Chin. Geogra. Sci. 2012 Vol. 22 No. 6 pp. 673–682
doi: 10.1007/s11769-012-0570-9
www.springerlink.com/content/1002-0063

Relationship Between Changes of River-lake Networks and Water Levels in Typical Regions of Taihu Lake Basin, China

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Abstract: The typical regions of the Taihu Lake Basin, China, were selected to analyze the variation characteristics of river-lake networks under intensive human activities. The characteristics of the fractal dimension of river networks and lakes for different periods were investigated and the influences of river system evolution on water level changes were further explored through the comparison of their fractal characters. The results are as follows: 1) River network development of the study area is becoming more monotonous and more simple; the number of lakes is reducing significantly, and the water surface ratio has dropped significantly since the 1980s. 2) The box dimension of the river networks in all the cities of the study area decreased slowly from the 1960s to the 1980s, while the decrease was significant from the 1980s to the 2000s. The variations of lake correlation dimension are similar to those of the river network box dimensions. This is unfavorable for the storage capacity of the river networks and lakes. 3) The Hurst exponents of water levels were all between 0.5 and 1.0 from the 1960s to the 1980s, while decreased in the 2000s, indicating the decline in persistence and increase in the complexity of water level series. The paper draws a conclusion that the relationship between the fractal dimension of river-lake networks and the Hurst exponents of the water level series can reveal the impacts of river system changes on flood disasters to some extent: the disappearance of river networks and lakes will increase the possibility of flood occurrence.

Keywords: river network; lake; water level changes; fractal; Taihu Lake Basin

Citation: Yin Yixing, Xu Youpeng, Chen Ying, 2012. Relationship between changes of river-lake networks and water levels in typical regions of Taihu Lake Basin, China. *Chinese Geographical Science*, 22(6): 673–682. doi: 10.1007/s11769-012-0570-9

1 Introduction

The Taihu Lake Basin is one of the most developed regions with the fastest urbanization rate and plays an important role in China. With the intensified human activities and the rapid development of urbanization, the impacts of human activities on river networks and hydrological processes are very prominent. A large number of rivers and lakes have disappeared, and the storage function of river networks has declined. There were about 300 river channels around the Taihu Lake in the early 20th century, and there were only 125 left according to the field survey in 1993, with 92 river channels into lakes and 33 out of lakes. There were only 13 effective discharge channels, and most of the original river networks around the influent-effluent lakes were blocked (Huang, 1993). Flood regulation and storage function of the river networks is very important in the

Received date: 2011-10-20; accepted date: 2012-04-18

Foundation item: Under the auspices of Special Fund for Scientific Research in the Public Interest, granted by Ministry of Water Resources (No. 2012010072, 200701024), Key Program of National Natural Science Foundation of China (No. 40730635), Open Foundation of State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (No. 2011491111), Research Foundation of Nanjing University of Information Science and Technology (No. 20100406), a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD)

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Taihu Lake Basin. Calculations showed that the regulation and storage capacity of the river networks is about 50% of that of Taihu Lake, and the total regulation and storage capacity of the river networks together with those of many other lakes will equal the storage capacity of Taihu Lake (Wang *et al*., 1999). However, from 1954 to 1980, the whole surface area of flood storage in the basin decreased by 650 km^2, equivalent to 1/4 of the Taihu Lake, and this led to the decrease of storage function, also intensified the flood disasters in the 1990s.

Fractal theory has been widely used in hydrology since it was established, and it has become one of the most important research methods in hydrology. There are lots of researches on fractal theory in hydrology at home and abroad, including the fractal research on river networks and hydrological time series. On the one hand, current fractal research on drainage networks is mainly carried out in natural river networks (Feng and Feng, 1997; Chen and Liu, 2001; Zhu and Cai, 2003), while few researches have been carried out on the river structure and fractal characteristics in drainage basins with a large number of artificial river channels such as the Taihu Lake Basin (Yuan *et al*., 2005a; 2005b; Yang, 2006; Yuan *et al*., 2006). Su and Yang (2008) studied the scale-free structure of the Nanhe drainage of the Taihu Lake Basin, and found that the power law of the drainage structure showed the differences of human disturbance. On the other hand, many researches are about the fractal dimension of different characteristics of domestic and foreign river systems, while the research on the evolution characteristics of fractal characteristics of the same river system during different periods are relatively rare. In addition, the fractal research on morphology of river systems and hydrological time series is often carried out separately at present, and few studies focus on the relationship between them. In China, Yang and Zhu (2002) explored the relationship between the fractal dimension of the flood time series and river systems of China's major river basins; Ma *et al*. (2009) investigated the relationship between the characteristics of river systems and the complexity of runoff series by using fractal dimension to describe the characteristics of river system and using the Hurst exponent to describe the runoff complexity. Similar studies in foreign countries have rarely been reported. Therefore, further research is needed to explore the relationship between the morphology and structure of river networks and hydrological time series based on fractal theory.

