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Correlation between flood frequency and geomorphologic complexity of river network -A case

study of Hangzhou China

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Abstract: Urban flooding is a combined product of the climate and watershed geomorphology. River system is one of the vital components of watershed geomorphology. The geomorphic characteristics of rivers have important effect on the formation of flooding. However, there have been few attempts so far to investigate the relationship between flooding frequency, the probability of flooding, and the geomorphological complexity of river system. Such relationship is essential in order to predict likely responses of flooding frequency to the large-scale changes in the complexity of the river networks induced by accelerating urbanization around river. In this study we investigate the correlation between geomorphological characteristics of river system and the probability of flooding. Hangzhou city in China, which has suffered severe flooding, is chosen as a case study to evaluate this correlation and to investigate the impact of changes of drainage networks morphology on the local flooding. The fractal dimension, which is used to quantitatively assess geomorphological complexity of river network, is calculated by using box-counting method based on fractal geometry for eight sub river networks in Hangzhou. A model based on the correlation of flooding frequency and fractal dimension is established. The model is applied to investigate the

effect of the rapid urbanization induced changes of river geomorphology on the local flood frequency in two typical regions in Hangzhou. The results show that the flood frequency/events increases with the decrease of fractal dimension of the river network, indicating that the geomorphologic complexity of river network has an important effect on flooding. This research has great referential value for future flood quantitative investigation and provides new method for urban flood control and river system protection.

1. Introduction

Flood is one of the natural disasters that cause catastrophic losses to human lives and economy. Relevant statistics data show that 50.8％of the world's population affected by natural disasters was resulted from flooding (Cheng, 2008). Flood is a combined product of the climate and watershed geomorphology. Global climate change will very likely increase the strength and frequency of flood, while urbanization usually has negative impacts on watershed geomorphology. This has been evidenced by the rapid urbanization in China where many cities have expanded around the river networks, having greatly changed morphology around the river catchment. As such, water area is reduced by, for example, straightening the river bends. As a result, flood disaster has been increasing.

The river network is an important component of basin geomorphology and has important impact on flood. Therefore, an accurate description of river networks geomorphology is crucial for

investigating the river flow, sediment transport and flood (Ariza et al., 2013). Traditional morphologic methods for describing the river networks are to consider the pattern characteristics, such as radius of river bend curvature, channels length, and other parameters. These approaches often have little relationship with the actual drainage. As such, these methods can only investigate the simple geometric configurations (Snow, 1989) and poorly describe natural features of complex river networks (Mandelbrot, 1977; Schuller et al., 2001; Hassan and Kurths, 2002; Guillermo et al., 2004). Several studies have recognized the importance of the irregular components in river networks (e.g. meanders and compound) (Leopold and Wolman, 1960; Schumm, 1977; Fredsoe, 1978; Strahler and Strahler, 1992). Fractal geometry method (Mandelbrot, 1983), in contrast, includes river shapes characterized by irregularities. As such, the models based on fractal geometry to quantitatively describe the geomorphologic features have been developed rapidly in recent years (Veltri et al., 1996; Vladimir et al, 2005; Endre et al, 2007; Shen et al., 2011; Jesus et al., 2013). Recent applications of these models have demonstrated the importance of fractal geometry in the study of geomorphological characteristics of river networks and other hydrological variables (Samuele et al., 2006).

Though some studies have been conducted by using fractal analysis to investigate the river networks（Horton, 1945; La Barbera, et al., 1989; Han and Lu, 2009; Joanna, 2013, there have been few attempts to investigate the correlation between the geomorphological complexity of river network and the possibility of flood. Therefore, the main objective of this study is to investigate the correlation between flood frequency, possibility of flood and the complexity of river system geomorphology. This study will be greatly useful for quantitative investigation of flood and will provide a new method for urban flood control and water environment protection in the future. As a

validation of the method, Hangzhou city, in the lower reach of the Qiantang River and having been suffered from severe flood in recent decades, is used as a case study. To this end, the method is used to predict the responses of the frequency and probability of flood to large-scale changes of drainage networks in Hangzhou.

