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IMPACT OF URBANIZATION ON STRUCTURE AND FUNCTION OF RIVER SYSTEM

—Case Study of Shanghai, China

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ABSTRACT: Urbanization can affect the physical process of river growth, modify stream structure and further influence the functions of river system. Shanghai is one of the largest cities in the world, which is located in Changjiang (Yangtze) River Delta in China. Since the 1970s, the whole river system in Shanghai has been planned and managed by the Shanghai Water Authority. The primary management objectives in the last 30 years have been to enhance irrigation and flood-control. By using Horton-Strahler classification and Horton laws as a reference, a novel method of stream classification, in conjunction with the traditional and specially designed indicators, was applied to understanding the structure and functions of the river system in Shanghai. Correlation analysis was used to identify the interrelations among indicators. It was found that the impact of urbanization on the river system was significant although natural laws and physical characteristics marked a super-developed river system. There was an obvious correlation between the degree of urbanization and the abnormal values of some indicators. Urbanization impacts on river system such as branches engineered out, riverbank concreting and low diversity of river style were widely observed. Each indicator had distinct sensibility to urbanization so they could be used to describe different characteristics of urban river system. The function indicators were significantly related to structure indicators. Stream structure, described by fractal dimension and complexity of river system, was as important as water area ratio for maintaining river's multi-function.

KEY WORDS: river system; stream classification; Horton law; urbanization; Shanghai

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1 INTRODUCTION

Since the 1750s, promoted by Industry Revolution and the rapid development of science and technology, large-scale urbanization swept over the world. So far, it is estimated that more than 60% of the rivers in the world have been experienced high levels of human modification (ALLAN, 1995). River systems have now become one of the most deeply human-affected ecosystems in the earth. To approach the impact of human activities on river system as a multidiscipline topic has been a focus of research for the last 30 years. Researches demonstrated the various impacts of urbanization on river system from different aspects. It had been considered that the change of geomorphology of river systems was an important and neglected factor of environmental change (SEAR and NEWSON, 2003). The study results of SURIAN and RINALDI (2003) showed that considerable channel adjustment, mainly exhibited as incision and narrowing caused by human disturbance, has been commonly recognized in Italian rivers as well as in UK and America. Urbanization also had a dramatic impact on the health of river system, which led to a series of studies on river condition assessment (ZANDBERGEN, 1998; ISIDORI et al., 2004). A case study in Toronto, Canada expressed that the factors of both urban land use and riparian landscape decided river water quality. When the ratio of urban land use was over 50%, it was hard to maintain a good water quality even if forest covered the whole of the riverside (ALLAN, 1995).

Although there had a great number of papers focused on natural river networks, little attention is given to the urbanization impact on the structure and functions of river systems. Early in 1945, Horton proposed two laws to

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Biography: YUAN Wen (1965-), female, a native of Changzhou of Jiangsu Province, Ph.D., professor, specialized in regional environmental change and urban hydrology. E-mail: wyuan@admin.ecnu.edu.cn explain the growth of river system. One described the negative relationship between stream order and the logarithm of the number of streams, and the other was about the positive relationship between stream order and the logarithm of stream length (ALLAN, 1995). Horton's research spurned quantitative methodologies to analyze river systems. Numerous works followed and developed his idea in many countries. For example, GU (1984) demonstrated that stream structure was generally determined by watershed shape, river system stability, river hydrological regime and flood carrying capacity. ZHOU (1997) and GAO and YANG (1994) had their discussion of the stream structure of the Beipan and Wu rivers in the southwest of China based on Horton's hierarchical classification system. There have also been studies that explored the structure of channel networks and dividers within watersheds in America, France, Colombia and China (PUENTE and CASTILLO, 1996; GRAVE and DAVY, 1997; FENG and FENG, 1997). More researches have been conducted in the fields of fractal description of natural river systems and identifying the limitations of Horton's laws (LA BARBERA and ROSSO, 1989; ROSSO et al., 1991; ROTH et al., 1996; VELTRI et al., 1996; CHEN and LIU, 2001; KIRCHNER, 1994; TARBOTON, 1996; LUO, 1998; WANG, 2002).

