an urban lake on the eastern edge of Wuhan (Figure 1), East Lake was the largest urban lake in China before 2014, and the most typical city lake in the Yangtze River

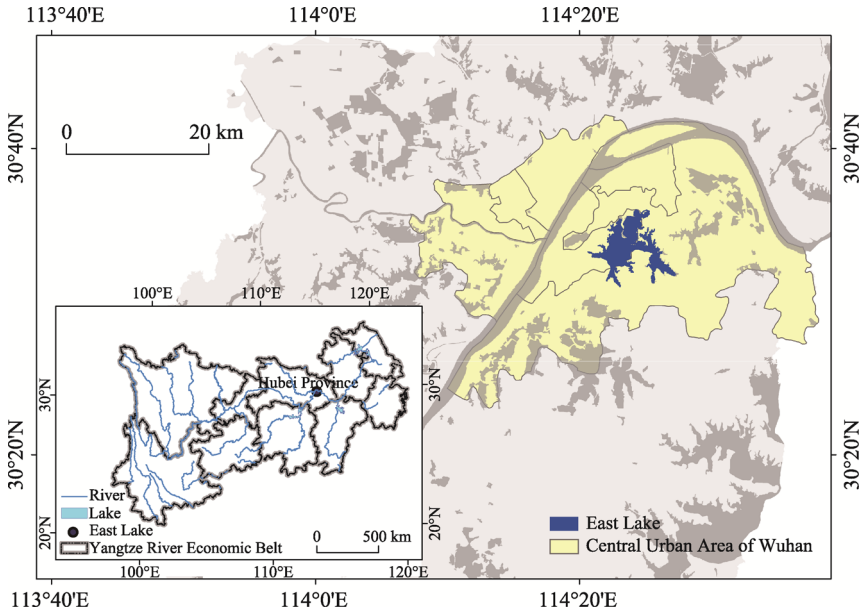

Figure 1 The location and shape of East Lake

Economic Belt. In 2014, due to the expansion of the central urban area of Whuan, part of East Lake's water body was reclaimed, which resulted in Tangxun Lake in Wuhan Jiangxia District becoming the second largest urban lake in China.

The lake has a subtropical climate, with a mean annual temperature ranging from 15.8 to 17.5℃ and an annual precipitation of 1205 mm. Heavy precipitation (~80%) occurs in the rainy season from April to August.

2.2 Data collection

An important criterion in selecting satellite images for the analysis of changes in a lake is the consistency in the acquisition date of the images. In addition, all images should be cloud-free. In this study, Landsat TM images acquired on December 5, 1995, and Landsat TM/ETM+ images acquired on December 8, 2005 and November 26, 2015 were selected to extract the surface area of East Lake. All images were cloud-free. The study area was entirely contained within path 123, row 39 for Landsat TM/ETM+. Images were downloaded from the United States Geological Survey (http://glovis.usgs.gov/). The reference data included the following: (1) detailed topographic maps of the 1990s, at a scale of 1:10,000; (2) a panchromatic image, with a resolution of 15 m in 2005; and (3) the 30-m resolution images from Google Earth in 2015.

A radiometric correction of the images had already been conducted by NASA. Accurate geometric correction is essential for the spatial analysis of change detection, because the potential exists for registration errors to be interpreted as lake or landscape changes, leading to an overestimation or underestimation of the actual change. This geometric correction was used to perform image-to-image rectification of the images from 1995, 2005, and 2015 using the Auto-sync model of ERDAS 9.3, with a root mean square error (RMSE) of less than 1 pixel. The Landsat images were rectified to the Universal Transverse Mercator (UTM) projection system (spheroid WGS 84, datum WGS 84, zone 50).

2.3 Methods

2.3.1 Normalized difference water index (NDWI)

The use of the NDWI for delineating an open water body was introduced by McFeeters (1996). The mid infrared (*MIR*) and near infrared (*NIR*) bands are most suitable for extracting the surface area of lakes by evaluating different NDWI values based on the different spectral bands of TM and ETM+ (Ouma *et al*., 2006). In this study, the NDWI was calculated based on the *MIR* band 5 and *NIR* band 4 for Landsat TM/ETM+. For Landsat 8, the NDWI was calculated based on the *MIR* band 6 and *NIR* band 5.

$$NDWI = \frac{B_{MIR} - B_{NIR}}{B_{MIR} + B_{NIR}} \tag{1}$$

where B_{MIR} represents the *MIR* band, and B_{NIR} represents the *NIR* band.

2.3.2 Landscape shape index (LSI)

The LSI was introduced to analyze the intensity of landscape interference by human activities (Kearns *et al*., 2005; Kong *et al*., 2006). It is the ratio of the actual length of a polygon boundary to a square with the same area (Zhang *et al*., 2006; Wu *et al*., 2017). The LSI re-

flects the complexity and disturbance conditions of a landscape. The smaller the LSI value, the simpler the geometric landscape shape, indicating that the landscape has been seriously influenced by human activities (Qian *et al*., 2015; Zhou *et al*., 2017). The higher the LSI, the more complex the geometric landscape shape, which means that landscape has experienced slight interference by human activity. There are significant differences in the shoreline shape between a natural water body and a water body altered by human interference. Generally, a shoreline affected by artificial interference is straighter and sleeker. Thus, differences in the LSI for the same water body in different periods can reflect the intensity of human activities.

$$LSI = \frac{L}{4\sqrt{A}} \tag{2}$$

where L represents the total length of all patch boundaries of East Lake and A is the total area of East Lake.

2.3.3 Centroid method

The centroid is an important indicator for describing the spatial distribution of geographic objects (Malavasi *et al*., 2014). It was introduced into geographical research to study urban expansion and land use change in recent years. The centroid coordinate of year t can be expressed as follows:

$$Q_X = -\frac{1}{6}\sum_{i=0}^{n}(\mathrm{x}_{i+1} - \mathrm{x}_i)(\mathrm{y}_i^2 + \mathrm{y}_i\mathrm{y}_{i+1} + \mathrm{y}_{i+1}^2) \tag{3}$$

$$Q_y = -\frac{1}{6}\sum_{i=0}^{n}(\mathrm{y}_{i+1} - y_i)(\mathrm{x}_i^2 + x_i x_{i+1} + x_{i+1}^2) \tag{4}$$

$$x' = \frac{Q_y}{A},\ y' = \frac{Q_x}{A} \tag{5}$$

$$L_{t+1} = \sqrt{(\mathrm{x}'_{t+1} - \mathrm{x}'_t)^2 + (\mathrm{y}'_{t+1} - y'_t)^2} \tag{6}$$

In equations 3–6, Q_x is the integration of the x-axis; Q_y is the integration of the y-axis; the value of $(y_{i+1}–y_i)$ and $(x_{i+1}–x_i)$ represent the difference of two adjacent points on the y-axis and the x-axis, respectively; A is the polygon area; x' and y' are the centroid coordinates of the polygon; and L_{t+1} is the transfer distance of the centroid coordinates from time t to time t+1. The direction of East Lake's evolution can be measured by comparing the position of the centroid in different periods.