2. Study area

Hangzhou, capital city of Zhejiang province in the East of China, is located between 29 ° 11 ′ -30 ° 34 ′north latitude and 118 ° 20 ′ -120 ° 7' east longitude. It has eight districts, namely central Hangzhou, Xiaoshan, Yuhang, Fuyang, Tonglu, Linan, Chunan and Jiande, shown as in Fig.1. The area of Hangzhou is about 16596 km^2 and the central city area is 728 km^2. Hangzhou has the typical water network, including the Qiantang River and the Grand Canal. However, the rapid urbanization, river regulation and reclamation of tidal flat in the Qiantang River estuary have caused significant geomorphologic changes of the river networks. As such, flood disasters in Hangzhou have increased in recent years.
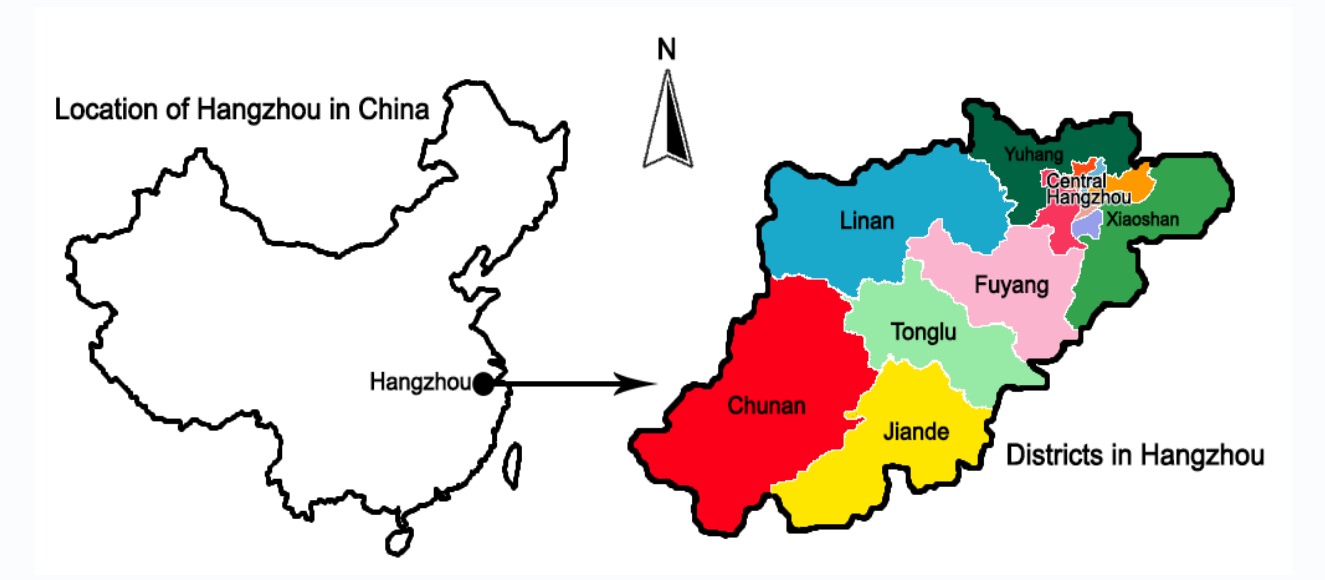

Fig.1. Location of Hangzhou

3. Data and methods

3.1 Data sources

The data of river networks in this study, shown in Fig.2, are obtained from the river network map in Hangzhou (Hangzhou Water Conservancy Compilation Committee, 2009). The paper map was converted to a digital vector form through scanning and digitizing procedures. The river networks of different districts in Hangzhou, shown as in Fig.3, are then obtained from the digital vector.

