Impacts of urbanization on river system structure: a case study on Qinhuai River Basin, Yangtze River Delta

Xiaomin Ji, Youpeng Xu, Longfei Han and Liu Yang

ABSTRACT

Stream structure is usually dominated by various human activities over a short term. An analysis of variation in stream structure from 1979 to 2009 in the Qinhuai River Basin, China, was performed based on remote sensing images and topographic maps by using ArcGIS. A series of river parameters derived from river geomorphology are listed to describe the status of river structure in the past and present. Results showed that urbanization caused a huge increase in the impervious area. The number of rivers in the study area has decreased and length of rivers has shortened. Over the 30 years, there was a 41.03% decrease in river length. Complexity and stability of streams have also changed and consequently the storage capacities of river channels in intensively urbanized areas are much lower than in moderately urbanized areas, indicating a greater risk of floods. Therefore, more attention should be paid to the urban disturbance to rivers.

Key words | Qinhuai River Basin, river structure, urbanization, water environment, water resource

Xiaomin Ji
Youpeng Xu (corresponding author)
Longfei Han
Liu Yang
School of Geographic and Oceanic Science,
Nanjing University,
Nanjing 210093,
China
E-mail: *Xuyp305@163.com*

INTRODUCTION

Urbanization, characterized by high intensity of land use and cover change, exert an impressive influence on the hydrological processes (Brun & Band 2000; Jennings & Taylor Jarnagin 2002; Beighley *et al.* 2003; Brandes *et al.* 2005; Barco *et al.* 2008; Chen *et al.* 2009; Xu *et al.* 2010; Zhou *et al.* 2013), which is observed in variability of hydrological features, such as precipitation, river channel, base flow, water level, and stream flow (Gregory *et al.* 1992; Barnett *et al.* 2008; Sang *et al.* 2013; Xu *et al.* 2014; Yang *et al.* 2014). Previous research showed that over 60% of the river channels in the world have undergone profound changes due to urbanization (Sear & Newson 2003). The urban river system is one of the most intensive zones of interaction between natural processes and human activities. However, the impervious area has increased and a large number of river systems have been destroyed due to the urbanization process. Consequently, shortening of flood concentration time, increasing flood peak (Zhou *et al.* 2013), enlargement of runoff coefficients during the storm flood processes, and decreasing regulation and storage capacity (*SC*) of river networks of are taking place in urbanized areas. All these changes result in increased risk of vulnerability after heavy rains in these areas, which has been a serious threat to human survival and regional economic development. Therefore, investigating the characteristic of river systems is necessary under the background of urbanization.

The studies about impacts of human activities on the river system began in the mid-nineteenth century. Marsh (1864) discovered that human activities induced changes in river development as early as in the 1860s. Horton (1945) theorized a well-known law of stream number and length, expanding new directions for quantitative study of a river system. By studying the hydrological effects of urbanization of Monks River in south-central England, Gregory *et al.* (1992) reported that the spatial pattern of rivers changed, width of main river channels increased by approximately 2.2 times, depth decreased by approximately 0.4 m, and capacity increased by about 2.2–2.5 times. Vanacker *et al.* (2005) studied the hydrological response of river systems to land-use and land-cover change in southern Ecuador Deleg, based on aerial photographs and field surveys. They discovered that general river channels narrowed by over 45%, riverbed deepened by over 1 m, and riverbed deposition fraction decreased from 13.2 to 4.7 cm. These findings reveal that the impact of urbanization on river structure is complicated. So far, there have been some studies about the impacts of urbanization on river network characteristics in China. Most of them were concentrated in Yangtze River Delta