In this paper, the typical regions of the Taihu Lake Basin are selected as the study area. Firstly, the paper analyzes the evolution of river network characteristics by extracting digital river maps of the three periods of the 1960s, 1980s and 2000s. Secondly, it explores the fractal characteristics of the river networks and lakes under the influence of intensive human activities based on fractal theory. Thirdly, it attempts to reveal the linkage mechanism between the changes of river-lake networks and water level process in the Taihu Lake Basin through the comparison of their fractal characteristics.

2 Materials and Methods

2.1 Materials

Taihu Lake Basin (30°05′–32°08′N, 119°08′–121°55′E) is one of the most economically developed and densely populated areas in China (Fig. 1). The most typical plain river network regions of the Taihu Lake Basin, three of the eight hydraulic divisions of the basin, i.e., Wuchengxiyu Region, Yangchengdianmao Region and Taihu Region, were selected to analyze the variation characteristics of river networks. The data source for extraction of river networks are the 1∶50 000 topographic maps in the 1960s and 1980s, and 1∶50 000 digital maps in the 2000s. The river network maps of different periods were obtained through the manual screen digitalization of historic topographic maps (1960s and 1980s), and the element extraction of recent digital maps (2000s). The results of river network extraction include two parts: one is linear features, and the other is area features, indicating the changes of drainage density and water surface ratios. And the river network maps of the 1960s, 1980s and 2000s were eventually obtained, reflecting the river network characteristics of different periods. The lakes and double-line rivers were considered as area features, and the rest as linear features when they were processed in ArcMap. Upon the completion of the single digital topographic map and the extraction of features, all the river network maps in the study area were joined together according to their sheet numbers and the overall river network maps of the three periods would be obtained.

The study area includes nine cities (Changzhou, Wuxi, Jiangyin, Zhangjiagang, Kunshan, Suzhou, Taicang, Wujiang, and Changshu), and the river-lake network characteristics of each city were explored respectively (There is a small area belonging to Shanghai City, but we do not consider this area here). Nine representative water level gauging stations within each city were also selected to analyze water level changes (There is no gauging station available in Zhangjiagang City, and Chenshu station is used instead). The locations of the study area, nine cities and representative water level stations are shown in Fig. 1. The selected gauging stations are representative of the control points of major rivers and lakes, and constitute the main river network nodes. What is more, the data series are quite long (Most of the stations have monthly water level series from 1954 to 2006, but the series of Chenmu station are from 1962 to 2006, and the series of Zhitang station are from 1976 to 2006), and have a stable relationship with the surrounding water level stations.

2.2 Methods

2.2.1 Indicators of river network changes

Some indicators that can characterize the structure of river networks, such as drainage density, water surface ratio, average length ratio, complexity and structure stability of the river networks were selected to describe the main features of river network evolution in the study area. Complexity of river network (*CR*) was used to de-