3 Results

3.1 Changes in the area of East Lake

The area of East Lake decreased by 3.13 km^2 from 1995 to 2015, accounting for 9% of its whole surface area. However, this downtrend improved during the period of 2005–2015. From 1995 to 2005, the area of East Lake decreased by 2.13 km^2, accounting for 6% of its entire area. Between 2005 and 2015, the area of East Lake still declined, but at a slower rate, with the area decreasing by 1 km^2 in total, accounting for 3% of the lake's whole surface area (Table 1). The most significant changes in the area of East Lake occurred in the north-

eastern and southern regions, while in the western region the area of the lake only decreased slightly. As can be seen from Figure 2, from 1995 to 2015, the area of the northeastern part of East Lake decreased and many small patches disappeared in the southern and western parts.

Table 1 Changes in the morphology of East Lake

Period	Area (km^2)	Perimeter (km)	Distance (km)
1995–2005	–2.13	–21.89	–0.58
2005–2015	–1	–0.67	–0.08
1995–2015	–3.13	–22.56	–0.66

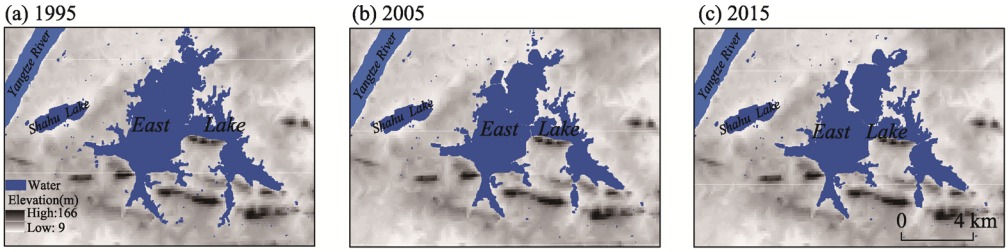

Figure 2 Changes in the area of East Lake in 1995, 2005, and 2015

3.2 Changes in the length of the shoreline

The length of East Lake's shoreline decreased between 1995 and 2015, which was consistent with the change in its area. It can be seen from Table 1 that East Lake's shoreline experienced a sharp to slight decreasing trend during the period of 1995–2015. Specifically, the length of East Lake's shoreline decreased by 21.89 km, which accounted for 13% of its whole length. However, the length of East Lake's shoreline declined by only 0.67 km between 2005 and 2015, which was much smaller than the decline during the period of 1995–2005, and constituted only 0.5% of the whole length of the shoreline. With regard to spatial variation, the shoreline of East Lake was smoother in 2015 than in the previous years investigated. The outline of East Lake became easier to observe over time and its boundary became smoother, with some lake branches disappearing, especially in the northeastern and southern regions (Figure 3). Compared to the period from 2005 to 2015, the decrease in the length of the shoreline was sharper between 1995 and 2005.

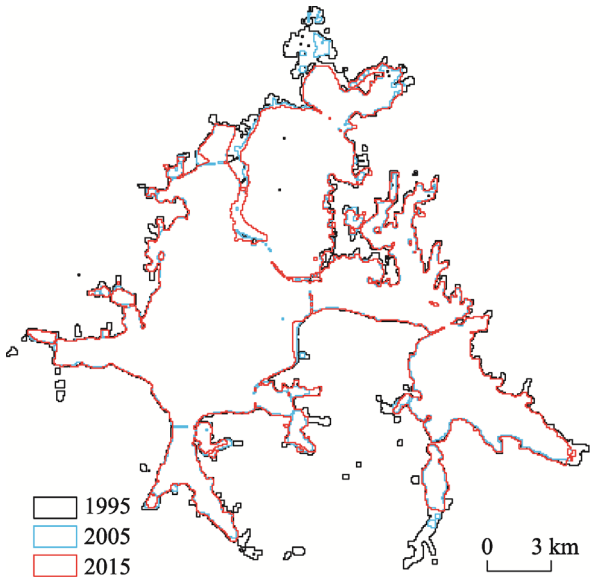

Figure 3 Changes in the shoreline of East Lake in 1995, 2005, and 2015

3.3 Changes in the landscape shape index

It can be seen from Table 1 that the sharp to slight decreasing trend of East Lake's area was consistent with that of its shoreline length. The LSI of East Lake also displayed the same

trend, with a declining trend during 2005–2015 that was much smaller than the decline during 1995–2005.

The LSI of East Lake declined from 7.04 in 1995 to 6.46 in 2005 and then to 6.38 in 2015. The LSI of East Lake decreased by 0.58 between 1995 and 2005, and then decreased by 0.08 from 2005 to 2015 (Figure 4). In general, the LSI changed significantly from 1995 to 2005 compared to the period of 2005 and 2015. This indicates that the shape of East Lake has been affected by human activities, with the dominant change occurring in the period between 1995 and 2005.