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(Yang *et al.* 2004; Yuan *et al.* 2005b; Chen *et al.* 2007; Cheng *et al.* 2007; Su & Yang 2008; Wang *et al.* 2012) and Zhujiang Delta (Huang *et al.* 2008). These studies showed that urbanization has resulted in declining trends in river length, water surface ratio (*WSR*), river network structure stability, and *SC*. However, no studies have been found on the response of streams to urbanization in the suburbs of Nanjing, located in the midstream and downstream of Qinhuai River Basin. This area has been urbanized rapidly for nearly 30 years. Natural and socio-economic conditions of Qinhuai River Basin have changed tremendously, making water, environmental, and ecological problems such as soil erosion, water shortages, water pollution, and flood intensification more outstanding (Wang *et al.* 2009). Therefore, the objective of this study is to evaluate the hydrological effects of urbanization in Qinhuai River Basin so as to provide a reference for improving the water environment and developing a sustainable regional water resources usage.

MATERIALS AND METHODS

Study region

Qinhuai River Basin is located downstream of Yangtze River, southwest of Jiangsu Province. Lishui River and Jurong River converge at the northwest village in Jiangning District and enter the Yangtze River through Qinhuai New River from the northwest corner and Wuding gates. The Qinhuai River is about 34 km long, with a watershed catchment area of 2,631 km^2. The topography of Qinhuai River Basin is a fan-shaped tectonic basin, surrounded by hills and mountains. Riverbanks of midstream and downstream from Qianhan village are low-lying polders with a ground elevation of 6–8 m. After the polders, there are hills and mountain areas with a ground elevation of 300 m or less. Meteorologically, the basin is located in the subtropical semi-humid monsoon climate zone, which has abundant rainfall with annual average rainfall of 1047.8 mm and average annual runoff of 6.95×10^8 m^3. The climate possesses such features that the flood and heat occur in the same period, and floods and droughts also occur sometimes.

With rapid development of urbanization in Nanjing City, the degree of urbanization in the basin reached 59.3% in 2000. The underlying surface, river network structure, and hydrological processes changed greatly due to urban trails and construction of development zones. Water area decreased and impervious surface increased significantly. In addition, the basin encounters huge floods, and the lives of people and property are threatened when large rainstorms occur due to the limited capacity of the pipe network and river drainages and low standard of flood control and drainages.

In this study, midstream and downstream river networks of Qinhuai River Basin, from Qianhan village down to the Wudingmen floodgate and Qinhuai New River floodgate were selected (Figure 1). Referring to the topographic condition of the Qinhuai River Basin and adjusting as per the Nanjing water resources planning maps, the study area

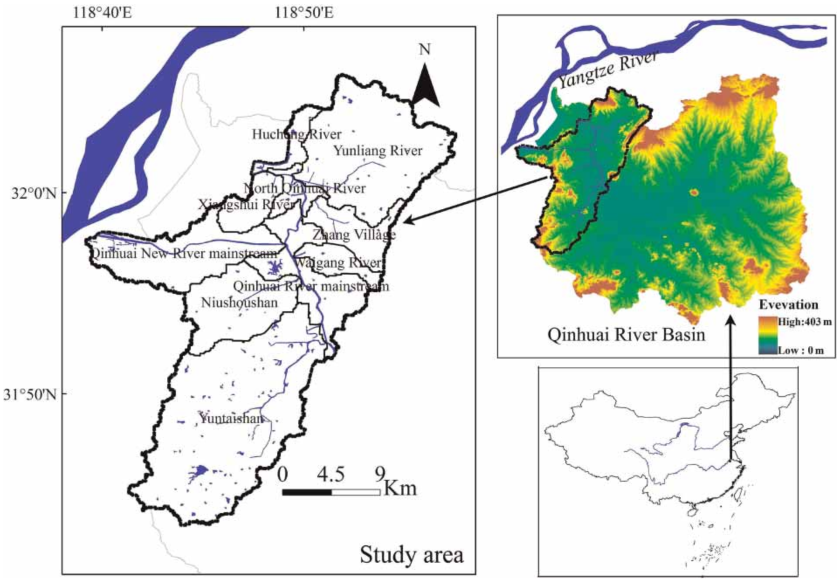

Figure 1 | Location of study area.

was divided into 10 water conservancy districts, namely Yuntaishan, Niushoushan, Waigang River, Qinhuai New River, Qinhuai River mainstream, Zhang village, Xiangshui River, North Qinhuai River, Huchang River, and Yunliang River as shown in Figure 1.