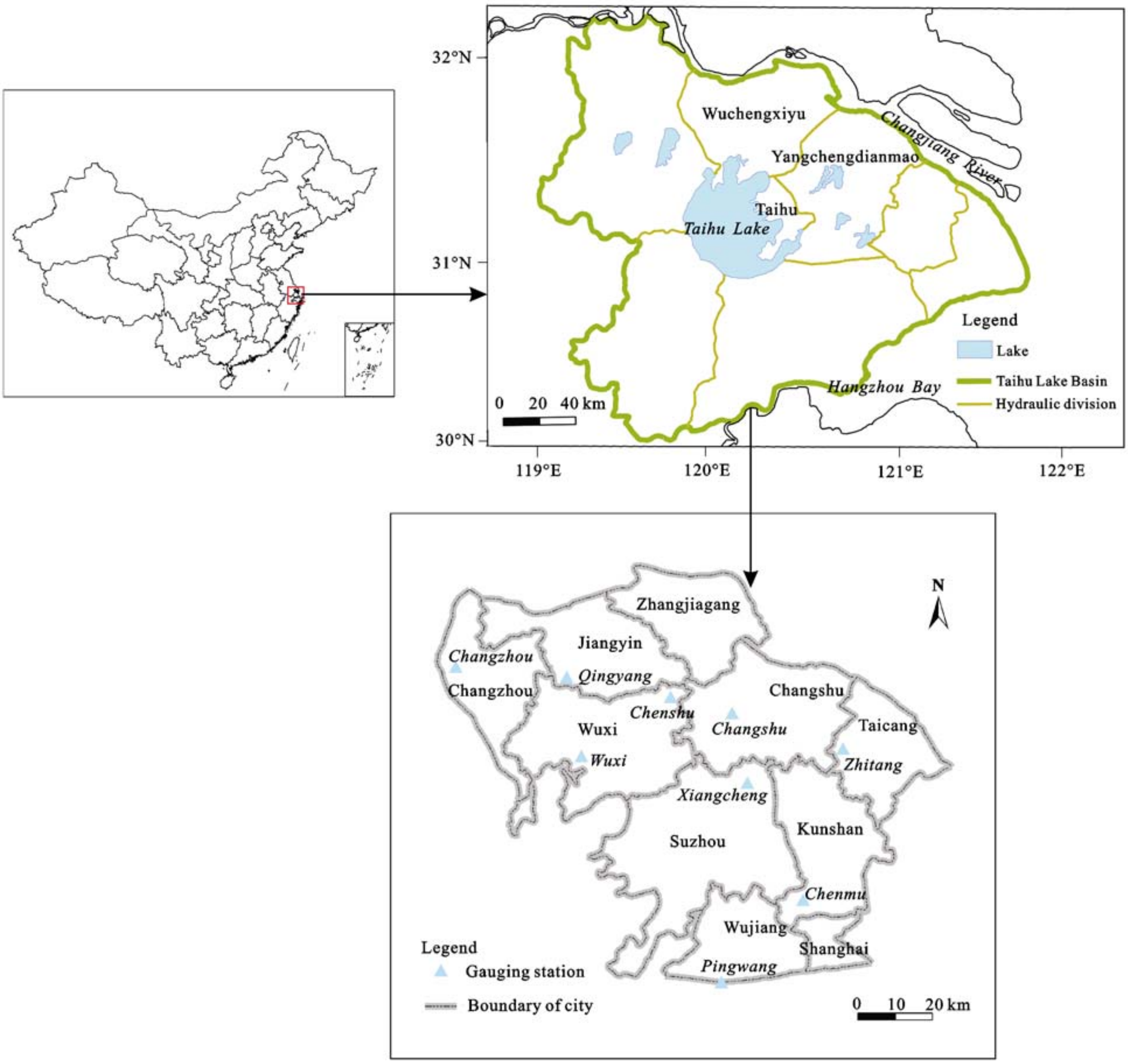

Fig. 1 Location of study area and water level gauging stations

scribe the development degree of river number and length, and it is the combination of branching ratio and length ratio. The greater the value is, the richer the composition levels of the river networks are, and the more developed the tributaries to support the trunks of the rivers are. Structure stability of river network (*SR*) is the ratio of river network length to the area of river channel. Since the non-synchronous evolution of river length and area is a direct result of changing river network structure, this indicator can be used to calculate the structure stability of river network during different periods (Yuan *et al*., 2006). Complexity and structure stability of the river network are calculated as follows (Yuan *et al*., 2005b):

$$CR = N_c \times (L / L_m) \tag{1}$$

$$SR = (L_{i+n} / RA_{i+n}) / (L_i / RA_i) \tag{2}$$

where N_c stands for the stream order; L and L_m are the total length and mainstream length of the rivers, respectively. L_{i+n}, RA_{i+n}, L_i, and RA_i stand for the total length and total area of the river channels of the year $i+n$ and i, respectively. In this paper, stream ordering is performed based on the river network maps of the 1960s, 1980s and 2000s according to Strahler′s stream order system (Yang, 2006). And the width of the river is the basis for stream ordering in the current research: rivers with channel width greater than 20 m are classified as the fourth order; rivers with channel width between 10–20 m are classified as the third order; the second order refers to those rivers with channel width lower than 10 m, and the first order refers to those rivers which have a channel width lower than 10 m and are not connected to other river channels.

2.2.2 *Box dimension of river networks*

Box dimension, also known as box-counting dimension, is one of the most frequently utilized fractal dimensions. The calculation process is: First, take a small box with side length of r to cover the fractal object. Some small boxes will be empty, and some boxes will cover part of the fractal object because there are a variety of levels of holes and cracks inside the fractal object. Second, count the number of non-empty small boxes, denoted by $N(r)$. Third, reduce the size of the boxes, thus the value of $N(r)$ will increase. When $r \to 0$, the fractal dimension (D_0) defined by box-counting method is obtained (Cui *et al*., 2004):

$$D_0 = -\lim_{r \to 0} \frac{\ln N(r)}{\ln r} \tag{3}$$

In practice, we can only take limited number of r, so the usual practice is to get a series of r and $N(r)$, and then calculate the slope of the line in the double logarithmic coordinates. It should be noted that the establishment of Equation (3) requires the existence of scaling relationship (Cui *et al*., 2004):

$$N(r) \propto r^{-D_0} \tag{4}$$

If there is no such scaling relationship, the concept of fractal dimension can not be used. Box dimension generally reflects the complexity of the river system, and the capacity of river network filling the entire plane as well (Wang and Wu, 1998).