Since the 1980s, China has maintained a trend of rapid urbanization: the percentage of urbanized land had risen from 18% in 1980 to 36% in 2000 and the rate of urbanization for the next 20 years had been estimated to be 0.8%- 2.0% per annum (National Bureau of Statistics of China, 2003). Meanwhile, after more than 20 years' rapid economic growth, some large cities, such as Shanghai, are beginning to recognize the demands for "city regeneration" in the same way as happened in Europe during the mid-1990s. One response to the pressure for regeneration has been the implementation of initiatives involving river system planning and rebuilding for the purposes of more safe water environment, ecosystem restoration and biodiversity, and more natural space (XU and ZHANG, 2001; CHEN, 1998).

To study the structure and functions of urban river system under strong human modification is for providing guidance for those charged with managing the river system in the continued rapid urbanization process. It is a new challenge because we need not only to transfer our attention to those watersheds that have been extremely modified by urbanization but also new techniques for analyzing urbanized river systems. In this paper, taking some indicators commonly used for characterizing river networks, such as fractal dimension, bifurcation and stream lengths ratio, and Horton's laws as reference, integrated with three specially designed indicators, we introduced a novel system including new stream order classification and new catchment's division for plain river system that were more closely related to river management. Therefore, it is possible to gain an insight into the structure and functions of a river system under huge human disturbance. Such insights are beneficial in recognizing the changes that have taken place, understanding the effects of the changes on the river system and maintaining reasonable structure and functions of river system in the future.

2 STUDY AREA

Shanghai, located in the Changjiang River Delta, is a typical tidal area with a high density of rivers in the eastern China and one of the largest cities in China, with a total population of 16 ×10^6 and a total area of 6340km^2. The urbanization level was 77.6% in 2003 but only 58.7% in 1978. The area within the outer cycle lines was commonly recognized as central urban area. The catchment with more than 50% of its area in central urban area was defined as high-urbanized catchment (Fig. 1).

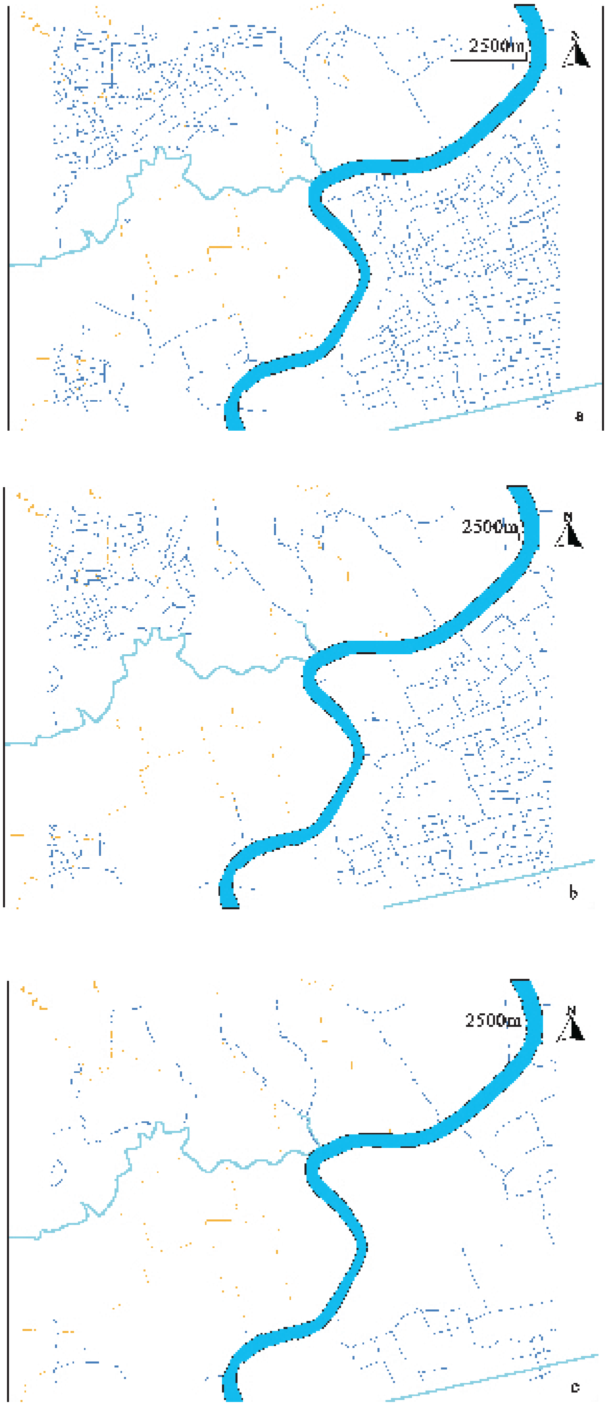
Fig. 1 Catchment distribution in Shanghai