Data

The data include two topographic maps at the scale of 1:50000 in the 1980s and 2009, and 14 Landsat TM images in 1979 and 2009. Combined with the remote sensing images, the topographic maps were used to extract the water system. The elements in the water system are represented by polygons or polylines according to their characteristics. The lakes, ponds, and rivers with width greater than 20 m are represented as polygons, while other rivers are represented as polylines. The rivers wider than 20 m are viewed as the mainstream of Qinhuai River, and the rivers with width between 10 and 20 m are viewed as the first tributaries. Other rivers with width less than 10 m are viewed as the secondary tributaries.

The TM images were used to perform mapping of land cover in the Qinhuai River Basin. There are seven images each from 1979 to 2009 with the spatial resolution of 30 m. After geometric correction and image mosaic, the TM images were classified into urban area, water, forest, paddy field, and nonirrigated farmland by manual interpretation.

River structure indicators

In this study, a total of seven indices are selected to investigate the variation of stream structure and its response to urbanization. The definitions of these indices are displayed below.

Drainage density (*Dd*) is the basic parameter in quantitative geomorphic method (Strahler 1957), and *WSR* plays an important role explaining the ecological degradation in river ecosystems under the background of urbanization (Gao *et al.* 2012).

Dd and *WSR* were calculated as below:

$$Dd = L_R/A \tag{1}$$

$$WSR = A_w/A \tag{2}$$

where, L_R and A are the total length and area of the basin, and A_w represents water area.

Complexity of river (*CR*) has been used in describing the evolution status of river number and length (Yuan *et al.* 2005b). A greater *CR* value indicates more complexity of the river structure and more developed tributaries supported by the main river. It is a synthesis index of branching ratio and length ratio. Stability of river (*SR*) indicates the ratio of total length and total area of the river (Yuan *et al.* 2005b). Since the synchronized evolution of river length and area is directly resulting from changes in river structure, the *SR* indicator can be applied to calculate the stability of river structure over different years. *CR* and *SR* were calculated as follows:

$$CR = N_c(L_R/L_m) \tag{3}$$

$$SR_t = (L_t/RA_t)/(L_{t-n}/RA_{t-n})n > 0, t > n \tag{4}$$

where *Nc* is the number of stream orders; L and L_m are the total length of the whole rivers and main rivers, respectively; SR_t represents the stability of the river in the past n years in year t; and L_t, RA_t and L_{t-n}, RA_{t-n} represent the total length and area of rivers in year t and t-n, respectively. *SR* with a value greater than 1 indicates that length development is better than area development, and SR of less than 1 indicates that area development is better than length development.

SC per unit area and regulation capacity per unit area (*RC*) are used to present the storage and *RC* of the river systems in the plain river network (Yuan *et al.* 2005a).

SC and *RC* were calculated as below:

$$SC = C_h/A; RC = (C_h - C_n)/A \tag{5}$$

where C_h and C_n are the total water volume the river can store at high and normal water level, respectively, and A is areas of corresponding basin.

The land expansion strength index (*LEI*) model was applied to analyze spatial difference in urbanization (Liu *et al.* 2000). The *LEI* represents urban land expansion strength, indicating the ratio of urban land expanded area and total land area in the study period, defined as below:

$$LEI = 100*[(ULA_{i,t+n} - ULA_{i,t})/n]/TLA_i \tag{6}$$

where $ULA_{i,t+n}$ and $ULA_{i,t}$ are urban land use area in year $t+n$ and t, and TLA_i is the total land use area.