2.2.3 *Spatial correlation dimension of lakes*

This paper considers all the planar water in the study area as lakes, and studies their fractal characteristics. The spatial correlation dimension ($C(r')$) of the lakes is defined as follows (Liu and Chen, 1999):

$$C(r') = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \theta(r' - d_{ij}) \qquad (i \neq j) \tag{5}$$

where r' stands for yardstick; d_{ij} stands for the Euclidean distance (crow distance) between lake i and lake j (Kaye, 1989); and θ is the Heaviside function, conforming the following equation (Liu and Chen, 1999):

$$\theta(r' - d_{ij}) = \begin{cases} 1, \text{ when } d_{ij} \leq r' \\ 0, \text{ when } d_{ij} > r' \end{cases} \tag{6}$$

If the spatial distribution of the lake system is fractal, it should be scale invariant, i.e. $C(\lambda r') \propto \lambda^{\alpha} C(r')$ (λ is a constant), therefore $C(r') \propto (r')^{\alpha}$. Here $\alpha = D_2$ is the fractal dimension, and can be named as spatial correlation dimension. When $r' \to 0$, we have (Dai and Ding, 2006)

$$D_2 \ln r' = \ln C(r') \tag{7}$$

The calculation of correlation dimension: first, calculate the distance between the lakes, and obtain the crow distance matrix; second, calculate the $C(r')$ value, and change the value of r', obtaining a series of $C(r')$ values; third, plot the double-logarithmic plots of (r', $C(r')$), and the correlation dimension D_2 can be eventually calculated by using the least-squares method.

As for the characterization of spatial distribution, spatial correlation dimension reflects the spatial distribution balance of the lakes. Generally, D_2 is in the range from 0 to 2: when $D_2 \rightarrow 0$, it indicates a high concentration of lakes in one place (forming a primary lake); when $D_2 \rightarrow 2$, it indicates that the spatial distribution of lakes is very homogeneous. The greater the value of D_2 is, the more balanced the spatial distribution of lakes is. When $D_2 \rightarrow 1$, it implies that the distribution of the lakes is close to a curve. The special function of spatial correlation dimension is that it can reflect the accessibility between the lake systems, which reveals the correlation degree between the lakes.

2.2.4 Hurst exponent of water level series

The Hurst exponent is highly predictable of time series trends, and there is a relationship between the Hurst exponent (H) and correlation function ($C(t)$) as follows (Mandelbrot and Wallis, 1969):

$$C(t) = 2^{2H-1} - 1 \tag{8}$$

When $H > 0.5$, we have $C(t) > 0$, and the correlations in the time series are persistent (i.e., an increment is very likely to be followed by another increment, and a decrement by another decrement). On the other hand, when $H < 0.5$, we have $C(t) < 0$, and the correlations in the time series are anti-persistent (i.e., an increment is very likely to be followed by a decrement). When $H = 0.5$, we have $C(t) = 0$, and there are only short-range correlations (or no correlations at all) in the time series, displaying properties of a standard non-correlated sequences (e.g., white noise).

Exponential law in Rescaled Range Analysis (R/S analysis) is the counterpart of scale invariance in the fractal theory. In fact, the Hurst exponent and the fractal dimension (D) of time series has the following quantitative relationship (Castillo and Melin, 2001):

$$D = 2 - H \tag{9}$$

Therefore, the Hurst exponent can be calculated by using R/S analysis method, and then the fractal dimension of time series can also be obtained, consequently, R/S Analysis can also be considered as a component of the fractal theory. Fractal dimension of time series can reflect the complexity of time series, and the Hurst exponent can also reflect the complexity of time series. In general, the more complex the time series are, the greater the fractal dimension is, and the smaller the Hurst exponent is.

3 Results

3.1 River-lake network changes

The morphological and structural features of river-lake networks were obtained for different periods in the study area, and the results are shown in Table 1 and Table 2. It can be seen that the changes of drainage density and water surface ratio were not significant between the 1960s and 1980s, decreasing by 11.20% and 7.63% respectively; while the changes were quite severe between the 1980s and 2000s, reducing by 36.90% and 20.80% respectively (Table 2). Therefore, the regulation and storage capacity of the river-lake networks has greatly weakened in the study area since the 1980s. In addition, the complexity of the river networks (CR) is 16.40 in the 2000s, far less than that of the 1960s (21.80), indicating that the more intensive human activities are, the smaller the complexity of the river networks is. And river network development of the study area is becoming more monotonous and more simple. Meanwhile, the stability of river network (SR) fell from 0.95 in the 1980s to 0.84 in the 2000s, indicating that the structure of river network was changing rapidly during that period.

3.2 Fractal characteristics of river-lake networks

Analysis of fractal characteristics of river-lake networks within the scope of each city was carried out, and the results are shown in Fig. 2 and Fig. 3. Table 3 shows correlation coefficients of the fractal analysis. As can be

Table 1 Characteristics of river-lake networks during different decades

	Drainage density (km/km^2)	Water surface ratio (%)	Average length ratio	CR	SR
1960s	3.75	13.10	3.35	21.80	–
1980s	3.33	12.10	3.25	20.50	0.95
2000s	2.10	9.58	2.85	16.40	0.84

Notes: CR stands for complexity of river network; SR stands for stability of river network. '–' means that there is no data for SR because it is calculated between two decades here

Table 2 Changes of characteristics of river-lake networks between different decades (%)

	Drainage density	Water surface ratio	Average length ratio	CR	SR
Decrease from 1960s to 1980s	11.20	7.63	3.00	5.96	–
Decrease from 1980s to 2000s	36.90	20.80	12.30	20.00	11.58

seen from Table 3, the calculated correlation coefficients of fractal dimension are all above 0.96, indicating that there exist fractal characteristics in the scale-free interval in the river systems within the scope of each city.