According to the investigation of the Shanghai Water Resources Survey conducted by Shanghai Water Authority in 2000, there were 23 787 rivers in Shanghai, the river density was 3.41km/km^2, and water area covered 8.41% of the whole city (WANG and RUAN, 2001). This is not a static position and the results estimated by this paper is based on the "Shanghai Central City River System GIS" finished by Shanghai Drainage Company and East China Normal University (Fig. 2). It is shown that the stream length and water area in the center of Shanghai City have decreased by 60% and 27% respectively from the 1950s to the late 1990s (Table 1). Importantly the rate of reduction of stream length and water area was accelerating. Having recognized such trends, so the aim of this research was to demonstrate clearly the impact of urbanization on the river system in Shanghai.

Due to the flat terrain and tidal influence, the rivers flow slowly mainly from west to east and flow direction changes twice each day. The complex hydrological regime combined with anfractuous channel networks made it difficult to study and manage river systems properly. In 1977, 14 catchments covering 97% of the total area of Shanghai were planned by Shanghai Water Authority in order to meet city's basic demands for flood proofing and irrigation. Each catchment was taken as independent drainage basin. At the same time, a stream classification system that considered both the natural channel relations and the roles of steam within river system, namely city level, district level, town level and village level streams were designed as a tool for river planning, management and protection (WANG and RUAN, 2001) (Table 2 and Fig. 1).

3 DATA AND METHODS

The research reported here focused on 11 mainland catchments of the 14 ones in Shanghai except for three island catchments. In order to analyze the impact of urbanization on structure and functions of river system in Shanghai, the 11 catchments were divided into three groups (high, middle and low) according to the degree of urbanization (Table 2). Because those catchments under the low urbanization kept their original state well, this paper set such catchments as basement for understanding the impacts of urbanization on river system. The hierarchical classification system designed by Shanghai Water Authority in the 1970s, which divided streams into city, district, town and village levels, was adopted in this paper. Horton's hierarchical classification system was used as a reference. Streams in the village level were defined as first order, and ones in the town level, the district level and the city level as the second, third and fourth orders respectively. Thus we have a criterion to describe the structure of river system after urbanization.



a: 1950, b: 1979, c: 2003; Area of study region: 191.3km^2

Fig. 2 River system change in central area of Shanghai

Data on the Shanghai river system, i.e. stream number, stream lengths in each level, the ratio of water area to the total area of Shanghai and riverbank type, derived from the "Shanghai Water Resources Survey Report" (WANG and RUAN, 2001), the "Shanghai river survey report" finished by Shanghai River and Watergate Management Office in 2001, the "Shanghai Riverbank Sur-

Table 1 Change of stream structure in central area of Shanghai since the 1950s①

	Stream length (km)	Water area (km^2)	Stream length/ Water area	R_S②
1950s③	440.8	10.58	41.66	-
1960s③	403.1	10.04	40.15	0.96
1979	332.5	9.40	35.37	0.80
1984	281.9	8.86	31.82	0.90
1989	279.9	8.79	31.84	1.00
1994	278.3	8.76	31.77	0.99
1999	175.4	7.72	22.72	0.72

Notes: ① Area of study region: 191.3 km^2; ② Stability of the river system, $R_s= (L_{i+n}/WA_{i+n})/(L_i/WA_i)$, L_{i+n}, WA_{i+n} and L_i, WA_i are the total stream length and total water area in year i+1 and year i; ③ Because there had not enough materials that covered the whole research area in one year, the data in the 1950s and 1960s were the combination based on materials in partial area and different year.