RESULTS

The change of land cover from 1979 to 2009

Based on land cover maps from 1979 and 2009, the area of each type of land cover was calculated and is shown in Figure 2. In the Qinhuai River Basin, the change in urban area and forest was more significant than that for the other three types. In 1979, the size of the urban area was only 17.2 km^2, but it increased to 158.81 km^2 in 2009, which is more than eight times the size in 1979. On the other hand, the area of forest decreased from 242.26 km^2 in 1979 to 64.15 km^2 in 2009. In total, the reduced area of the forest was 178.11 km^2, which accounts for 73.52% of the forest area in 1979. However, there was not much change in paddy fields and nonirrigated farmlands. From 1979 to 2009, the area of paddy field decreased by 14.5 km^2, while the area of the nonirrigated farmland increased by 34.64 km^2. The area of water bodies also increased, but the increment was very small.

The form and structure of the river system

River structural indicators were calculated and are summarized in Tables 1 and 2. The characteristics of the change in the river system structure of Qinhuai River Basin are described below.

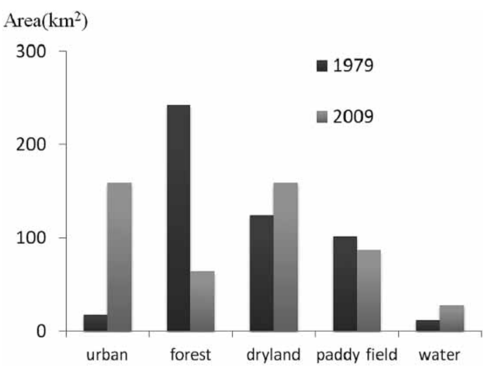

Figure 2 | The change of land cover from 1979 to 2009 in Qinhuai River Basin.

The length and density of rivers

Compared to the 1980s, the number of rivers reduced significantly, and river length and density decreased greatly in 2009. From the 1980s to 2009, the river length shortened by 345.90 km, and the *Dd* decreased by 41.03%. Meanwhile, the reduced amount of rivers and the progress of urbanization had a significant negative relationship, indicating that *Dd* became sparse through natural evolution and human impacts over 20 years of urbanization progress in Qinhuai River Basin.

River network structure

In the temporal scale, the river network complexity dropped by 23.72% from 18.50 in the 1980s to 14.11 in 2009. In the spatial scale, the higher the level of urbanization, the more obviously the river complexity decreases, leading to a simplified river network structure. The river composition hierarchy of the study area is becoming simplified; tributaries that support main rivers are gradually disappearing, showing from complex to simple, polyhydric to single trends of river development.

Overall, the rivers were widened significantly, with an increment trend in ratio of main rivers.

It is mainly caused by the impacts of man-made channels, gates, dams, dikes, and other water conservancy construction. By comparing the river in the same order, higher level of urbanization often results in more significant decrease or smaller increase in river length and area. It can be concluded that lower class (highest class corresponding to rivers of first order) rivers are more likely to be influenced by urbanization, while higher class rivers are less affected, mainly reflected by the area difference after the river is filled.

River stability

From the 1980s to 2009, the length area ratio of every water conservancy district showed an obvious downward trend (Table 2). With the accelerated process of urbanization, the speed of decline increased. This was due to the disappearance of mainstream-supporting tributaries caused by

Table 1 | River system structure of Qinhuai River Basin

Length (km)			Area (km^2)			*Dd* (km/km^2)			*WSR* (%)			*CR*		
1980s	2009	Rate of change (%)	1980s	2009	Rate of change (%)	1980s	2009	Rate of change (%)	1980s	2009	Rate of change (%)	1980s	2009	Rate of change (%)
842.94	497.04	–41.03	24.89	32.28	29.66	1.70	1.00	–41.03	6.38	7.52	17.86	18.50	14.11	–23.72

Table 2 | River system structure in different water conservancy districts in 1980s–2009

