

Identifying hydrological regime and eco-flow threshold of small and medium flood of the Xiaoqing River in Jinan city

Yang Liu and Sheng-Le Cao

School of Civil Engineering, Shandong University, Jinan 250061, Chain

Abstract. It was known that hydrological regime was the main influencing factor of river ecosystem, but the regime of different flow rates of urban rivers was poorly understood. We collected daily inflows at the Huangtai station of the Xiaoqing River from 1960 to 2014 and divided the data into three periods. Then we calculated hydrological parameters by the method of EFCs (Environmental Flow Components) and analyzed the tendency and change rates of each component respectively in the three periods. Combined with the ecological significance of environmental flow components, we identified the small and medium flood had the greatest impact on the river regime and ecosystem. And then we used the hydraulic parameters in the good ecosystem period as control conditions, to calculate the ecological threshold of the flow component under the current situation. This study could provide technical support for restoring and improving hydrological regime and ecological environment of the Xiaoqing River in Jinan city.

1 Introduction

Rivers were an important part of urban ecological civilization that was paid more and more attention. However, due to the rapid development of urbanization, human activities had made great impact on the physical structure, hydrological regime and ecological environment of urban rivers. While the hydrological regime was the core of river ecology, deciding and influencing the river ecosystem including material cycles, energy processes physical habitats and biological interactions^[1,2]. Currently, studies about the river hydrological regime had been increasingly evolved, such as Richter, B.D. et al.^[3] analyzed the regime by combining ecological models with dam operations, and then put forward suggestions of ecological regulation and water resources management, DAI, Xiangqian et al.^[4] investigated the ecological implication of Chaobaihe River regime and divided the ecological flow into five spectrums in consistent with IHA, and then they provided suggestions to protect and rehabilitate health of river ecosystem in Chaobaihe River, Zhang, Hongbo et al.^[5] implicated RVA to diagnose the influence of water diversion on flow regime and ecosystem of Weihe River, SHU, Chang^[6] proposed an estimation method to calculate ecological flow by analyzing the parameters of IHA of Niqu river and applying RVA. Meanwhile, combined with other references, most of them were focused on hydrological regime of the natural river flow, little research for hydrological regime of different flow rates and ecological thresholds of urban rivers. Therefore, the aim of this paper was to assess the hydrological regime of urban river at different stages of development in city quantitatively and then identified the flow component that had the greatest impact on the river hydrological regime as well as calculated the corresponding ecological flow threshold.

2 Data and Method of Study Area



2.1 Data of Study Area

The Xiaoqing River in Ji'nan city was located in the upstream of the river, the length from Muli gate to Hongyuan gate was 23.8km, the basin area was about 340km². It was a man-made river as well as the main channel for flood discharge of Ji'nan city. In recent years, with the development of urbanization, the urban region was expanding to the range which was west form Yufu River and east to Daxin River, north from the Yellow River and south to southern mountain^[7], the development of main city zone was shown in Figure 1. However, the sharp increase of impervious area in Ji'nan city led to flood concentration time was shortened and the Rain Island Effect was significantly enhanced^[8], subsequently small and medium flood would format large flood peak that caused the significant changes of hydrological regime of Xiaoqing River in Ji'nan city.