Table 2 Physical feature of 14 catchments in Shanghai

Group	Catchment	Stream number	Stream length (km)	Area (km^2)
High-urbanized catchment	Yunnan	816	593	173
	Dianbei	680	412	179
Mid-urbanized catchment	North Jiabao	3866	3275	699
	Diannan	901	600	187
Low-urbanized catchment	Pudong	10882	7259	1977
	Qingsong	2098	2622	758
	East Punan	1573	2007	479
	West Punan	909	1150	293
	Taibei	308	269	85
	Tainan	266	283	100
	Shangta	76	81	32
Island catchment	Chongming	1119	2027	1070
	Changxing	138	208	77
	Hengsha	141	193	49

vey Report in Central City A rea" finished by Shanghai River and Watergate Management Office in 2002 (Table 3 and Table 4).

Following indicators were used to describe the river system in Shanghai. The mean bifurcation ratio (MR_b) was calculated as:

$$MR_b=10^{|K_n|} \tag{1}$$

where K_n is the slope of line x-lgN_x (x is abscissa), N_x is the number of streams in order x; x indicates the number of stream order in a catchment. A high value of MR_b indicates that there are more branches in the river system. Generally, the value of MR_b in natural watershed is 3.0- 5.0.

The mean stream length ratio (MR_L) was calculated with following equation:

$$MR_L=10^{|K_L|} \tag{2}$$

where K_L is the slope of line x-lgL_x (x is abscissa), L_x is the average stream length in order x; x indicates the number of stream order in a catchment. A high value of MR_L indicates that branches are longer in the higher order stream. The value of MR_L in natural watershed is 1.5- 3.5.

The fractal dimension (D) is an indicator describing the spatial distribution of the river system in a catchment. It is calculated as:

$$D=\lg MR_b/\lg MR_L \tag{3}$$

Generally, the value of D in natural watershed is 1- 2. A larger value indicates that the river network is well developed in the whole watershed area.

Other indicators used are water area under average water level (W_p); total stream lengths in area of 1km^2 (R_D); river channel storage reflecting the quantity of water resources (CS); and adjustable river channel storage reflecting the ability for flood control (ACS).

As mentioned above, the indicators and their normal range were more credible for natural river system. From Table 3, the values of some indicators were found to be outside their normal range. This is most likely explained by both the complex hydrological regime and the effects of urbanization that had greatly modified the river system in Shanghai. Therefore, three new indicators were

Table 3 Collection of stream structure and function indicators of 11 catchments of Shanghai

	W_P (%)	R_D (km/km^2)	MR_b	MR_L	D	CS (m^3/km^2)	ACS (m^3/km^2)	R_c
Yunnan	3.03	3.42	1.05	2.72	0.05	0.89	1.37	4.36
Dianbei	3.63	2.30	2.51	3.39	0.76	2.77	3.27	7.05
Diannan	4.34	3.21	5.48	4.47	1.14	3.44	4.36	7.80
North Jiabao	4.98	4.69	5.96	3.32	1.49	4.75	6.53	16.46
Pudong	5.25	4.22	5.69	3.31	1.45	7.03	5.38	17.18
Qingsong	5.53	3.46	5.27	2.91	1.56	9.31	8.90	17.21
East Punan	4.12	4.19	5.72	2.76	1.72	4.71	5.97	23.46
West Punan	4.96	3.92	4.41	2.40	1.69	9.61	6.75	18.44
Taibei	11.35	3.16	4.64	2.31	1.83	20.80	19.11	19.60
Tainan	3.96	2.83	3.78	2.42	1.50	5.93	5.37	19.50
Shangta	10.70	2.50	8.00	2.56	2.21	17.59	13.82	41.90

Notes: W_P, water area under average water level ; R_D, total stream length in an area of 1km^2; MR_b, mean bifurcation ratio; MR_L, mean stream length ratio; D, fractal dimension; CS, river channel storage; ACS, adjustable river channel storage; R_c, complexity of the river system.

Table 4 Riverbank type in central area of Shanghai

	Natural① (%)	Ecological② (%)	Concreted③ (%)	R_n④
River in city level	19.5	23.4	57.1	0.43
River in district level	48.3	24.0	27.7	0.72

Notes: ① Riverbank formed by natural actions. ② Ecological riverbank rebuilt by human being. ③ Concreted riverbank that stopped the exchange between river and surroundings. ④ Naturalness of the river system. $R_n=LB_n/LB$, LB_n is the length of natural and ecological riverbank and LB is the total length of riverbank

designed to reflect the effects of urbanization on river systems with the similar physical characteristics in Shanghai. They were the complexity (R_c), naturalness (R_n) and stability (R_s) of the river system.