Water conservancy districts	High level of urbanization			Medium level of urbanization							Low level of urbanization			Total area
	Waigang River district	Xiangshui River district	Average	North Qinhuai River district	Qinhuai River mainstream district	Zhang village district	Niushoushan district	Yunliang River district	Qinhuai New River mainstream district	Average	Hucheng River district	Yuntaishan district	Average	
LEI	2.98	2.67	2.83	2.15	2.1	2.01	1.55	1.42	1.36	1.77	0.66	0.46	0.56	1.736
SR	0.74	1.26	0.96	0.75	0.45	0.93	0.78	0.98	0.43	0.67	0.92	0.94	0.93	0.76
CR 1980s	47.06	31.92	38.1	10.72	11.91	16.46	10.82	41.4	13.5	15.3	6.96	33.29	26.51	18.5
2009	17.82	30.52	19.1	5.53	5.82	6.35	10.53	30.78	7.41	13.1	5.1	17.3	15.12	14.11
Rate of change (%)	−62.1	−4.36	−50	−48.43	−51.13	−61.4	−2.7	−25.7	−45.07	−15	−26.76	−48.03	−42.95	−23.72

urbanization, which led to a decrease in river stability. Therefore, regions with higher degree of urbanization often had lower river stability.

Water area

From the 1980s to 2009, the *WSR* was less than 8%, which was 6.38% in the 1980s and 7.52% in 2009. The little increase in water surface is due to a large increase in ponds which were constructed for fish culture in the suburbs of Nanjing despite the decrease of river number and length. Spatially, the *WSR* decreased in the highly urbanization, but increased slightly in areas of medium and low degree of urbanization because of the constructing of ponds. Hence, except for a slight increase in Zhang village and Yuntaishan districts, both the water body area and the *WSR* have an overall decreasing trend from the 1980s to 2009. Dividing the water bodies into lakes, rivers, and low-grade rivers, the lake and low-grade area decreased, while the area of main rivers increased from the 1980s to 2009,

During the urbanization process, soil became less permeable to water due to building constructions. Many small water bodies were buried, gradually disappeared, and replaced by urban impervious surface. Caused by dikes, artificial lakes, and other hydraulic construction along with farming and other human activities, some small water bodies fragmented into smaller pieces, resulting in significantly reduced area of small water bodies. Among them, the most obvious area reduction of lakes occurred in Qinhuai New River district and Qinhuai River mainstream district. These apparently indicated the impacts of the high level of urbanization along the Qinhuai River.

Regulation and *SC* of river network

Table 3 indicates that the storage and *RC* per unit area of every water conservancy district had a negative relationship with the level of urbanization. In other words, as the level of urbanization increased, the storage and regulation capacity of rivers decreased. For example, values of storage and *RC* per unit area were 8.34×10^5 and 4.45×10^5 km^3/km^2 for highly urbanized regions, while they increased dramatically to 20.23×10^5 and 10.76×10^5 km^3/km^2 for those medium urbanized regions, respectively.

Urbanization makes changes to *WSR*, which affects the ability of storage and regulation, and naturalness and fractal dimensions reflected by the river network structure. There are obvious simplified phenomena in regions with rapid urbanization, while tributaries supporting main

Table 3 | Storage regulation and capacity of river network of different water conservancy districts in 2009

Water conservancy districts	*SC* (10^5 km^3/km^2)	*RC* (10^5 km^3/km^2)
Waigang River district	10.87	5.96
Xiangshui River district	6.33	3.3
Areas with high level of urbanization	8.34	4.45
North Qinhuai River district	61.24	32.21
Qinhuai River mainstream district	35.96	19.8
Zhang village district	10.95	5.95
Niushoushan district	11.08	5.97
Yunliang River district	11.33	6.03
Qinhuai New River mainstream district	27.47	13.95
Areas with medium level of urbanization	20.23	10.76
Hucheng River district	39.34	20.33
Yuntaishan district	13.73	7.49
Areas with low level of urbanization	15.24	8.29
Total area	17.73	9.52

rivers have significantly decreased. However, compared to water-delivering and flood-discharge functionalities of high class rivers, a major role in storage, regulation and flood convergence is played by lower class rivers. By taking advantages of high level connectivity, low class rivers have saved water for the dry season and delayed flood peak impacts. Lower urbanized areas are mainly concentrated in the lower reaches of Qinhuai River Basin where a high density of low class rivers, and natural and artificial water bodies occurs. Therefore, compared to areas of medium and low degree of urbanization, highly urbanized areas are often less capable of storing and regulating water.