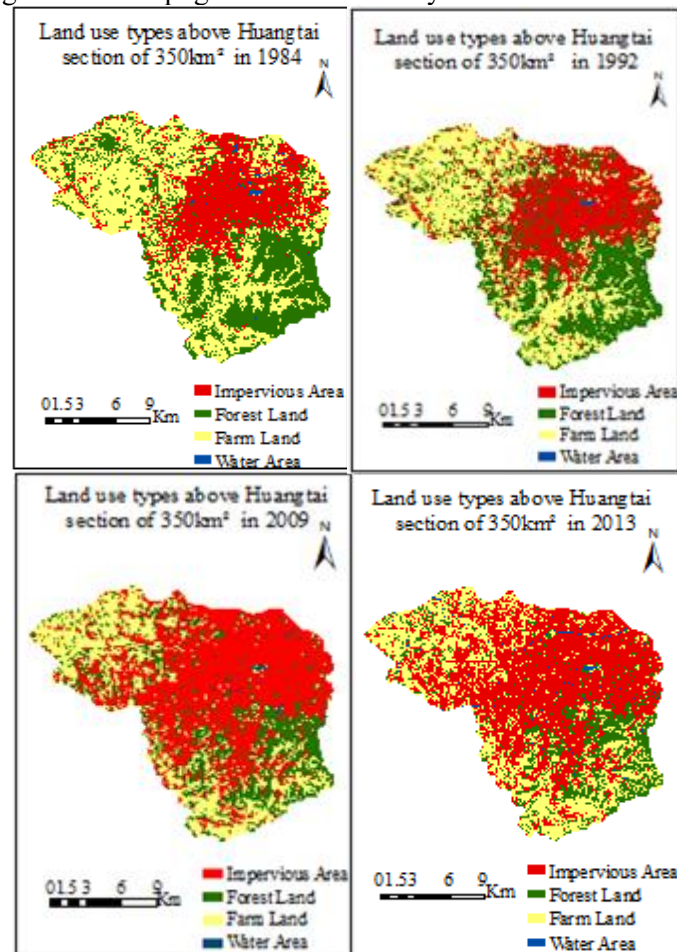


Figure 1. The Changes of land use types from upper basin above Huangtai Bridge of the Xiaoqing River.

Xiaoqing River in Ji'nan city has a Huangtai hydrological station that was set from 1953 for daily runoff monitoring. According to the investigation data of historical ^[9,10], it still had capability of navigation until 1970's, in this period the river ecosystem was soundness, so called "water clear and fish play" and the hydrological regime was less disturbed by human activities. But in the 1980's, with the rapid development of urbanization, the river ecosystem had been seriously destroyed and meanwhile the channel was severe deposition, it became a "dark and smelly river". Coupled with the rapid increase of impervious area in the basin, the river hydrological regime was disturbance severely. Subsequently, with increasing emphasis on the aquatic ecosystems and urgent need for urban development, a series of comprehensive treatment projects in Xiaoqing River in Ji'nan city were implemented in 2008, the river ecosystem had been recovered to a certain degree. In order to study the influence of changes of hydrological regime, combined with the actual situation, this paper selected

1960-1985, 1986-2007, 2008-2014 for the three study periods, they respectively represented the good ecosystem period, the significant effects of urbanization period and the ecological management period.

2.2 Research Method

IHA (Indicators of Hydrologic Alteration) was proposed by Richter, B.D. in 1996. It was used for evaluating the influence of water conservancy project on river runoff process. And then Richter, B.D. et al. proposed the EFCs [11], which divided hydrological events into several types that represented the full spectrums of flow conditions of flow events that must be maintained in order to sustain riverine ecological integrity. Generally, hydrological events were divided into five groups: extreme low flow, low flow, high flow, small flood and large flood. But considering the characteristics of urban river, we defined high flow and small flood as the small and medium flood, extreme low flow and large flood as annual extreme flow.

In this paper, EFCs method was used to analyze each flow component of the Xiaoqing River in Ji'nan city in three periods and then calculate their change rates. The equations of change rates were defined as:

$$\psi_j = \frac{D_{ij} - D_{oj}}{D_{oj}} \quad (1)$$

$$\bar{\psi} = \frac{1}{n} \sum_{j=1}^n |\psi_j| \quad (2)$$

Where ψ_j = the change rates of j^{th} hydrological parameters, $j=1,2,\dots,4$, D_{ij} = the value of j^{th} hydrological parameters in i period, $i=1,2$, D_{oj} = the value of j^{th} hydrological parameters in the good ecosystem period, $\bar{\psi}$ = the average value of number of indexes of each component.

Through the above analysis and calculation, the flow component that had the greatest impact on river ecological system would be identified. For the identified flow component, hydrologic and hydraulic parameters in good ecosystem period were selected as the control conditions to calculate the ecological suitable threshold in the current river section.

3 Environmental Flow Components

3.1 The influence of human activities on precipitation and runoff

Figure 2 showed the fluctuation of daily runoff in the three periods, the average values were $7.83m^3/s$, $9.56m^3/s$ and $16.26m^3/s$. Figure 3 showed the fluctuation of annual precipitation and multi-year average precipitation in three periods. The multi-year average precipitation changed little ($651.4mm$, $653.4mm$ and $651.5mm$), but the precipitation was more and more concentrated in flood season ($449.7mm$, $527.6mm$ and $531.4mm$). From the above data, we could see although the multi-year precipitation changed little in the three periods but the runoff increased significantly since the second period. It indicated that the human actives were the main reason for the runoff changes of Xiaoqing River in Ji'nan city. Meanwhile, due to the enhancement of the Urban Rain Island Effect, the precipitation was more and more concentrated in the flood season.