It can be seen from Fig. 2 that the fractal dimensions of the river networks are quite high in the study area, reflecting the high development degree of river networks in the region. Taicang City had the highest box dimension in the 1960s (up to 1.83), and the lowest was in Jiangyin City in the 2000s (the value dropped to 1.64). Meanwhile, the fractal dimension showed a downward trend from the 1960s to the 2000s for all the cities: the decline was small from the 1960s to the 1980s, while significant from the 1980s to the 2000s. The decline of fractal dimension is the most significant in Jiangyin and Zhangjiagang, and small in Suzhou and Wujiang.

Figure 3 shows the correlation dimension of the lakes within all the cities during different decades. Correlation dimension of the lakes from the 1960s to the 2000s was generally on a downward trend. The decline of correlation dimension indicates that the balance of the spatial distribution of lakes for all the cities is on the decrease, and this may be due to the intensity discrepancy of human activities in space, leading to the differences in disappearance of lakes in different regions. What is more, correlation dimension also reflects the accessibility between the lake systems. Therefore, the result implies that the accessibility between the lakes is on the decline in the study area, which is unfavorable for the flood storage capacity of the lakes. It should also be noted that we use the Euclidean distance to calculate spatial correlation dimension in this paper. Euclidean

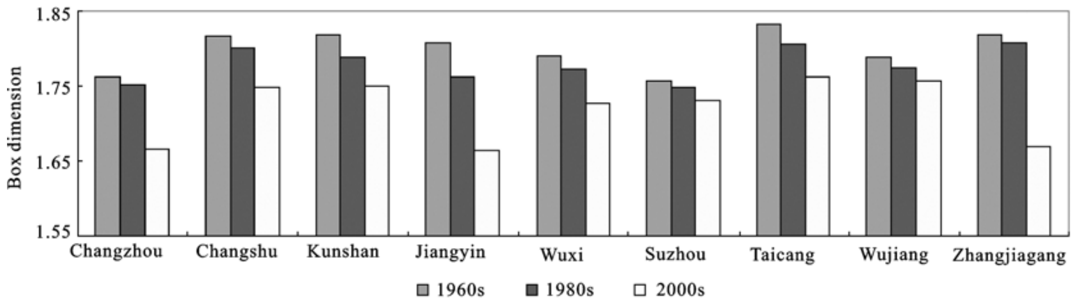

Fig. 2 Box dimension of river networks in each city during different decades

Table 3 Correlation coefficients of fractal analysis in each city

	Changshu			Changzhou			Jiangyin		
	1960s	1980s	2000s	1960s	1980s	2000s	1960s	1980s	2000s
Box dimension	0.998	0.993	0.988	0.988	0.978	0.969	0.989	0.988	0.985
Correlation dimension	0.998	0.998	0.997	0.999	0.998	0.997	0.998	0.999	0.999

	Kunshan			Suzhou			Taicang		
	1960s	1980s	2000s	1960s	1980s	2000s	1960s	1980s	2000s
Box dimension	0.995	0.998	0.981	0.995	0.985	0.986	0.997	0.989	0.991
Correlation dimension	0.996	0.995	0.995	0.998	0.996	0.995	0.999	0.997	0.996

	Wuxi			Wujiang			Zhangjiagang		
	1960s	1980s	2000s	1960s	1980s	2000s	1960s	1980s	2000s
Box dimension	0.995	0.960	0.967	0.963	0.979	0.983	0.967	0.972	0.972
Correlation dimension	0.995	0.994	0.995	0.999	0.998	0.997	0.996	0.995	0.994

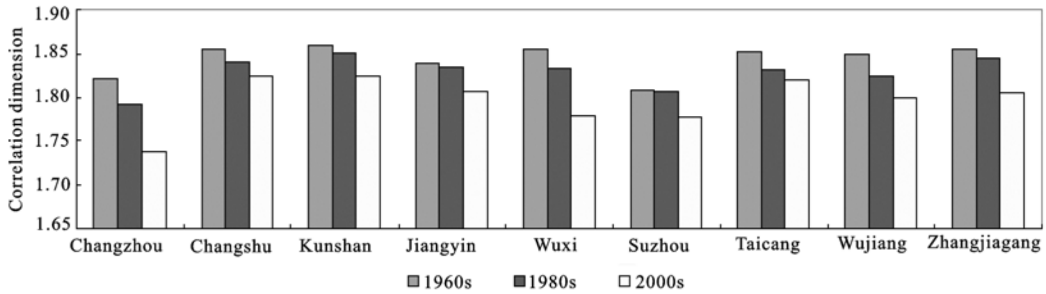

Fig. 3 Correlation dimension of lakes in each city during different decades

distance is not perfect to reflect the accessibility between the lakes, thus the actual accessibility between lakes is more complicated.