Complexity of the river system (R_c) describes the degree of branching and the development of branch length. It is calculated with formula:

$$R_c=\omega_x\times(L/L_m) \quad (x=1, 2, 3, ..., n) \tag{4}$$

where ω_x is the stream order number; x indicates the number of stream order in a catchments; and L and L_m are the total stream length and the main-stream length. The larger the value of R_c, the higher the stream order and the longer branches there are within the system.

Naturalness of the river system (R_n) reflects human modification on river system and the ecological value of the riverbank. It is assumed that a natural or ecological bank has more biodiversity than heavily modified one, and the natural channel substrate and bank may have been replaced by concrete. It is calculated with equation:

$$R_n=LB_n/LB \tag{5}$$

where LB_n is the length of natural and ecological riverbank; and LB is the total length of riverbank. A larger value of R_n indicates good protection of a riverbank's ecological functions.

Stability of the river system R_s is calculated as follows:

$$R_s= (L_{i+n}/WA_{i+n})/(L_i /WA_i) \tag{6}$$

where L_{i+n}, WA_{i+n} and L_i, WA_i are the total stream length and total water area in year i+n and year i, respectively.

Methods of correlation analysis was used to identify relationships among the indicators.

4 RESULTS AND DISCUSSION

From Table 2, the area of high and middle urbanized catchments only occupied 24.95% of the total area of the 11 mainland catchments; stream number and lengths in 7 low-urbanized catchments occupied 72.00% and 73.69% of the total of 11 mainland catchments. The percentages of stream number and lengths in 2 high-urbanized catchments were only 6.69% and 5.42%. This meant that the area of river system suffered from strong disturbance in Shanghai was limited. On the other side, the values of MR_b, MR_L and D in each catchment were varying, and most of the data were larger than that in natural watershed.

From the view of 11 mainland catchments, the values of MR_L in 10 catchments varied within 1.5 - 3.5, which was coincident with the researches developed from Horton's laws (Table 3). However, the values of MR_b did not correspond to the existing literature (ALLAN, 1995; CARLOS and CASTILLO, 1996; GAO and YANG, 1994; GU, 1984; FENG and FENG, 1997; ZHOU, 1997). From Table 3, the reasonable values of MR_b all occurred in low-urbanized catchments (West Punan, Taibei and Tainan), in the other 6 middle and low-urbanized ones, the values of MR_b were more than 5. Only in two high-urbanized catchments, Yunnan and Dianbei, were the values of MR_b less than 3. These results indicated that the impact of urbanization on MR_b was greater than that on MR_L. Therefore, MR_L was still a useful indicator to reflect stream structure development in urban areas and the aberrancy of MR_b was effective to show urbanization effect on river system.

The values of D in 8 catchments were 1 - 2. The great aberrancy of MR_b, whatever low or high, could cause the aberrancy of D. It is concluded that D, as an indicator used to identify the impact of urbanization on river system, is more effective when describing the extreme situation, poorly and highly developed river system.

The values of R_c greatly varied in different catchments (Table 3). The higher values were concentrated on the low-urbanized catchments especially on the ones located in the west and southwest part of Shanghai (Fig. 1), which have been planned as protection zones of drinking water resources since the 1970s. Industry was strictly limited in that area, the urbanization level was lowest in Shanghai and the river system was protected well. The high and middle-urbanized catchments had the lower values of R_c. Therefore, R_c seemed to be one of the most effective indicators to reflect the impact of urbanization on river system.

R_s is designed to express changes in the ratio of water area to stream length. If water area is kept stable in a certain period, R_s will show the changing process of stream structure. During the last 50 years, loss of water area was much smaller than that of stream length (Table 1). This has caused a significant change of stream structure in Shanghai. The values of R_s manifested a rapid change from 1994 to 1999, which coincided with a period of large-scale urban construction in Shanghai.

R_n is used to measure the human effects on the river system function as an ecological corridor. The values of

R_n in the district level were larger than that in the city level (Table 4). A large value for R_n could result from one of two situations: where the river system was still in its original state or where the river channel had experienced a process of eco-reconstruction. A smaller value for R_n, therefore, reflects the destruction of natural riverbanks and indicates bad quality of stream structure.