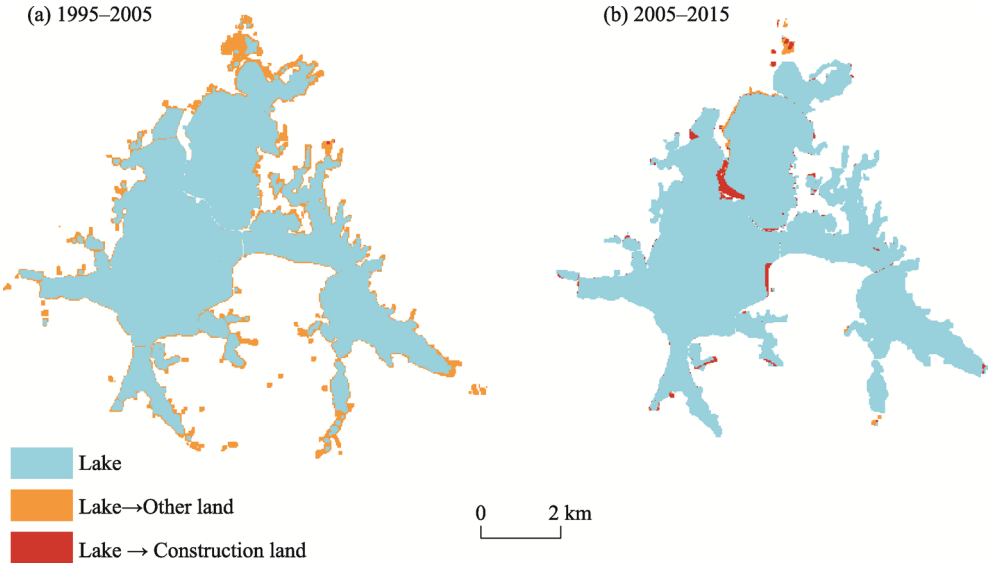

Figure 4 Land use changes around East Lake during 1995–2015

3.4 Changes in the lake centroid

There were obvious changes in East Lake's spatial heterogeneity, with the centroid shifting to the southeastern part of the lake from 1995 to 2015. The movement of the centroid reflects the dynamic changes of East Lake (Figure 5). During the period between 1995 and 2005, the centroid of East Lake shifted 131.69 m toward the northeast. From 2005 to 2015, the centroid moved 122.87 m toward the southeast. The direction and distance of movement in these two periods were almost the exact opposite. From 1995 to 2005, the direction of centroid movement was northeastern, indicating that the lake area recession occurred mainly in the southwest of East Lake. From 2005 to 2015, the centroid moved toward the southeast, indicating that the water body was affected by human activities in the northwestern part of the lake. The centroid transferred toward the southeast by 74.58 m during the period of 1995–2015. The area of the lake that disappeared in the northeast was much larger than that in the southeast, which was contrary to the direction of urban expansion in the two periods investigated.

In general, the centroid of East Lake moved in an inverted "V-shaped" pattern. In terms of its orientation, the inverted "V-shaped" pattern reflected that the spatial direction of Wuhan's urban development was consistent with the changes of the East Lake centroid. From the perspective of spatial balance, in the early stage of urban development, an unbalanced de-

velopment strategy is generally adopted, with a focus on the development of a certain region. Over time, the overall strength of the development increases and the principle of an overall balance is taken into account to ensure the spatial balance of development.

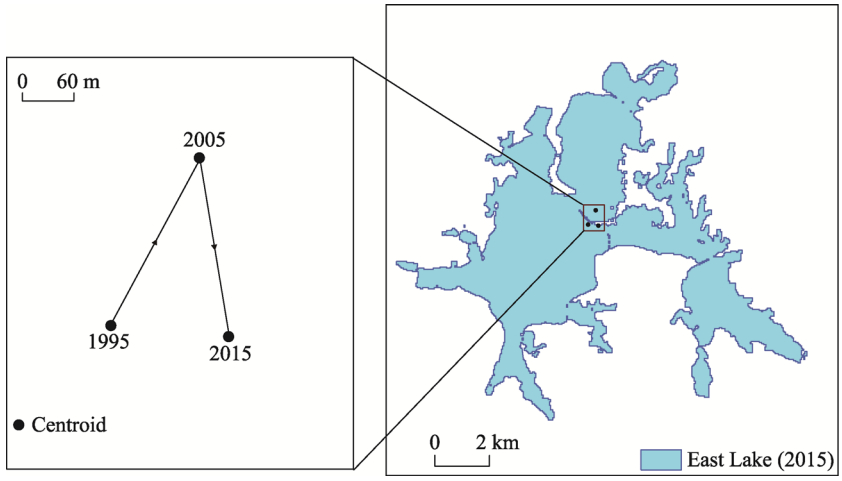

Figure 5 The direction and distance of movement of the centroid in East Lake during 1995–2015

4 Discussion

4.1 The relationship between centroid change and urban development

The centroid of East Lake first moved toward the northeast and then to the southeast. According to the image analysis, East Lake was on the outskirts of the urban built-up area in 1990, while the southern and western parts of East Lake were adjacent to downtown Wuhan. However, the western and southern parts of East Lake were the main areas of urban expansion between1995 and 2005, especially in the southwest. East Lake has been an urban lake since 1990. During this period, the southern and western parts of East Lake were filled-in to accommodate the East Lake high-tech development district (Figure 6). Thus, the centroid of East Lake transferred to the northeastern part of the lake.

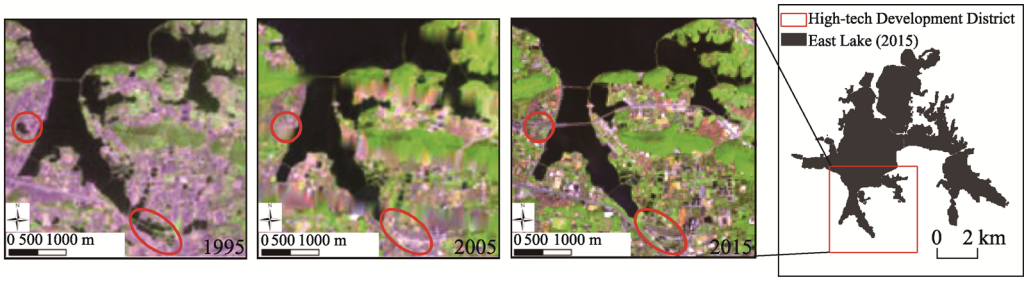

Figure 6 The development of East Lake high-tech development district caused the recession of the southern part of the water body of East Lake during 1995–2015

During 2005–2015, with the construction of Wuhan high-speed railway station in the northeast of East Lake (Figure 7), the urban development around East Lake transferred toward the northwest. The key projects were mainly located in the north of East Lake, includ-

ing Wuhan high-speed station and Wuhan Happy Valley theme park. East Lake became an urban lake with the development of the northern region. The northern part of East Lake used to be a major component of the whole water body and the wetland of East Lake. The decline of the East Lake water body affected the shape of East Lake and caused the centroid to shift to the southeastern part of the lake.