The area of each district is obtained from China City Statistical Yearbook in 2004. The statistic disasters are based on The Zhejiang Province Flood and Drought Disaster from 1949 to 2000 (Water conservancy department of Zhejiang province, 2002).
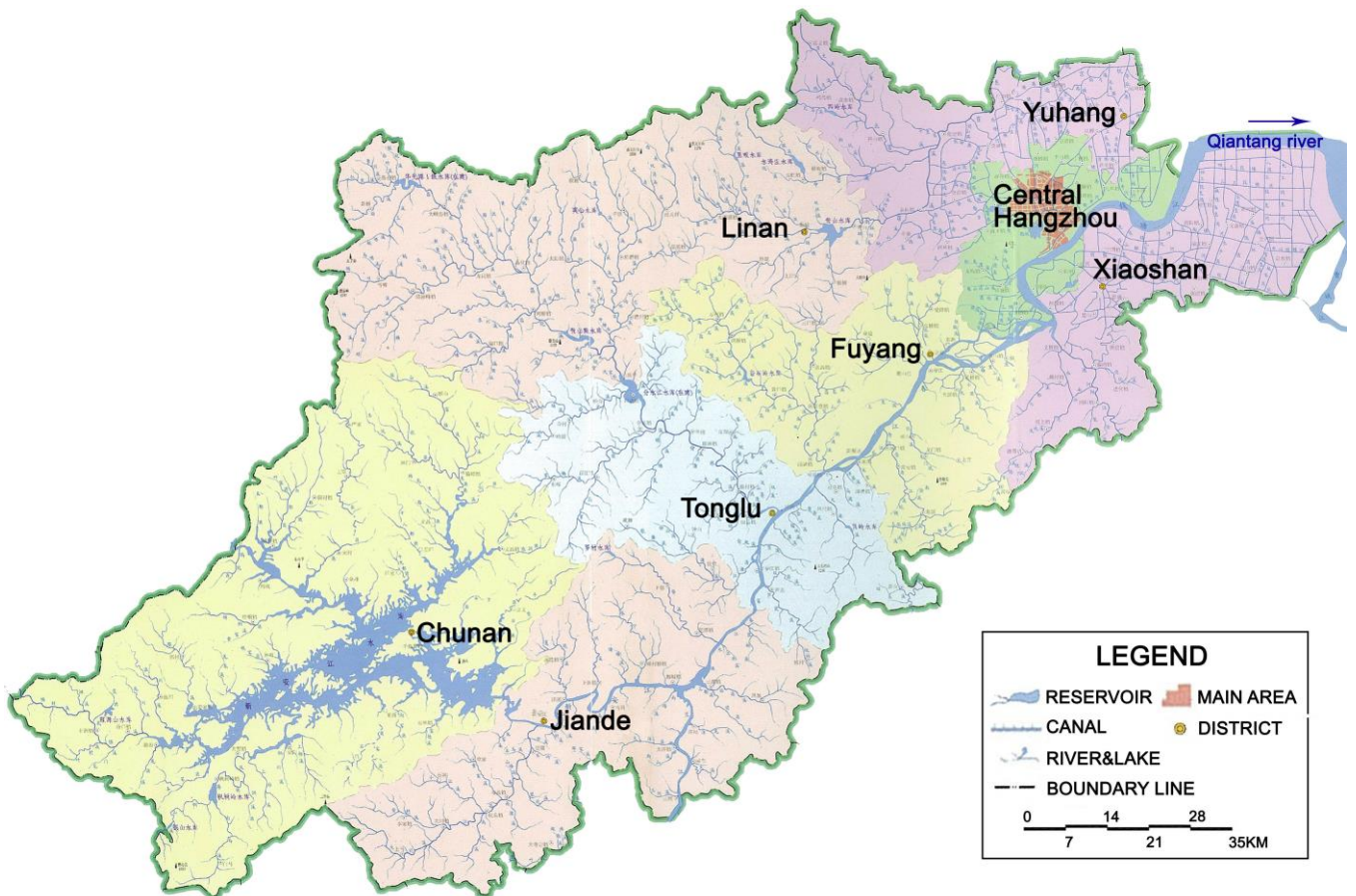
Fig.2. River network map in Hangzhou in 2003 (Hangzhou Water Conservancy Compilation Committee, 2009)
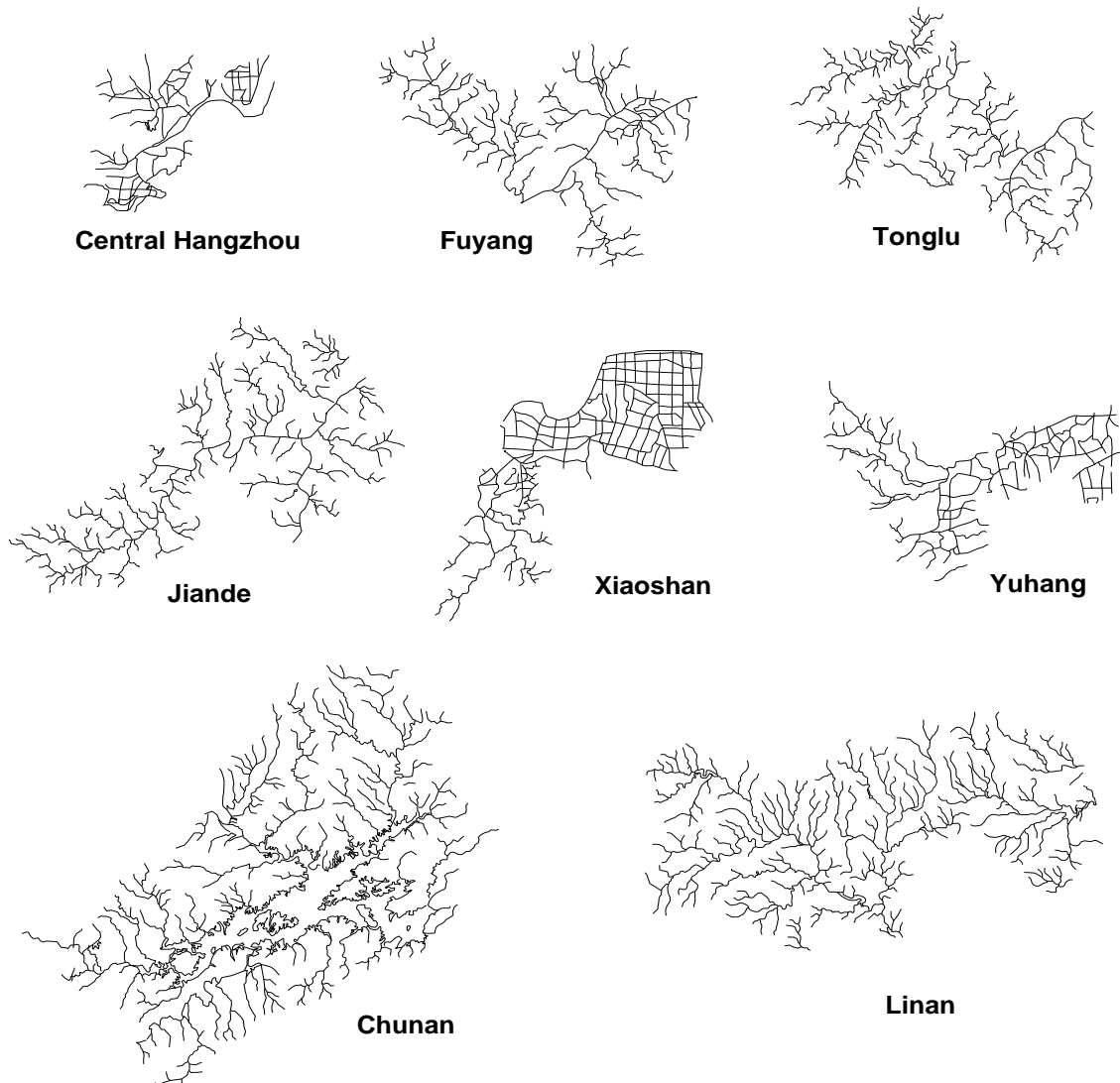
Fig.3. River network maps of eight districts in Hangzhou in 2003(scanned and digitized from Fig.2)