3.3 Hurst exponents of water levels

Figure 4 shows the Hurst exponents of water level series of representative stations in each city. In this paper, the river-lake network maps of the 1960s, 1980s, and 2000s correspond to water level changes of 1950s–1960s, 1970s–1980s and 1990s–2000s. In the calculation, the entire study period 1954–2006 was divided into three time slices: 1954–1969 water level series correspond to the river-lake networks of the 1960s, marking as ′1960s′ in Fig. 4; 1970–1989 water level series correspond to the river-lake networks of 1980s, marking as ′1980s′; 1990–2006 water level series correspond to the river-lake networks of 2000s, marking as ′2000s′.

It can be seen in Fig. 4 that the Hurst exponent of Changzhou City was 0.57 and 0.55 in the 1960s and 1980s, respectively, while it reduced to 0.52 in the 2000s. The decline of Hurst exponent of Wujiang City is the biggest: the Hurst exponent reduced from 0.76 in the 1960s to 0.52 in the 2000s. The Hurst exponent was between 0.5 and 1.0 for each city in the 1960s and 1980s, so that there was persistence in the water level series; and it decreased in the 2000s, so the persistence of water level series declined. The Hurst exponents of Changshu City and Suzhou City were even lower than 0.5 in the 2000s, showing a certain degree of anti-persistence. Because there is quantitative relation between the Hurst exponent and fractal dimension: the smaller the Hurst exponent is, the larger the fractal dimension is, and the more complex the time series are. Thus the changes of fractal dimension characteristics can also be obtained during different decades. Namely, the complexity of the water level series was on the increase from the 1960s to the 2000s. The decline of flood storage capacity of river-lake networks causes less high-fequency components of the water level to be filtered, so water level series will change more frequently and the persistence will decline, causing the downward trend of the Hurst exponent.

4 Discussion

4.1 River-lake network changes

Since the 1980s, the river channels have been shortened by about 10 879 km in the study area, and the river area that has been filled up is up to 163 km^2. As a result, the average drainage density and water surface ratio reduced by 36.90% and 20.80%, respectively (Table 2). In addition, previous researches show that the length ratio of the basin is generally 1.5–3.5 (Smart, 1972), and the average length ratio of the river networks in the study area is within this range, indicating that the river network structure is still in accordance with the laws of

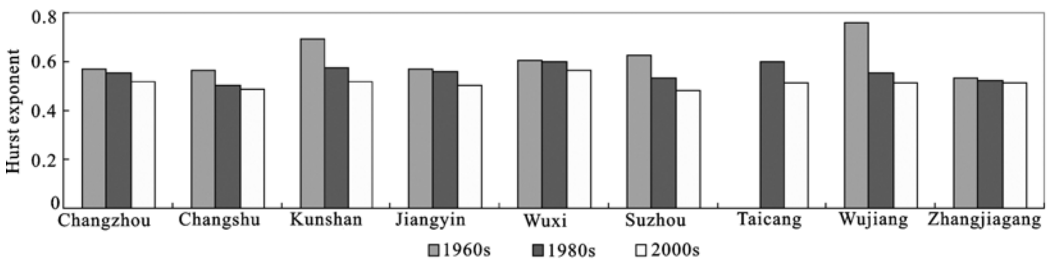

Fig. 4 Hurst exponent of water level series in each city during different decades

natural river development. Under the background of river length decreasing continuously, the river network is still in relatively good state of development, providing the basis for reconstruction of the river system for the study area.

The river-lake networks in the study area before the 1960s was little influenced by human activities, and the river-lake networks between the 1960s and the 1980s suffered from weak human disturbance, while the river-lake networks after the 1980s suffered from high-intensity of human activities. As for the reasons, human activities affecting the regional river-lake networks was mainly lake reclamation before the 1980s, but after the 1980s there are a wide range of human activities including the impacts of rapid urbanization, large-scale water conservancy construction, road construction, river regulation and so on.

4.2 Fractal characteristics of river-lake networks

Barbera and Rosso (1989) and Rosso *et al*. (1991) found that the fractal dimensions of typical river networks are between 1.5 and 2.0 from a large number of river network analysis. Claps and Oliveto (1996) held that the average value is about 1.7. As we can see in Fig. 2, the box-counting dimensions of river networks within different cities are generally between 1.65–1.85, which is consistent with the above-mentioned results.