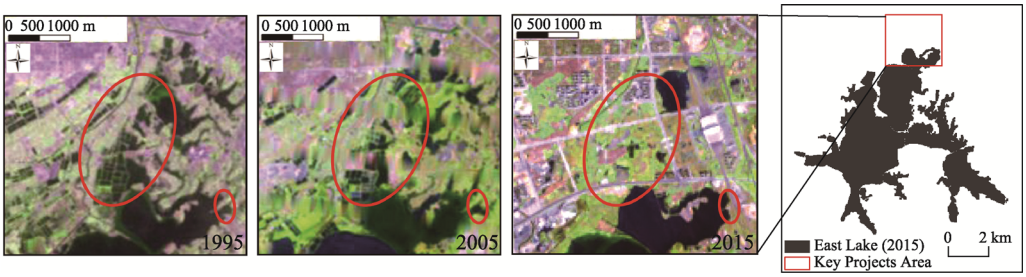

Figure 7 Wuhan high-speed railway station occupied a large part of the water body and the surrounding wetland in the northeastern region of East Lake during 1995–2015

Urban development began in Wuhan between 1995 and 2005. At this time the intensity of human activity was not very high. During 2005–2015, Wuhan experienced rapid economic growth and urban expansion, which had a great impact on the southeastern part of East Lake. Therefore, the shift of the centroid to the southeastern region in recent years was much greater than the shift toward the northeastern region during the earlier period, which was consistent with the rapid development of East Lake. However, there was an overall tendency for a shift toward the southeastern part of the lake over the whole study period. Similar to East Lake, Taihu Lake and Chaohu Lake (Ye *et al*., 2018), which are also located in the Yangtze River Economic Belt and have experienced rapid urbanization, have suffered from lake shape changes caused by urban development.

4.2 Analysis of the causes of the morphological evolution of East Lake

For thousands of years, Wuhan city has had a good reputation in terms of its urban water system. However, in recent decades, human activities have been impacting on the natural system due to urban development and expansion, resulting in the filling-in of the lake area, flow interruption, channelization, revetment hardening, and destruction of the wetland system. Most researchers believe that there are four main factors affecting the morphology of urban lakes in Wuhan, especially East Lake: infrastructure construction, the growth in urban housing, development of scenic spots for tourism, and illegal building construction (Zhong, 2008; Wu, 2010; Pei *et al*., 2018).

4.2.1 Infrastructure construction

In recent years, urbanization in Wuhan has occurred with a remarkable pace of development. The built-up area increased from 234.23 km^2 in 1995 to 566.13 km^2 in 2015. The urbanization process in Wuhan developed steadily from 1995 to 2005, with the characteristics of an outward expansion in urban construction (Wang, 2009). The built-up area and GDP growth of Wuhan has presented a steady growth trend (Figure 8). The period from 2005 to 2015 was characterized by rapid urbanization. The investment in and construction of urban infrastruc-

ture has been the main driving force promoting urban development and stimulating economic growth. Therefore, infrastructure construction has been one of the most important activities in Wuhan in recent years. Infrastructure includes public buildings and transport facilities. Many public facilities have been established around East Lake in recent years (Figure 9), such as Liyuan Hospital, East Lake Hospital, Wuhan University, Huazhong University of Science and Technology, Hubei Provincial Museum, and Hubei Provincial Museum of Art. Several transport facilities were completed around East Lake, such as Wuhan Railway Station, the third public transport circulation line, and a high-speed railway. The completion of these infrastructure projects has had a major impact on the morphological evolution of East Lake through the filling-in of the water area, which was easy to exploit for development. In recent decades, the whole Yangtze River Economic Belt has been undergoing rapid urbanization, which has been accompanied by infrastructure construction. The construction around East Lake is typical of this phenomenon.

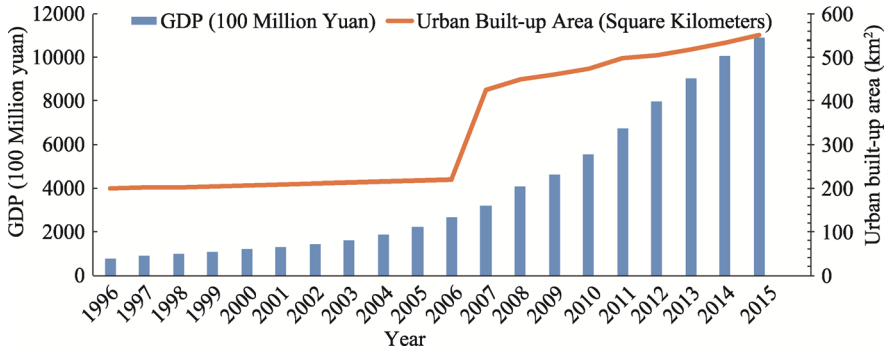

Figure 8 Changes in the GDP and built-up area of Wuhan during 1995–2015

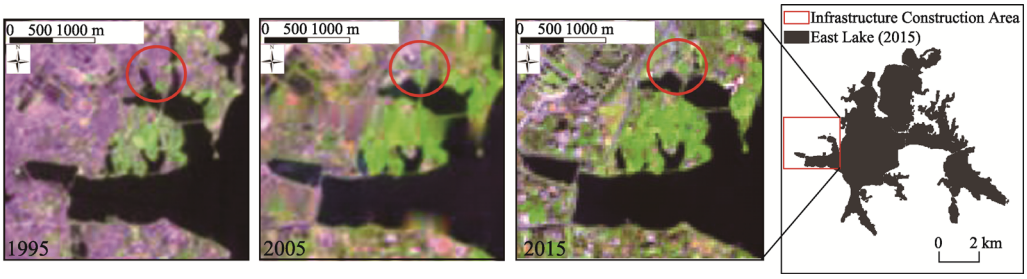

Figure 9 In the western part of East Lake, the water body was occupied mainly by Hubei Provincial Museum and Hubei Provincial Museum of Art during 1995–2015

4.2.2 Development of urban housing

The surrounding natural features, such as lakes and mountains, have always been the focus of real estate development due to their attractive environment. As an area where lakes are concentrated, the Yangtze River Basin has attracted the attention of developers. As the most typical urban lake in the Yangtze River Economic Belt, the real estate development activities around the lake in the past decade have been very intense (Figure 10). The demand of urban residents for housing has increased with the rapid urbanization of Wuhan. At the same time, the central government has also provided support for the development of the real estate in-

dustry. Reform and commercialization of the housing system occurred after a housing reform issued by the State Council in 1994. Since then, the supply of urban housing increased as the market transformed. On August 12, 2003, the State Council formally issued the "Notice of the State Council on Promoting the Sustainable and Healthy Development of the Real Estate Market" (http://www.gov.cn/zhengce/content/2008-03/28/content_4797.htm), making it clear that the real estate industry had become a pillar industry of the national economy for the first time. Wuhan, as the most populous city in central China, has experienced rapid development of its real estate industry. Since the beginning of 2004, the total investment in the real estate industry of Wuhan was 16.95 billion yuan, representing an increase of 27.92% compared with the previous year. The capital invested in the tangible land market was 5.89 billion yuan, and the actual transaction amount was 4.04 billion yuan, an increase of 137% compared with the previous year. Because it contained the most beautiful natural scenery in Wuhan, the East Lake area became the key location for the development of the real estate industry. The Wuhan company, Overseas Chinese Town (OCT), built a large residential district on the waterfront that occupied the surrounding wetland and lake area of East Lake. The shoreline became structured during the process of housing construction.