3.2 Fractal dimension analysis and calculation

Fractal geometry describes irregular and complex features of nature. Fractals are self-similar statistically for a range of scales. Mandelbrot (1967) revealed that the total length (L) (e.g., coastline) increases nonlinearly with the decrease of small segment length ε ., For coastlines, individual rivers or any other two-dimensional features, the equation $L = N\varepsilon$ is used to approximate the total length (L) of the curve, where N is the number of small segments of river or coastline. The relationship of N and ε can be

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represented as following: (Guillermo et al., 2004):

$$N(\varepsilon) \propto \varepsilon^{-D} \tag{1}$$

where D is a non-Euclidean value which can be represented by fractional values. For an irregular curve river or coastline, D has a fractal dimension between 1 and 2.

The above line segment method is appropriate for non-branching fractals, such as coastlines or individual rivers. However, this method is not applicable for river networks. To better describe the river networks, in this paper, the fractal dimension D for each river is estimated by applying box counting approach.

The principle of the box counting method is similar to the line segment method and has been successfully applied in several studies for river networks and coastlines (Turcotte, 1992). The procedure for estimating D for eight river networks in Hangzhou is as following:

(1) Square box with side length ε is generated. A box with spacing ε is placed over the fractal object (e.g. river networks). The number of boxes, $N(\varepsilon)$, in which a part of the fractal falls, is then counted. $N(\varepsilon)$ increases with the decrease of the size of box. Fig.4 is an example of the box-counting method applied to the river networks in Fuyang district.

Analysis shows that decreasing ε will improve the accuracy of the estimation of the length of total water system using $L = N\varepsilon$. In theory, $L = N\varepsilon$ will give the actual length of the total water network when ε tends to 0. This relationship can be represented by:

$$D = -\lim_{e \to 0} \frac{\lg N(e)}{\lg e} \tag{2}$$

(2) Performing this method for different grid spacing generates the relationship between log $N(\varepsilon)$ and log (ε) for each river network. The fractal dimension D is obtained as the slope of a straight line by rewriting equation (2) as following:

$$\lg N(e) = -D \lg e + C \qquad\qquad (3)$$

where C is a constant of proportionality which allows for the relationship between N and ε. The value D determines the development of river networks. River network density increases with the increase of D. When D approaches 2.0, river network is fully developed and covers almost the whole drainage basin (Schuller et al., 2004; Du et al., 2009).

The box size is between 600 m to 19200 m in this study, while 600 m is the map pixel size. The smallest box whose size approaches the map pixel size contains the smallest indivisible line element of river. When box size is chosen, the number of box can be determined using equation (3). The fractal dimension can then be evaluated. Using this approach and fractalyse 2.4.1 software, the Fractal dimension D and its correlation coefficient (R) for the river network in Hangzhou can be estimated (see Table 1).

Table 1 Fractal dimension (D) and its correlation coefficient (R) for the river network in Hangzhou

Districts	D	R
Central Hangzhou	1.428	0.997
Fuyang	1.505	0.993
Tonglu	1.45	0.998
Jiande	1.503	0.995
Chunan	1.602	0.993
Xiaoshan	1.471	0.993
Yuhang	1.451	0.991
Linan	1.552	0.998

Table 1 shows that the correlation coefficient R of the fractal dimension of river networks in all districts is greater than 99%, indicating that the designed fractal structure of river networks is objectively real. Table 1 also shows that the fractal dimension of districts varies from 1.42 to 1.61 with the averaged value of 1.495. These values agree well with those obtained by Feng and Yan (1997) and Schuller et al. (2004) who applied the box-counting technique.

