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Spatial–temporal evolution of the distribution pattern of river systems in the plain river network region of the Taihu Basin, China

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A B S T R A C T

Understanding the spatial–temporal distribution characteristic and evolution tendency of river systems is important in integrated river basin management. In this paper, six indicators were adopted to describe the physical characteristic of river systems. The spatial–temporal evolution of the distribution pattern of river systems in the plain river network region of the Taihu Basin (PRNRTB) during the 1960s–2000s was analyzed using exploratory spatial data analysis (ESDA) and the gravity centre model. The impacts of urbanization were then investigated. Results indicated that the global distribution patterns of box dimension and river density were all statistically significant spatially clustered, and river sinuosity was partially spatially clustered, while water surface ratio, main river area length ratio and river development coefficient were not spatially clustered. Moreover, the water surface ratio was the most stable parameter, box dimension was also relatively stable parameter, but the others were unstable. Meanwhile, the mutual transformations of hot and cold spots of river systems especially water surface ratio, river development coefficient, and river sinuosity were frequent. The hot spot regions were mainly located in the northeast region. In addition, most gravity centres migrated gradually from southeast to northwest with low distance, except those of river development coefficient and river density. These aforementioned differences were caused by the rapid urbanization. Based on the integrated river basin management suggestions for PRNRTB, the river density, box dimension and river sinuosity should be maintained and restored across the whole watershed, and the river conservation and restoration should focus on countermeasures against the reduction of river development coefficient, and main attention should be paid on the river systems conserving and restoring in Haiyan and Haining in southeast PRNRTB.

1. Introduction

River systems are important natural heritage sites. The formation and development of river systems is influenced by many natural factors, such as geology, topography, soil, hydrology, climate, and vegetation. Moreover, river systems are usually altered to meet the needs of people in water, energy, transportation, recreation, storage and discharge (Costanza et al., 1997; Nilsson et al., 2005; Dolédec and Statzner, 2008; Jia and Chen, 2013). The influences of urbanization on river systems have been widely recognized as the most significant among all human activities. Approximately 60% of river systems have been changed profoundly because of urbanization (Sear and Newson, 2003). These changes have strongly threatened the ecological integrity and ecosystem functions of river systems (Dudgeon, 2006). Thus, an increasing need to investigate the impacts of urbanization on river systems for the sustainable planning, management and conservation of rapidly urbanized river basins has been realized (Karr, 1999; Norris and Thoms, 1999; James and Marcus, 2006; Junior et al., 2010; Pinto and Maheshwari, 2011).

The impacts of urbanization on river systems have been introduced and investigated as a broad and specific question since the mid-20th century (Lane, 1955; Strahler, 1956). Considerable progress has been achieved in rapidly urbanized regions around the world over the past 60 years (Chin, 2006). These studies documented that urbanization could change the quantity, morphology and structure of river systems. River lengths and water surface areas have generally deteriorated in rapidly urbanized regions.

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Main rivers have also been widened because of the increase in runoff volume caused by river channel dredging and impervious surface increase, while the tributaries have been narrowed gradually and even disappeared because of river channel sedimentation and urban occupation (Vanacker et al., 2005; Gregory, 2006). Moreover, spatial distribution of the urbanization impacts has been observed, and found that the impacts typically decrease from the city to suburbs (Yuan et al., 2006).

The variations of river systems can be considered as spatial–temporal processes. These procedures are controlled in spatial and time scale by many natural and social factors, particularly urbanization. Moreover, the spatial distribution of urbanization and its effects on river systems has the characteristic of agglomeration and dispersion. Previous studies have generally focused on the numeric characteristic of river system variation. These studies assumed the existence of mutual independence in spatial distribution (Yang et al., 2004; Xu et al., 2013). However, studies on the spatial association and spatial heterogeneity of the variations of river systems are lacking. Understanding the spatial–temporal distribution characteristic and the evolution tendency of river systems is necessary for sustainable river basin management. Exploratory spatial data analysis (ESDA) has been used successfully in the variation studies of economic patterns, ecological environments and social issues (Le Gallo and Ertur, 2003; Buttafuoco et al., 2005; Anselin et al., 2007; Ye and Wu, 2011; Rincón et al., 2013). However, the methodology of ESDA in the evolution of river systems research is still at the beginning. Moreover, the plain river network region of the Taihu Basin (PRNRTB) is one of the regions with the fastest rate of urbanization in China. Rapid urbanization has caused significant changes in river systems, such as water degradation, flood disaster and other ecological and environmental problems. Therefore, many major indicators are selected to describe the physical characteristic of river systems. ESDA and the gravity centre model are employed to explore the spatial–temporal evolution of the distribution pattern of river systems in PRNRTB. The aim of this study is to analyze the evolution characteristics and laws of the distribution pattern of river systems, to discuss the possible impacts of urbanization, and finally to provide scientific basis and decision-making references for integrated river basin management in PRNRTB.