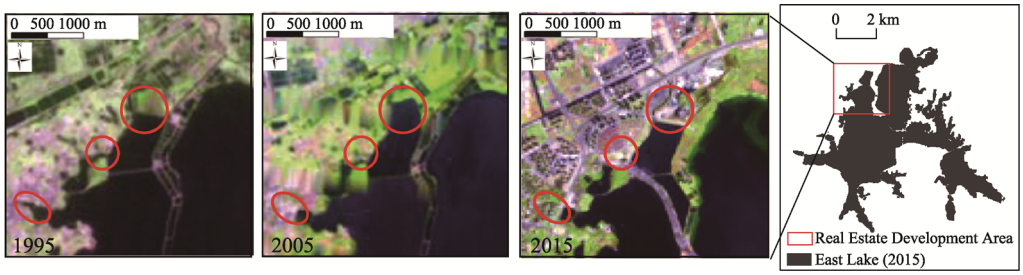

Figure 10 Real estate industry development encroached onto the surrounding wetland and lake area of East Lake during 1995–2015

4.2.3 Development of scenic spots for tourism

East Lake is a national 5A scenic area, and is the most important tourist location in Wuhan due to the scenic views of East Lake and its wetland resources. The exploitation of East Lake for tourism started in the 1950s with the formation of six sightseeing districts with distinctive features: Tingtao, Moshan, Luohong, Luoyan, Chuidi, and Baima scenic spots. Tingtao and Moshan scenic areas were the first East Lake tourism developments. Luoyan, Chuidi, and Baima scenic areas were developed from the 1990s, which was the time that East Lake began experiencing morphological changes (Figure 11). The development of the East Lake scenic areas was in accordance with the urbanization of Wuhan, which was also consistent with the morphological changes of the lake. The spatial distribution of tourism development showed a development sequence of Tingtao, Moshan, Luoyan, Chuidi, and Baima scenic areas. In recent years, the state and residents have paid increasing attention to the improvement of the urban environment, and natural features such as lakes have naturally become highlights of tourist parks. The inevitable urban transformation that occurs during this process will also have an impact on the lake, and is a common phenomenon in the cities of the Yangtze River Economic Belt.

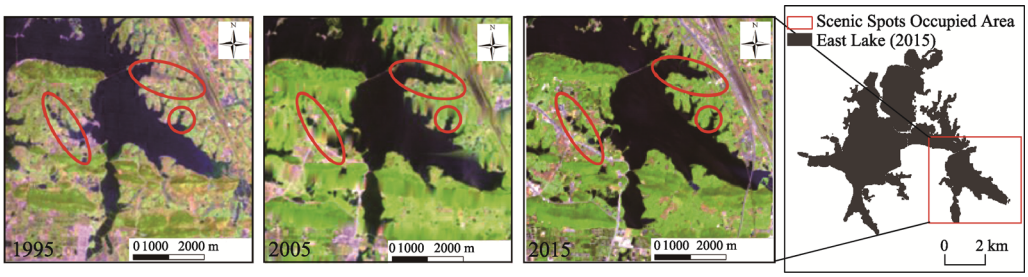

Figure 11 Development of scenic spots in the water body of East Lake during 1995–2015

4.2.4 Illegal construction

Alongside the formal developments undertaken by large real estate companies, the illegal occupation of land by small enterprises and individuals is also an important factor affecting the evolution of the lake. Demands for economic benefits and an improved living environment are prevalent in cities throughout the Yangtze River Economic Belt, and have become important driving factors affecting changes in natural features, such as lakes and mountains. The impact of human activity on the morphological evolution of East Lake is recognizable both in the short-term and at large-scales. The influence of illegal construction and development is subtle and occurs over the long-term. The East Lake area is a national 5A scenic area. Therefore, a variety of tourism-related industries have been established to promote the industry, such as hotels and small attractions. Furthermore, many villages were distributed in the East Lake area. The value of land continually increased with the urban expansion and development of East Lake scenic areas. The villagers discretely built a large number of illegal buildings (Figure 12), and thus the area of East Lake became smaller.

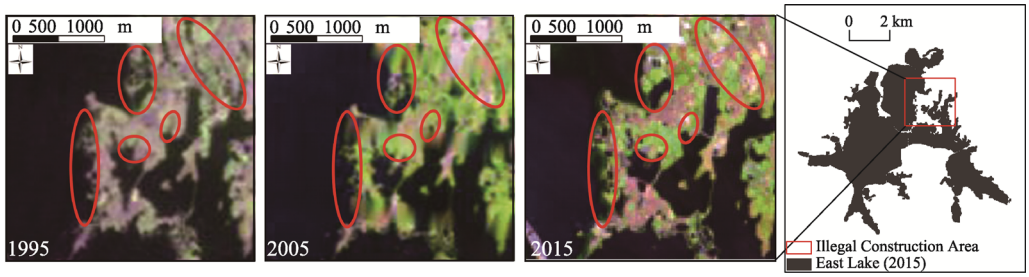

Figure 12 Illegal construction reduced the area of East Lake during 1995–2015

4.3 The mechanisms controlling the morphological changes of East Lake

The main driving forces of the morphological changes of East Lake were human activities along the lake, including infrastructure construction, real estate development, illegal construction, and the development of scenic sites for tourism. The reason for the importance of these driving forces is the demand for significant amounts of land with the rapid increase of population, economic development, and urbanization of Wuhan city during 1995–2015. Population, GDP, and urbanization rate data obtained from the Wuhan city yearbooks during 1996 to 2016 (http://www.stats-hb.gov.cn/tjbs/fztjbs/112085.htm) were subject to a regression analysis to indicate the development tendency of Wuhan in recent years. Figures 11–13 show that all the three factors fitted a linear regression well, and there was an exponential