The value of D is determined by the geomorphologic shape of the river network. The complex geomorphologic shape of the river network will produce larger D. In this study, the largest D is 1.62, taking place in Chunan river network, which has complex geomorphologic shape with the most tributaries and bending form (see Fig.3). The river system of the Central Hangzhou, in contrast, is the simplest. As such, its fractal dimension is the smallest. This means that D can be used as an index of complexity of river geomorphology and can provide a quantitative description of the characteristics of river network.
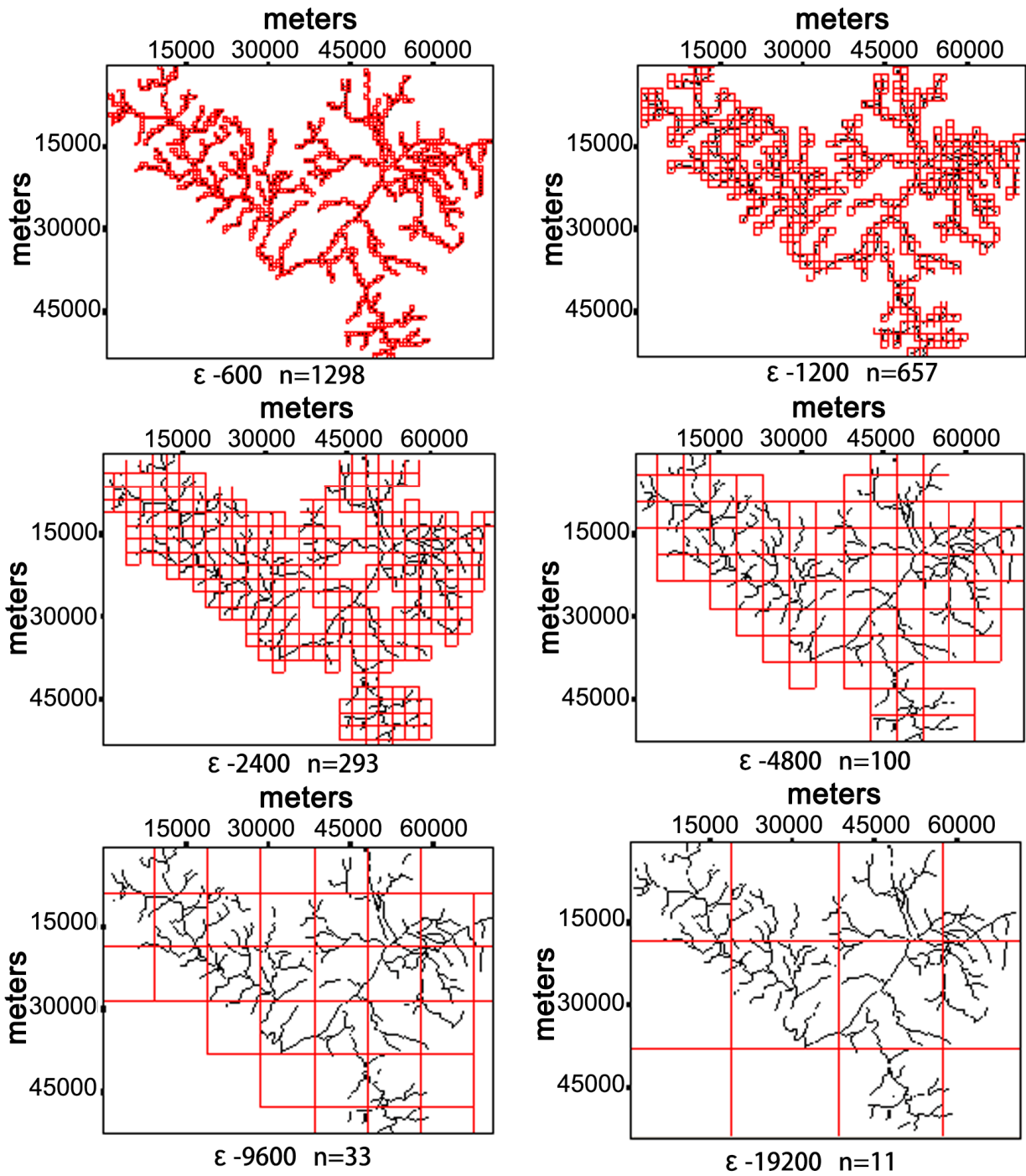
Fig.4. Example of the box-counting method applied to the Fuyang river networks

3.3 Flood disasters statistic analysis

The total number of flood events in different river basins of Hangzhou during the period from 1949 to 2000 was obtained from the long-term statistic data of flood disasters in Zhejiang province in this period

(Water conservancy department of Zhejiang province, 2002). Due to the difference of each area of sub river basins in Hangzhou, total number of flood events in each sub watershed failed to indicate reasonably their comparative serious degree of the flood. Therefore, we adopted the flood frequency (F), namely the average time of flood events in per 100 km^2 river basin area, to show exactly the comparative degree of the local flood events or the probability of flood events. The statistic data of flood disasters and estimated results are listed in Table 2.