It is possible to identify three major effects of urbanization on the river system in Shanghai. Firstly, smaller branches have been engineered out of the system and this had resulted in a relatively simple stream structure. From the Shanghai Central City River System GIS and 2003 remote sensing photos of the whole Shanghai, obvious changes on river system can be observed in central Shanghai in 1950, 1979 and 2003 (Fig. 2). Especially from 1979 to 2003, quite a lot of rivers were disappeared and the typical network characteristic of river system in central Shanghai was fully changed. Secondly, the original river geomorphology has been extensively modified following the demand for flood control. As a result of the rapid urban development, only the river section with the maximum flow remained in existence and this had resulted, directly, in decrease of diversity of river style. Thirdly, the riverbank and riverbed were canalized and their banks were concreted, especially in the urban area. Based on the site survey, 57% of the rivers in the city level and 28% in the district level were concreted whereas the percentage of natural riverbank in district level was much greater than that in city level (Table 4). The more important the rivers for city were, the stronger the impacts of human activities were. The results of such civil engineering showed in two aspects: the destruction of the riverside ecology and the weakness of the river function as a "media" and "pathway" of the urban ecosystem.

Correlation analysis was used to find the interrelations among the indicators. The results were listed in Table 5.

W_p was most significantly correlated with ACS, R_c, also correlated with CS and D (Table 5). It indicated that W_p was the most important indicator both for city water safety and stream structure development. It is necessary to have sufficient water area to ensure a well-developed stream structure and enough storage for flood prevention. Hence, with respect to the process of urban regeneration and ecosystem restoration, more attention need to be paid to this indicator than to the others.

ACS was correlated with R_c on the 0.001 significant level, correlated with D on the 0.01 significant level. CS was correlated with D on the 0.001 significant level, correlated with MR_b on the 0.01 significant level and R_c on the 0.05 significant level. This identified the close relationship between stream structure and function. Bigger values of W_p and R_c all occurred in the Taibei and Shangta (Table 3). Therefore, a well-developed stream structure is as important as W_p in keeping the multi-functions of river system.

R_c was significantly correlated with W_p and D. D was significantly correlated with MR_b, R_c and W_p. It showed that water area and hierarchically development of stream number were two factors that affected the structure of river system.

Table 5 Correlation coefficient between indicator and is significant level

	W_p	R_D	MR_b	MR_L	D	CS	ACS	R_c
W_p	1							
R_D	0.2534	1						
MR_b	0.5478	0.2040	1					
MR_L	0.3824	0.0752	0.0900	1				
D	0.6674*	0.0933	0.8516***	0.3226	1			
CS	0.6832*	0.0919	0.7791**	0.4759	0.8507***	1		
ACS	0.9661***	0.2285	0.5087	0.5163	0.7344**	0.6936*	1	
R_c	0.9612***	0.1729	0.5080	0.4523	0.7172**	0.6307*	0.9716***	1

Notes: *** The correlation between two indicators was significant on the P=0.001 level; ** The correlation between two indicators was significant on the P=0.01 level; * The correlation between two indicators was significant on the P=0.05 level

5 CONCLUSIONS

Natural laws and physical characteristics deeply affected the stream growth in Shanghai. However, urbanization had exhibited its effects on river system especially in central city. There had obvious positive relation between the degree of urbanization and abnormal indicators values. The values of MR_b, MR_L and D of three low-urbanized catchments were all normal. The values of MR_b and D of only two high-urbanized catchments were below the normal. The effects of urbanization on river system growth resulted in the disappearance of branches, the serious destruction of the original style of the river geomorphology and the concreting of river banks and beds.

The indicators had showed their distinct sensitivity to urbanization. MR_L was still a useful indicator to reflect stream structure development in urban areas and abnormal MR_b was effective to show urbanization effect on river system. D is more effective to describe the extreme situation, poorly and highly developed river system. Specially designed indicators R_c, R_n and R_s were proved to be feasible for explaining the impact of urbanization on river system. The next step is to identify the value and functions of three indicators by using more data from various urban areas.

The results of correlation analysis demonstrated that both the quantity of water area and the stream structure represented by D, R_c, and MR_b decided the ability of flood-proofing and flood absorption. W_p was the prerequisite to discuss reasonable stream structure and well-development stream structure ensured the multi-functions of river system.

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