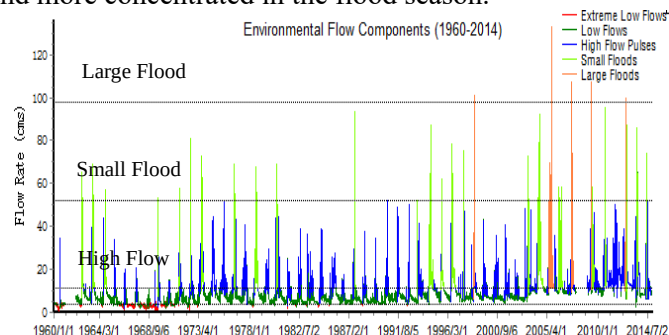


Figure 2. Variation characteristics of daily runoff from 1960 to 2014

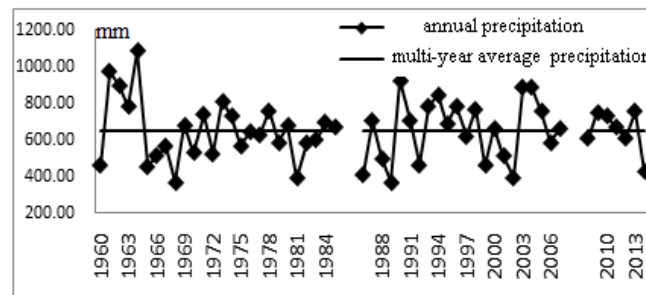


Figure 3. The annual precipitation and the multi-year average precipitation in three period

3.2 Analysis of Hydrological parameters of EFCs

According to the classification method of EFCs, the five types of environment flow components with different orders of magnitude were obtained. The hydrological parameters and ecological significances of each flow component were shown in Table 1^[12,13].

Table 1. The components of environmental flow parameters and their ecological significance

EFC Type	Hydrologic Parameters	Ecosystem Influences
Monthly low flow	Mean values of low flows	1. Provide adequate habitat for aquatic organisms, 2. Maintain suitable water temperatures, dissolved oxygen and water chemistry.
Extreme low flow	Peak flow	1.Enable recruitment of certain floodplain plant species, 2. Purge invasive, introduced species from aquatic and riparian communities, 3. Concentrate prey into limited areas to benefit predators.
	Duration	
	Frequency	
	Timing	
High flow	Peak flow	1.Shape physical character of river channel, including pools, riffles, 2. Determine size of streambed substrates, 3. Restore normal water quality conditions after prolonged low flows, flushing away waste products and pollutants, 4. Aerate eggs in spawning gravels.
	Duration	
	Frequency	
	Timing	
	Rise rate	
Small flood	Fall rate	1.Provide migration and spawning cues for fish and trigger new phase in life cycle, 2. Provide new feeding opportunities for fish, waterfowl, 3. Maintain diversity in floodplain forest types through prolonged inundation, 4. Control distribution and abundance of plants on flood plain, 5. To supple the water level of flood plain, prolong the soil wetting time and maintain the diversity of the plant species in flood plain.
	Peak flow	
	Duration	
	Frequency	
	Timing	
Lager flood	Rise rate	1. Maintain balance of species in aquatic and riparian communities, 2. Deposit gravel and cobbles in spawning areas; 3. Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes), 4. Flush organism materials and woody debris (habitat structures) into channel.
	Fall rate	
	Peak flow	
	Duration	
	Frequency	
	Timing	
	Rise rate	
	Fall rate	

3.2.1 Alteration of low flow. From Table 2, the low flow component in the three periods presented an increasing trend, it was mainly reflected in the monthly low flow in non-flood season was more and more close to flood season since the second period. This indicated that human activities had made a significant impact on the base flow of the Xiaoqing River in Ji'nan city, the main reason was the increase of transfer water used by industry, agriculture and residents, and then they were discharged to

the Xiaoqing River in the form of reclaimed water, which resulting in the low flow significantly increased.

Table 2. The calculation table of monthly low flow component

EFC Component		Mean Value(m^3/s)			Change rates(%)	
		1960 -1985	1985 -2007	2008 -2014	Second Period	Third Period
Low Flow	Jan.	5.44	7.45	9.53	37.7	75.4
	Feb.	5.31	7.18	10.1	35.6	89.5
	Mar.	5.07	6.96	9.71	37.2	92
	Apr.	6.06	6.46	9.54	7.1	57.7
	May	6.32	6.92	9.28	12	47
	Jun.	7.13	6.94	8.74	-3.3	23.8
	Jul.	8.14	8.14	8.87	0	9.9
	Aug.	8.50	8.10	9.26	-5.8	9.8
	Sept.	7.93	8.55	9.26	8.8	17.2
	Oct.	6.58	7.51	10.5	14.7	59.1
	Nov.	6.29	7.72	9.29	23.5	48.1
	Dec.	5.75	7.76	9.01	35	57.2
AVG					18.4	48.9