Wang *et al*. (2007) studied on the fractal characteristics of river networks in the Pearl (Zhujiang) River estuary, and concluded that the fractal dimension tended to decrease in general, indicating the decrease in complexity degree of the river networks. Further analysis showed that human activities are the major factor leading to the fractal characteristics changes in river networks in the Pearl River estuary. And this conclusion is similar to the results of this paper. Wang *et al*. (2006) compared the fractal characteristics between different sub-basins of Taihu Lake Basin, and they concluded that the fractal dimension of Taihu Lake Basin has the characteristics of 'small in the north and big in the south' in river course fractal dimension, and 'small in the west and big in the east' in river network fractal dimension. However, there are not significant spatial differences between regions in this paper due to the smaller study area here.

Li *et al*. (2005) studied the shoreline changes of major lakes of Taihu Lake Basin by using fractal box dimension based on shoreline length-area relation and the shoreline development index. The results showed that the box dimension of lakes shoreline was on the decline, and the shoreline structure has become monotonous for the recent 30 years, reflecting the increase in interference degree of human activities on the lake shoreline. This conclusion is similar to the results of correlation dimension of lakes in this paper.

4.3 Relationship between changes of river-lake networks and water levels

Storage capacity of the river-lake networks can filter out the high frequency components of the runoff or water level series, therefore, the stronger the river's storage capacity is, the more high frequency components are filtered out. Flood storage function of river-lake networks for the runoff and water level series is equivalent to low-pass filtering: excluding short-term fluctuations and retaining the long-term trends. The Hurst exponent of time series reflects the long-term trend, thus there is a positive correlation between river system storage capacity and the Hurst exponent of water level series. The bigger the storage capacity is, the higher the Hurst exponent will be; and the Hurst exponent will decrease with the reduction of storage capacity. Therefore, the Hurst exponent/complexity of water level time series can reflect the storage capacity of the river-lake networks to some extent.

The higher the fractal dimension of river-lake networks is (the more complex the river system is), the stronger its storage capacity is, and consequently the Hurst exponent of the water level series will be higher, and the water level process will be more simple. In addition, the complexity of the water level sequences can reflect the possibility of flood disasters to some extent: the more complex the water level sequences is, the higher the possibility of flood disasters will be. Therefore, the higher the fractal dimension (the more complex) of the river system is, the less likely the flood occurrence will be. In a word, the relationship between the fractal dimension and the water level sequences can reflect the impacts of river system changes on flood disasters to some extent: the disappearance of river-lake networks will increase the possibility of flood occurrence.

Research on the fractal characteristics of river-lake networks in the study area indicates that both the box dimensions of the river networks and correlation dimension of lakes in the study area decreased for the recent decades, as a result, storage capacity of river systems and lakes also significantly decreased. Meanwhile, the Hurst exponent of water level series in the representative stations showed a downward trend, and the fractal dimension (complexity) increased, reflecting increased regional flooding. Therefore, there exist linkage between the storage capacity and fractal dimension of river-lake networks in the plain river network regions with extensive human activities like the Taihu Lake Basin.

5 Conclusions

The typical regions of the Taihu Lake Basin were selected and digital river maps of the three periods of the 1960s, 1980s and 2000s were extracted to quantitatively characterize the evolution of river-lake networks in this paper. The fractal characteristics of the river networks and lakes were also investigated based on fractal theory, and they were further compared with the fractal characteristics of water level series, to preliminarily explore the influences of river network changes on water levels. The results show that river network development of the study area is becoming more monotonous and more simple; the number of lakes is reducing significantly, and the water surface ratio has dropped significantly since the 1980s. Meanwhile, the box dimension of the river system and correlation dimension of lakes for the study area both have decreased, reflecting the simplification of river networks and lake reduction, which corresponds well with the Hurst exponent decline of water level sequences. Therefore, the link between their evolution characteristics preliminarily reveals the mechanism of the impacts of river-lake network evolution on water level changes.

Fractal theory is an effective method to characterize the changes of hydrological time series and river-lake networks, and it is also of significance in understanding the relationship between the evolution of river-lake networks and flood changes. Nevertheless, as a mathematical method, fractal theory can not reveal the physical mechanisms of rainfall, water level and flood disaster evolution under the regional river system changes, thus we need to further establish the physically-based distributed hydrological model to simulate and explore the process in the future. In addition, mono-fractal only involves a single-fractal scale, yet not fully reflects the actual situation of the watershed and river-lake networks. Therefore, further analysis of plain river-lake networks should be based on multi-fractal characteristics of the region, and thus explore the link between the changes of river-lake networks and regional hydrological process in depth.

References

Barbera L, Rosso R, 1989. On the fractal dimension of stream networks. *Water Resources Research*, 25(4): 735–741. doi: 10.1029/WR025i004p00735.