CONCLUSIONS

From 1979 to 2009, the overall change in the underlying surface in the target area shows that along with the expansion of urban-construction land by more than eight times, the area of woodland drastically reduced by nearly 73.52%, while lands with other use patterns only changed slightly. The result clearly indicated that woodland is the most affected type of land in this area. A large area of woodland was encroached by urbanization.

Lower class rivers are more likely to be influenced by human activities than higher class rivers. Many lower level rivers were buried and gradually disappeared during the urbanization process. The impacts on main rivers were mainly reflected in the process of river widening. Along with the development, the stability of rivers is weakened. From a spatial perspective, the stability of rivers and the progress of urbanization had a significant negative relationship. The higher urbanization level resulted in an obvious greater decrease in river network complexity and a more simplified river structure, with a development trend from complex to simple.

Affected by urbanization, river regulation and *SC* showed a downward trend, and thus led to a situation commonly known as 'floods every year, floods after rains every year' in Nanjing in recent years. Protection and restoration of river systems are required in terms of sustainable urbanization.

The hydrological effect of urbanization is currently becoming a hot issue. Starting from the impacts of urbanization on river structure, this study explored the hydrological effects of urbanization, and provided a reference for studies in other similar regions. Due to the complexity of hydrological effects, the assessment should be site-specific and carefully performed.

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REFERENCES

Barco, J., Hogue, T. S., Curto, V. & Rademacher, L. 2008 Linking hydrology and stream geochemistry in urban fringe watersheds. *Journal of Hydrology* **360** (1–4), 31–47.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., Bala, G., Wood, A. W., Nozawa, T., Mirin, A. A., Cayan, D. R. & Dettinger, M. D. 2008 Human-induced changes in the hydrology of the western United States. *Science* **319** (5866), 1080–1083.

Beighley, R. E., Melack, J. M. & Dunne, T. 2003 Impacts of California's climatic regimes and coastal land use change on streamflow characteristics. *Journal of the American Water Resources Association* **39** (6), 1419–1433.

Brandes, D., Cavallo, G. J. & Nilson, M. L. 2005 Base flow trends in urbanizing watersheds of the Delaware River basin.

Journal of the American Water Resources Association **41** (6), 1377–1391.

Brun, S. E. & Band, L. E. 2000 Simulating runoff behavior in an urbanizing watershed. *Computers, Environment and Urban Systems* **24** (1), 5–22.

Chen, Y. X., Xu, Y. P. & Fu, W. J. 2007 Influences of urbanization on river network in the coastal areas of East Zhejiang province. *Advances in Water Science* **18** (1), 68–73 (in Chinese).

Chen, Y., Xu, Y. P. & Yin, Y. X. 2009 Impacts of land use change scenarios on storm-runoff generation in Xitiaoxi basin, China. *Quaternary International* **208**, 121–128.

Cheng, J., Yang, K., Zhao, J., Yuan, W. & Wu, J.-P. 2007 Variation of river system in center district of Shanghai and its impact factors during the last one hundred years. *Scientia Geographica Sinica* **27** (1), 85–91 (in Chinese).

Gao, C., Liu, J., Liu, X. Y. & Zhang, H. Y. 2012 Compensation mechanism of water surface ratio and pervious surface proportion for flood mitigation in urban areas. *Disaster Advances* **5** (4), 1294–1297.