2. Study area and data

2.1. Study area

PRNRTB is located in the centre of the Yangtze River Delta in eastern China and covers an area of 15,757 km^2, 2 m–4 m above sea level (Fig. 1). PRNRTB is one of the most densely populated regions in China with approximately 3.47 million inhabitants and a population density of 834 individuals per km^2. PRNRTB is also one of the most economically developed regions in China, i.e., PRNRTB had a local GDP of 3874.12 billion Yuan in 2013, approximately 7% of the GDP of China. However, the total area of the region is only 0.46% of the total area of China. Moreover, PRNRTB is one of the most rapidly urbanized regions in the world. There are 22 large, medium and small size cities around Taihu Lake, such as Hangzhou, Suzhou, Wuxi, Changzhou, Jiaxing, Huzhou, Kunshan and Jiangyin. As one of the famous water-towns in the world, this region is characterized by the presence of many rivers and lakes, such as the Jiangnan Canal (the southern section of the Beijing–Hangzhou Grand Canal), Wangyu River, Taipu River, Yangcheng Lake, Cheng Lake and Dianshan Lake. Rapid urbanization in the past 50 years has caused dramatic changes on the underlying surface of this region, particularly the river systems. Consequently, the rivers and lakes in PRNRTB have decreased significantly.

2.2. Data

The river systems data of the 1960s and 1980s is derived from digitalized paper topographic maps, the river systems maps and the data of 2000s is from a digital line graphic at a scale of 1:50,000. According to the classification method for streams (Strahler, 1952) and its natural feature and social attribute, rivers are divided into four stream orders in PRNRTB (Table 1). Rivers wider than 40 m are classified as primary rivers. Rivers with width between 20 and 40 m are considered as secondary rivers. Those sized between 10 and 20 m in width are classified as tertiary rivers. Rivers less than 10 m in width are the quaternary rivers. Primary and secondary rivers are viewed as main rivers, and tertiary and quaternary rivers are considered tributary rivers.

Table 1
Classification method of rivers of PRNRTB.

Types	Orders	Widths	Graphical representation		Main functions
			Paper topographic map	Digital line graphic	
Main rivers	Primary rivers	>40 m	Double line rivers (>0.8 mm)	Planar canal, surface rivers and main channel	Discharge
	Secondary rivers	20–40 m	Double line rivers (0.4–0.8 mm)	Planar canal, surface rivers and main channel	
Tributary rivers	Tertiary rivers	10–20 m	Wide single line rivers (0.3 mm)	Linear surface rivers and main channel	Storage
	Quaternary rivers	<10 m	Narrow single line rivers (0.15 mm)	Linear branch channel	

3. Methodologies

3.1. Characteristic indicators of river systems

River systems can be characterized by their physical properties, including original descriptive indicators and complex integrated indicators. The original descriptive indicators of river systems, including river length, river number, river bifurcation, stream order and water surface area, have rarely been used directly in previous studies. The river complex integrated indicators were in the other hand have been widely used in recent decades, such as river density, river frequency, water surface ratio, river development coefficient, river systems complexity, river systems stability, river bifurcation ratio, river length ratio, river sinuosity, main river area length ratio, box dimension and other complex integrated indicators of river systems (Tarboton et al., 1988; Roth et al., 1996; Schuller et al., 2001; Wang et al., 2011). In our research, these complex integrated indicators are classified into quantitative characteristics, morphological characteristics and structure characteristics indicators. In accordance with the characteristics of river systems in PRNRTB and the possibility of data acquisition, we select six indicators, including river density, water surface ratio, river development coefficient, river sinuosity, main river area length ratio and box dimension to describe the physical characteristic of river systems in PRNRTB (Table 2).