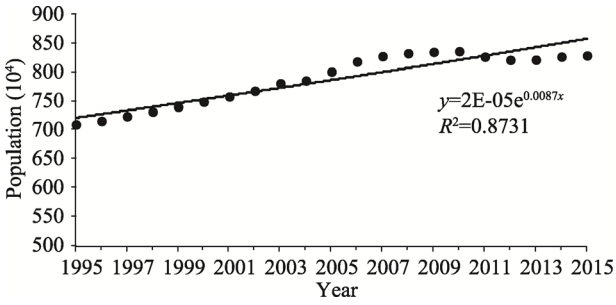

Figure 13 Exponential increase in the population of Wuhan city during 1995–2015

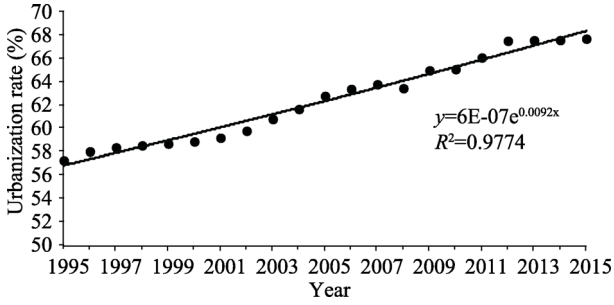

Figure 14 Exponential increase in the urbanization rate of Wuhan city during 1995–2015

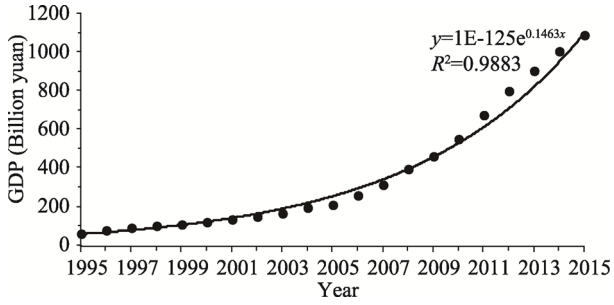

Figure 15 Exponential increase of the GDP of Wuhan city during 1995–2015

increase in the influence of these factors, especially GDP, over the period studied. Thus, land is urgently needed to support these developments. As a large lake surrounded by an urban area, East Lake's water surface is prone to be filled-in for development, leading to changes in the morphology of the lake over time.

There was a steady and rapid increase in the urban population of Wuhan from 1995 to 2015 (Figure 13). The growth of the city resulted in a large number of rural migrants entering the urban area, with some of them settling in the urban village area, resulting in a large population growth. The increase in the urban population generated enormous pressure on the urban infrastructure and the increase of the urban village population also promoted the continuous increase of illegal construction.

During the research period, the urbanization rate of Wuhan tended to be consistent with the changing trend of its urban population, and the annual growth of the urbanization rate was slightly higher than the annual growth rate of the population (Figure 14). Urbanization will inevitably result in urban infrastructure construction, real estate development, and the development of urban scenic sites.

Wuhan's GDP displayed an exponential growth trend between 1995 and 2015 (Figure 15). During the decade from 2005 to 2015, the investment in and construction of urban infrastructure were the main driving forces for urban development and economic growth. During this period, a large number of lakes in Wuhan were filled-in and urban construction was carried out.

The mechanism by which lake morphology evolves is a comprehensive system composed of elements of the human and social environment. The logical relationships among these driving forces are shown in Figure 16. Furthermore, the filling-in of urban lakes is closely related to the remarkable social and economic changes that have occurred in China. Since 1978, the implementation of the reform and opening-up policy has brought a market revolu-

tion to the national economy. As a land-use type, the price of urban lakes is cheap and the lands are rapidly developed by the market and capital driven by policies and interests. On the other hand, the ecological landscape resources around the urban lakes are very precious and scarce, which lead to the real estate developers and scenic area developers competing for the land resources around the urban lakes. Meanwhile, in the context of rapid urbanization, a large number of people have poured into large cities, and urban lakes have become areas of large-scale infrastructure construction, urban space building and low-cost illegal construction. Under the dual background of market economics and rapid urbanization, infrastructure construction, real estate development, the development of scenic areas for tourism, and illegal construction have become the main driving factors of urban lake environmental changes. East Lake is one of the most famous urban lakes in the whole Yangtze River Economic Belt. The summary of the mechanism by which its morphology has evolved can also be extended to other lake environments in the whole Yangtze River Economic Belt.

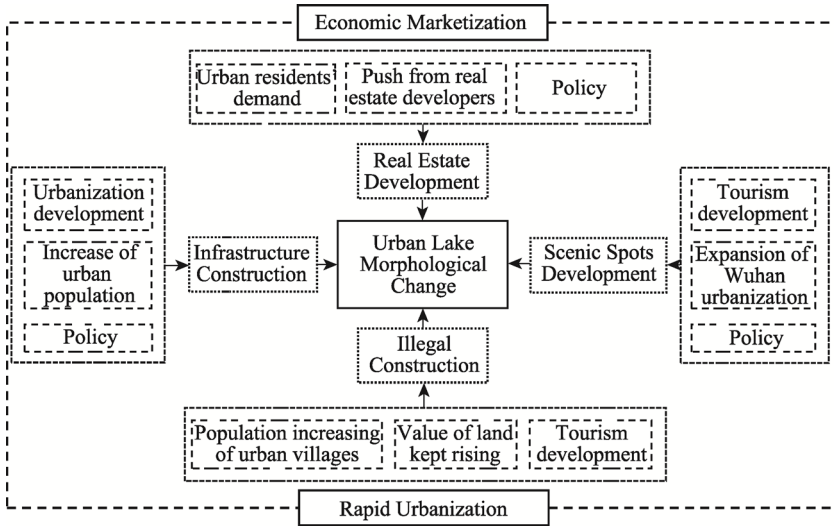

Figure 16 Formation mechanism model to explain the changes of urban lakes

5 Conclusions

Currently, under the guidance of the "Yangtze River Protection" principle in the Yangtze River Economic Belt Development Plan Outline, Wuhan has transformed its development strategy to treat the management of the city river valley environment as the dominant issue. In addition, as one of the most important cities in the Yangtze River Valley, the government of Wuhan has focused on developing the Yangtze River Economic Belt into a green ecological development zone and enhancing the comprehensive management of the river basin environment. Remote sensing and GIS were used to analyze the changes and landscape characteristics of East Lake in Wuhan from 1995 to 2015. The aim was to explore the changes of urban lake characteristics under the background of urbanization and to provide a reference for regional research and urban and scenic area planning and management.