Gregory, K. J., Davis, R. J. & Downs, P. W. 1992 Identification of river channel change to due to urbanization. *Applied Geography* **12** (4), 299–318.

Horton, R. E. 1945 Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin* **56** (3), 275–370.

Huang, Y., Wang, Y., Liu, Z., Zeng, X. & Chen, L. 2008 Stream construction characteristics in rapid urbanization area: Shenzhen city as a case. *Geographical Research* **27** (5), 1212–1220 (in Chinese).

Jennings, D. & Taylor Jarnagin, S. 2002 Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed. *Landscape Ecology* **17** (5), 471–489.

Liu, S. H., Wu, C. J. & Shen, H. Q. 2000 A GIS based model of urban land use growth in Beijing. *Acta Geographica Sinica* **55** (4), 416–426 (in Chinese).

Marsh, G. P. 1864 *Man and Nature, or Physical Geography as Modified by Human Action*. Sampson Low, Son and Marston, London, UK.

Sang, Y. F., Wang, Z. G., Li, Z. L., Liu, C. M. & Liu, X. J. 2013 Investigation into the daily precipitation variability in the Yangtze River Delta, China. *Hydrological Processes* **27** (2), 175–185.

Sear, D. & Newson, M. 2003 Environmental change in river channels: a neglected element. Towards geomorphological typologies, standards and monitoring. *Science of the Total Environment* **310** (1), 17–23.

Strahler, A. N. 1957 Quantitative analysis of watershed geomorphology. *Civil Engineering* **101**, 1258–1262.

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

Vanacker, V., Molina, A., Govers, G., Poesen, J., Dercon, G. & Deckers, S. 2005 River channel response to short-term human-induced change in landscape connectivity in Andean ecosystems. *Geomorphology* **72** (1), 340–353.

Wang, Y. J., Lu, H. J., Shi, Y. F. & Jiang, T. 2009 Impacts of land use changes on hydrological processes in an urbanized basin – a case study in the qinhuai river basin. *Journal of Natural Resources* **24** (1), 30–36 (in Chinese).

Wang, L., Xu, Y. & Yu, M. 2012 Analysis of the urbanization effect on the taihu plain river network – a case study of Wuchengxiyu region of Taihu basin. *Resources and Environment in the Yangtze Basin* **21** (2), 151–156 (in Chinese).

Xu, Y. P., Xu, J. T., Ding, J. J., Chen, Y., Yin, Y. X. & Zhang, X. Q. 2010 Impacts of urbanization on hydrology in the Yangtze River Delta, China. *Water Science and Technology* **62** (6), 1221–1229.

Xu, G., Xu, Y., Luo, X., Xu, H., Xu, X. & Hu, C. 2014 Temporal and spatial variation of water level in urbanizing plain river network region. *Water Science and Technology* **69** (11), 2191–2199.

Yang, K., Yuan, W., Zhao, J. & Xu, S. 2004 Stream structure characteristics and its urbanization responses to tidal river system. *Acta Geographica Sinica* **59** (4), 557–564 (in Chinese).

Yang, M., Xu, Y., Pan, G. & Han, L. 2014 Impacts of urbanization on precipitation in Taihu Lake Basin, China. *Journal of Hydrologic Engineering* **19** (4), 739–746.

Yuan, W., Yang, K., Tang, M. & Xu, Q. 2005a Stream structure characteristics and their impact on storageand flood control capacity in the urbanized plain river network. *Geographical Research* **24** (5), 717–724 (in Chinese).

Yuan, W., Yang, K. & Xu, Q. X. 2005b Effect of urbanization on growth of Shanghai River function and stream structure. *Resources and Environment in the Yangtze Basin* **14** (2), 133–138 (in Chinese).

Zhou, F., Xu, Y. P., Chen, Y., Xu, C. Y., Gao, Y. Q. & Du, J. K. 2013 Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. *Journal of Hydrology* **485**, 113–125.

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