Table 2 Statistic data of flood events in Hangzhou city (1949-2000) (Water conservancy department of Zhejiang province, 2002)

Districts	Area (km^2)	Total number of flood events	Flood frequency (number /100 km^2)
Central Hangzhou	728	20	2.75
Fuyang	1825	34	1.86
Tonglu	1829	41	2.24
Jiande	2321	31	1.34
Chunan	4427	35	0.79
Xiaoshan	1420	36	2.54
Yuhang	1223	36	2.94
Linan	3127	34	1.09

These data will be used to analyze the relationship of flood and fractal dimension.

4. Results and Discussion

4.1 The Correlation between flood frequency and fractal dimension

Comparing Table1 with Table2 demonstrates that in general, the flood frequency increases with the decrease of the fractal dimension. Figure 5 is the plot of the flood frequency versus the fractal dimension based on the data of Table 2. It is seen that a linear relationship between the flood frequency and the fractal dimension exists, which can be expressed as:
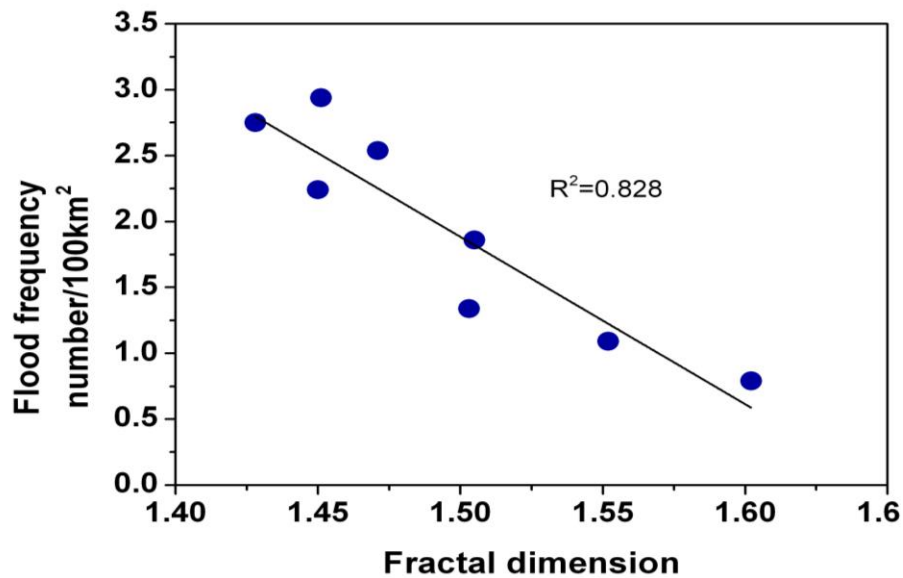

Fig.5. Correlation between Fractal dimension of river networks and Flood frequency

$$F = -12.767D + 21.028 \qquad （4）$$

The above relationship together with the relationship between the fractal dimension and complexity of river network reveals that the flood frequency is reduced by the complexity of river network. The result agree with that obtained by Ma et al.(2005).This can be ascribed to the fact that the complex river network has more bending tributaries which provide larger storage for runoff, leading to the reduction of flood events. On the contrary, river regulation and reclamation of intertidal zone in the Qiantang Estuary have made the geomorphology in these areas, such as central Hangzhou and Xiaoshan, be more regular. These human activities decrease the rainwater storage capacity, leading to the higher probability of flood events under the same rainfall conditions (see Table 2).

River basin with complex geomorphology also has larger resistance to the flow of runoff. As such, the time for the formation of flood peak is prolonged and the total volume of runoff spreads over longer period.

As a result, probability of flood events decreases. In contrast, the resistance of the river network with simpler and straighter geomorphological shape to surface runoff is smaller. Therefore, the time for the formation of flood peak is shorter. Consequently, the flood probability increases.

Therefore, it can be concluded that the fractal dimension of the river networks can be used to assess the probability of flood events. The correlation between the fractal dimension and flood frequency of the river network can be used to predict the tendency of flood induced by men-made changes of river system, providing a new method for urban flood control and river system protection.