(1) In the past 20 years, the water body of East Lake has experienced dramatic changes. The lake surface area and the shoreline length have continuously decreased. The annual shrinkage

rate accelerated in the period between 1995 and 2005 compared with previous decades.

(2) The LSI values were 7.04 (1995), 6.46 (2005), and 6.38 (2015), indicating an acceleration in the declining trend as the shape complexity of the water body was decreasing and human intervention was intensifying. The main drivers of the changes in the water body were infrastructure construction, urban housing development, illegal construction, and the development of scenic areas for tourism.

(3) The centroid of East Lake moved to the northeast and then to the southeast during the period studied. This indicates that urban expansion affected the west and south of East Lake during 1995–2005, and then affected the northwest of the lake from 2005 to 2015. The trend was in accordance with the urban development of Wuhan city.

(4) The morphological evolution of East Lake was mainly affected by human activities. The effect of organized and large-scale urban development has been dramatic. However, the impact of small illegal constructions encroaching on the water body of East Lake should be given more attention regarding their complexity and continuity.

(5) This study investigated the changes and landscape evolution of East Lake during 1995–2015 in a rapidly urbanizing area of central China, using multi-temporal Landsat TM and ETM+images. As the largest and the most typical urban lake among the many lakes in the Yangtze River Economic Belt, East Lake has been greatly influenced by the development of Wuhan city and even the development of the Yangtze River Economic Belt. It is a good example of the changes in lakes in the Yangtze River Basin under the influence of urbanization in the Yangtze River Economic Belt. The research methods adopted in this study can be used to further investigate other lakes affected by urbanization in the Yangtze River Basin.

References

Chen K L, Wang X, Li D *et al*., 2015. Driving force of the morphological change of the urban lake ecosystem: A case study of Wuhan, 1990–2013. *Ecological Modelling*, 318: 204–209.

Chi Y, Zheng W, Shi H H *et al*., 2018. Spatial heterogeneity of estuarine wetland ecosystem health influenced by complex natural and anthropogenic factors. *Science of the Total Environment*, 634: 1445–1462.

Cuffney T F, Brightbill R A, May J T *et al*., 2010. Responses of benthic macroinvertebrates to environmental changes associated with urbanization in nine metropolitan areas. *Ecological Applications*, 20(5): 1384–1401.

Cui L J, Gao C J, Zhao X S *et al*., 2013. Dynamics of the lakes in the middle and lower reaches of the Yangtze River Basin, China, since late nineteenth century. *Environmental Monitoring and Assessment*, 185(5): 4005–4018.

Dai X, Yang G S, Wan R R *et al*., 2018. The effect of the Changjiang River on water regimes of its tributary Lake East Dongting. *Journal of Geographical Sciences*, 28(8): 1072–1084.

Dai X, Wan R R, Yang GS, 2015. Non-stationary water-level fluctuation in China's Poyang Lake and its interactions with Yangtze River. *Journal of Geographical Sciences*, 25(3): 274–288.

Deng Y, Jiang W G, Tang Z H *et al*., 2017. Spatio-temporal change of lake water extent in Wuhan urban agglomeration based on Landsat images from 1987 to 2015. *Remote Sensing*, 9(3): 270.

Ding L, Chen K L, Cheng S G *et al*., 2015. Water ecological carrying capacity of urban lakes in the context of rapid urbanization: A case study of East Lake in Wuhan. *Physics and Chemistry of the Earth*, *Parts A/B/C*, 89: 104–113.

Du N R, Ottens H, Sliuzas R, 2010. Spatial impact of urban expansion on surface water bodies: A case study of Wuhan, China. *Landscape and Urban Planning*, 94(3): 175–185.

Han L F, Xu Y P, Yang L *et al*., 2015. Temporal and spatial change of stream structure in Yangtze River Delta and its driving forces during 1960s–2010s. *Acta Geographica Sinica*, 70(5): 819–827. (in Chinese)

Huang W D, Liao J J, Shen G Z, 2012. Lake change in past 40 years in the southern Nagqu District of Tibet and

analysis of its driving forces. *Remote Sensing for Land and Resources*, 24(3): 122–128. (in Chinese)

Ji P, Guo H D, Zhang L, 2013. Remote sensing study of glacier dynamic change in West Kunlun Mountains in the past 20 years. *Remote Sensing for Land and Resources*, 25(1): 93–98. (in Chinese)

Jiang C, Pan S Q, Chen S L, 2017. Recent morphological changes of the Yellow River (Huanghe) submerged delta: Causes and environmental implications. *Geomorphology*, 293: 93–107.

Jiang Q H, Liu Y F, Huang P J, 2013. The source-sink effect between urban diffuse pollution and Lake watershed: A case study in East Lake of Wuhan. *Ecology and Environmental Sciences*, 22(3): 469–474. (in Chinese)

Jiang W G, Pan Y Z, Hou P *et al*., 2009. Assessment and analysis of wetland ecosystem health in Dongting Lake. *Geographical Research*, 28(6): 1665–1671.

Jin G, Chen K, Wang P *et al*., 2019. Trade-offs in land-use competition and sustainable land development in the North China Plain. *Technological Forecasting and Social Change*, 141: 36–46.

Jin G, Deng X Z, Chu X *et al*., 2017. Optimization of land-use management for ecosystem service improvement: A review. *Physics and Chemistry of the Earth, Parts A/B/C*, 101: 70–77.

Jin G, Deng X Z, Zhao X D *et al*., 2018. Spatiotemporal patterns in urbanization efficiency within the Yangtze River Economic Belt between 2005 and 2014. *Journal of Geographical Sciences*, 28(8): 1113–1126.

Jin G, Li Z H, Deng X Z *et al*., 2019. An analysis of spatiotemporal patterns in Chinese agricultural productivity between 2004 and 2014. *Ecological Indicators*, 105: 591–600.

Kearns F R, Kelly N M, Carter J L *et al*., 2005. A method for the use of landscape metrics in freshwater research and management. *Landscape Ecology*, 20(1): 113–125.

Kong F H, Nakagoshi N, 2006. Spatial-temporal gradient analysis of urban green spaces in Jinan, China. *Landscape and Urban Planning*, 78(3): 147–164.

Li G D, Sun S A, Fang C L, 2018. The varying driving forces of urban expansion in China: Insights from a spatial-temporal analysis. *Landscape and Urban Planning*, 174: 63–77.