Castillo O, Melin P, 2002. Hybrid intelligent systems for time series prediction using soft computing techniques and fractal theory. *International Journal of Smart Engineering System Design*, 3(3): 187–194. doi: 10.1109/TNN.2002.804316

Claps P, Oliveto G, 1996. Reexamining the determination of the fractal dimension of river networks. *Water Resources Research*, 32(10): 3123–3135. doi: 10.1029/96WR01942

Chen Yanguang, Liu Jisheng, 2001. Fractals and fractal dimensions of structure of river systems: Models reconstruction and parameters interpretation of Horton′s laws of network composition. *Advance in Earth Sciences*, 16(2): 178–183. (in Chinese)

Cui Lingzhou, Xiao Xuenian, Li Zhanbin, 2004. GIS-based approach for measuring the fractal box dimension of watershed topography. *Bulletin of Soil and Water Conservation*, 24(2): 38–40. (in Chinese)

Dai Xuejun, Ding Dengshan, 2006. Correlation fractal dimension of spatial structure of tourist spots systems—A case study in Nanjing City. *Resources Science*, 28(1): 180–185. (in Chinese)

Feng Ping, Feng Yan, 1997. Calculation on fractal dimension of river morphology. *Acta Geographica Sinica*, 7(4): 324–330. (in Chinese)

Huang Xing, 1993. Evolution of rivers and lakes and flood disasters in the Taihu Lake basin. Nanjing: Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. (in Chinese)

Kaye B H, 1989. *A Random Walk Through Fractal Dimensions*. New York: VCH Publishers.

Li Xinguo, Jiang Nan, Wang Hongjuan *et al*., 2005. Dynamic changes of lake shorelines morphology in the Taihu basin during the past 30 years. *Journal of Lake Sciences*, 17(4): 294–298. (in Chinese)

Liu Jisheng, Chen Yanguang, 1999. Fractal dimensions of spatial structure of an urban system and the methods of their determination. *Geographical Research*, 18(2): 171–178. (in Chinese)

Mandelbrot B B, Wallis J R, 1969. Some long-run properties of geophysical records. *Water Resources Research*, 5(2): 321–340. doi: 10.1029/WR005i002p00321

Ma Zongwei, Xu Youpeng, Zhong Shanjin, 2009. Influences of river network fractal characteristics on runoff—Case study in the basin of upper and middle courses of Gan River. *Resources and Environment in the Yangtze Basin*, 18(2): 163–169. (in Chinese)

Rosso R, Bacchi B, Barbera L *et al*., 1991. Fractal Relation of mainstream length to catchment area in river networks. *Water Resources Research*, 27(3): 381–387. doi: 10.1029/90WR02404

Smart J S, 1972. Quantitative characterization of channel network structure. *Water Resource Research*, 8(6): 1487–1496. doi: 10.1029/WR008i006p01487

Su Weizhong, Yang Guishan, 2008. Scale-free structure of the Nanhe drainage of Lake Taihu watershed. *Journal of Lake Sciences*, 20(4): 514–519. (in Chinese)

Wang Dapeng, Wang Zhoulong, Li Deyi *et al*., 2006. River network fractal spatial difference of Taihu basin. *Zhejiang Hydrotechnics*, 3: 5–7. (in Chinese)

Wang Lachun, Xu Youpeng, Zhou Yankang *et al*., 1999. Analysis of the storage capacity of river network in the Taihu watershed. *Journal of Nanjing University* (*Natural Sciences*), 35(6): 712–718. (in Chinese)

Wang Qiao Wu Hehai, 1998. Study on fractal description of map information and automatic generalization. Wuhan: Wuhan Technical University of Surveying and Mapping. (in Chinese)

Wang Shijun, Huang Shengwei, Wang Hua *et al*., 2007. Fractal mechanism of the Pearl river network. *Tropical Geography*, 27 (2): 111–114. (in Chinese)

Yang Kai, 2006. Stream structure characteristics and its urbanization response in dense river network plain: A case study of Shanghai, China. Shanghai: East China Normal University. (in Chinese)

Yang Xiuchun, Zhu Xiaohua, 2002. Fractal analysis applied to the 7 drainage basins and the flood in China. *Journal of Catastrophology*, 17(3): 9–13. (in Chinese)

Yuan Wen, Yang Kai, Tang Min *et al*., 2005a. Stream structure characteristics and their impact on storage and flood control capacity in the urbanized plain river network. *Geographical Research*, 24 (5): 717–724. (in Chinese)

Yuan Wen, Yang Kai, Xu Qixin, 2005b. Effect of urbanization growth of Shanghai river function and stream structure. *Resources and Environment in the Yangtze Basin*, 14(2): 133–138. (in Chinese)

Yuan Wen, James P, Yang Kai, 2006. Impact of urbanization on the structure and function of river system—Case Study of Shanghai, China. *Chinese Geographical Science*, 16(2): 102–108. doi: 10.1007/s11769-006-0002-9

Zhu Xiaohua, Cai Yunlong, 2003. On box dimensions of river basins of China. *Advances in Water Science*, 14(6): 731–735. (in Chinese)