4.2 Impact of changes of the river networks on local flood frequency

The drainage networks of Tonglu and Fuyang, in the upper reach of the Qiantang River, have been significantly changed due to the large-scale urban development (see Fig. 6). Such urbanization has greatly reduced the geomorphological complexity of the river networks in these two districts, and implied negative impact on the flood control of Hangzhou.
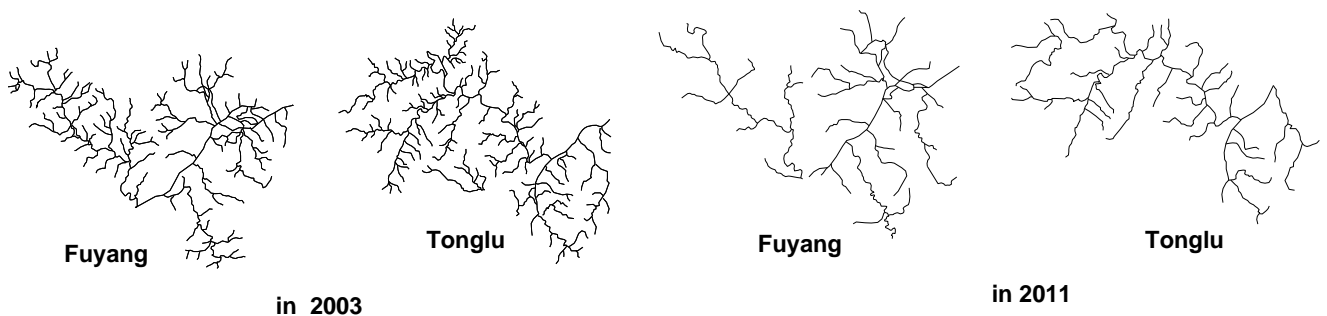

Fig. 6 Comparison of river networks of two typical districts in Hangzhou in 2003 and 2011

Table 3 Fractal dimension and flood frequency of Tonglu and Fuyang in 2003 and 2011

Period	Fractal dimension		Flood frequency (number /per year per 100 km^2)	
	Tonglu	Fuyang	Tonglu	Fuyang

2003	1.450	1.505	0.0475	0.0342
2011	1.313	1.352	0.0698	0.0632

To investigate the effect of urbanization on flood events, the box counting method is used to estimate the fractal dimensions of the river networks in Tonglu and Fuyang in 2003 and 2011, respectively. The corresponding flood events per 100 square kilometer in Tonglu and Fuyang in 2003 and 2011 are obtained from Water Conservancy Department of Zhejiang Province (personal communication). The results are listed in Table 3, which shows that the fractal dimensions in both Tonglu and Fuyang are significantly reduced due to urbanization in these two regions. The irregular, denser and complex river networks in two regions in 2003 become regular and simpler in 2011 after large-scale urbanization. This significantly reduces the runoff storage capacity of these two river networks. As a result, flood events greatly increase in these regions in this period. In particular, flood events in Fuyang in 2011 are more than double that in 2003. The result is consistent with the measured data at the hydrological station in the lower reach of the Qiantang River (Liang, 2012).

5. Conclusions

River network is an important part of watershed geomorphology. The geomorphic complexity of the river network can be assessed using fractal dimensions and has a vital impact on flood. In this study, the fractal dimension was estimated using the box counting method for eight sub river networks in Hangzhou. The results show that the denser and complex river network has larger fractal dimension. Analysis shows that there exists a correlation between fractal dimension and flood events. Flood frequency/event increases with the decrease of fractal dimension of the river network, showing that the geomorphological complexity of river system has an important impact on flood events. The study shows that the fractal dimension could be used as an index to indicate the probability of flood events in the future. The correlation between the geomorphological complexity of river system and flood frequency provides a new method and though for urban flood control and river system protection. And it suggested that an exact correlative formula between

them in other regions should be revised according to local river network shapes and flood data.

The effect of urbanization induced by changes of drainage geomorphological characteristics on floods has been discussed. The study on two districts of Hangzhou over eight years reveals that urbanization has greatly reduced the density, complexity and irregularity of river networks in these two regions. As such, fractal dimensions and the runoff storage capacity of these two river networks have been significantly reduced. Consequently, the flood events in these two regions greatly increase during eight years.

The study demonstrates that the fractal dimension D can be used as an operational parameter to adjust geomorphologic complexity of river networks in the planning of the urban constructions and hydraulic engineering around the river network.

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