Li H B, Yu S, Li G L *et al*., 2013. Spatial distribution and historical records of mercury sedimentation in urban lakes under urbanization impacts. *Science of the Total Environment*, 445: 117–125.

Li N, Yang L, Deng X W *et al*., 2018. Aquatic plant diversity in relation to lake morphology in the middle and lower reaches of the Yangtze River. *Plant Science Journal*, 36(1): 65–72. (in Chinese)

Li S C, Bing Z L, Jin G, 2019. Spatially explicit mapping of soil conservation service in monetary units due to land use/cover change for the Three Gorges Reservoir Area, China. *Remote Sensing*, 11(4): 468.

Malavasi M, Carboni M, Cutini M *et al*., 2014. Landscape fragmentation, land-use legacy and propagule pressure promote plant invasion on coastal dunes: A patch-based approach. *Landscape Ecology*, 29: 1541–1550.

McFeeters S K, 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7): 1425–1432.

Niu Y, Jiao W, Yu H *et al*., 2015. Spatial evaluation of heavy metals concentrations in the surface sediment of Taihu Lake. *International Journal of Environmental Research and Public Health*, 12(12): 15028–15039.

Ouma Y O, Tateishi R, 2006. A water index for rapid mapping of shoreline changes of five East African Rift Valley lakes: An empirical analysis using Landsat TM and ETM+ data. *International Journal of Remote Sensing*, 27(15): 3153–3181.

Pei L Z, Yan D P, Zhang H X *et al*., 2018. Research on evolution characteristics and causes of urban lakes in Wuhan from 1960s. *Geology and Mineral Resources of South China*, 34(1): 78–86. (in Chinese)

Peters J A, Cooper M J, Creque S M *et al*., 2014. Historical changes and current status of crayfish diversity and distribution in the Laurentian Great Lakes. *Journal of Great Lakes Research*, 40(1): 35–46.

Qian D W, Gong J, Gao Y J, 2015. Spatial-temporal difference and landscape pattern evolution of desertification in the middle reaches of the Heihe River: A case study of Linze County in Gansu. *Journal of Arid Land Resources and Environment*, 29(4): 85–90. (in Chinese)

Sahana M, Hong H Y, Sajjad H, 2018. Analyzing urban spatial patterns and trend of urban growth using urban sprawl matrix: A study on Kolkata urban agglomeration, India. *Science of the Total Environment*, 628/629: 1557–1566.

Shaikh Y H, Phathan J M, Maqdoom F *et al*., 2010. Application of fractal geometry to lakes. *Archives of Physics Research*, 1(2): 147–170.

Tang Z W, Cheng J L, Yue Y, 2009. Accumulations and risks of heavy metals in the sediments from 8 typical lakes in Wuhan, China. *Journal of Lake Sciences*, 21(1): 61–68. (in Chinese)

Tsai W L, McHale M R, Jennings V *et al*., 2018. Relationships between characteristics of urban green land cover and mental health in U.S. metropolitan areas. *International Journal of Environmental Research and Public Health*, 15(2): 340.

Wang L, Liu H, 2019. Comprehensive evaluation of regional resources and environmental carrying capacity using a PS-DR-DP theoretical model. *Journal of Geographical Sciences*, 29(3): 363–376.

Wang W G, 2009. Thoughts on the urbanization transformation of Wuhan. *Yangtze Tribune*, (4): 33–35. (in Chinese)

Wang X L, Ning L M, Yu J, 2008. Changes of urban wetland landscape pattern and impacts of urbanization on wetland in Wuhan city. *Chinese Geographical Science*, 18(1): 47–53.

Wu J, 2010. An empirical study of Wuhan lakefront landscape change [D]. Wuhan: Huazhong University of Science and Technology. (in Chinese)

Wu J, Xie H, 2011. Research on characteristics of changes of lakes in Wuhan's main urban area. *Procedia Engineering*, 21: 395–404.

Wu Y H, Zhang X, Zheng H X *et al*., 2017. Investigating changes in lake systems in the south-central Tibetan Plateau with multi-source remote sensing. *Journal of Geographical Sciences*, 27(3): 337–347.

Xu K, Kong C F, Liu G *et al*., 2010. Changes of urban wetlands in Wuhan, China, from 1987 to 2005. *Progress in Physical Geography*: *Earth and Environment*, 34(2): 207–220.

Yang B H, Ke X L, 2015. Analysis on urban lake change during rapid urbanization using a synergistic approach: A case study of Wuhan, China. *Physics and Chemistry of the Earth, Parts A/B/C*, 89: 127–135.

Yang Z F, Tang Z W, Shen Z Y *et al*., 2011. One-hundred-year sedimentary record of polycyclic aromatic hydrocarbons in urban lake sediments from Wuhan, Central China. *Water, Air, and Soil Pollution*, 217(1–4): 577–587.

Ye G B, Su W Z, Sun X X, 2018. Simulation of the built-up land expansion based on the Dyna-CLUE Model in Taihu Basin. *Resources and Environment in the Yangtze Basin*, 27(4): 725–734. (in Chinese)

Zeng G, Gao H J, Zhu G, 2013. Analysis of wetlands evolution process between Tarim Basin and Junggar Basin in the past 32 years. *Remote Sensing for Land and Resources*, 25(3): 118–123. (in Chinese)

Zeng H A, Wu J L, 2013. Heavy metal pollution of lakes along the mid-lower reaches of the Yangtze River in China: Intensity, sources and spatial patterns. *International Journal of Environmental Research and Public Health*, 10(3): 793–807.

Zhang L Q, Wang H Z, 2006. Planning an ecological network of Xiamen Island (China) using landscape metrics and network analysis. *Landscape and Urban Planning*, 78(4): 449–456.

Zhang X P, Gong Z Z, 2018. Spatiotemporal characteristics of urban air quality in China and geographic detection of their determinants. *Journal of Geographical Sciences*, 28(5): 563–578.

Zhong L, 2008. The study on waterfront landscape of urban lake sceneries: Taking Wuhan East Lake as an example [D]. Beijing: Central Academy of Fine Arts. (in Chinese)

Zhou M, Zhang F, Wang J *et al*., 2017. Effect of landscape pattern scale in the Ebinur Lake watershed, Xinjiang. *Arid Zone Research*, 34(5): 1184–1195. (in Chinese)

Zou Z H, Dong J W, Menarguez M A *et al*., 2017. Continued decrease of open surface water body area in Oklahoma during 1984–2015. *Science of the Total Environment*, 595: 451–460.