3.2.2 *Alteration of high flow and small flood.* Table 3 showed that in the second period the peak flow of the high flow changed little and the occurrence time slightly ahead of schedule, but the frequency and the rise and fall rates were greater changed compared to the first period, while in the third period, the peak flow and duration of high flow were both significantly increased, the occurrence time was also about 30 days ahead of the first period. The peak flow of small flood in the last two periods presented an increasing trend, the occurrence frequency and rise and fall rates also increased significantly, this suggested that hydrological regime of the Xiaoqing River in Ji'nan city had been disturbed, which led the values of high flow and low flow components were significantly increased, meanwhile the occurrence time was earlier and the rise and fall rates were more steep.

Table 3. The calculation table of high flow and small flood components

EFCs Component s		Mean Value			Change rates(%)	
		1960 -1985	1985 -2007	2008 -2014	Second Period	Third Period
High Flow	Peak Flow (m^3/s)	16.13	15.70	25.53	-2.7	58.3
	Duration (d)	2.90	2.00	12.75	-31.0	339.7
	Timing (d)	205.9	201.5	172.5	-2.1	-16.2
	Frequency	8.24	9.64	7.67	17.0	-6.9
	Rise Rate (%)	5.27	5.53	3.83	4.9	-27.3
	Fall Rate (%)	-2.92	-3.68	-1.93	26.0	-33.9
Small Flow	Peak Flow (m^3/s)	64.86	73.28	81.09	13.0	25.0
	Duration (d)	38.35	67.22	38.50	75.3	0.4
	Timing	206.8	208.6	200.6	0.8	-3.0

(d)	5					
Frequency	0.48	0.59	1.00	22.9	108.3	
Rise Rate (%)	15.47	22.60	20.47	46.1	32.3	
Fall Rate (%)	-4.00	-6.76	-9.42	69.0	135.5	
AVG				25.9	65.6	

3.2.3 Alteration of annual extreme low flow. Extreme low flow and large flood were extreme cases of hydrological regime, they appeared with low frequency but easy to cause huge losses. In Table 4, we could see the duration of extreme low flow and large flood was shorter and shorter and the occurrence time was forward in the last two periods, otherwise the number of occurrence of the large flood increased but the extreme flow decreased.

Table 4. The calculation table of annual extreme flow components

EFCs Components		Mean Value			Change rates(%)	
		1960 -1985	1985 -2007	2008 -2014	Second Period	Third Period
Extreme Low Flow	Peak Flow (m^3/s)	3.37	3.71	2.32	10.1	-31.2
	Duration (d)	4.83	3.19	2.00	-34.5	-59.4
	Timing(d)	140.6	171.8	164.0	22.0	17.1
Large Flow	Peak Flow (m^3/s)	8.24	1.05	0.17	-87.4	-98.7
	Duration (d)	--	113.7	107.3	--	--
	Timing(d)	--	82.67	30.00	--	--
	Frequency	--	229.0	160.5	--	--
	Rise Rate(%)	0.00	0.14	0.33	--	--
	Fall Rate(%)	--	21.26	27.67	--	--
AVG		--	-3.77	-6.51	--	--

4 Ecological Threshold of Small and medium flood of urban rivers

4.1 Characteristics of morphological structure of urban rivers

In order to meet the needs of urban development, the urban rivers were different from natural rivers in following aspects, such as morphology, function and space, and this resulted in the low meandering degree and the single cross section of urban rivers^[14]. Canalization and lining of urban river channels were serious and the function of material exchange with the surrounding environment has almost lost as well as the ecological supporting capability in and out of the river had decreased, at the same time, there were more and more factories and residential districts along the river because of the increasing urban land utilization, which made the spatial scope of the river to be squeezed. The changes of the morphology and structure of the urban rivers would lead to deterioration of the river ecological environment, which would have a negative effect on the aquatic life.

4.2 Definition of small and medium flood in urban rivers and their ecological significances

In the EFCs classification, the small and medium flood was defined as the return period of the runoff frequency from 2 to 10 years. TIAN, You & YANG, Xuejun^[15] defined the small and medium flood by the standards of the flood control engineering system, it suggested that less than the standard was small and medium flood and higher than the standard was the large flood. But in recent years due to

the continuous improvement in the standard of city flood control, the flood control standard of "important city" has reached a 100-year return period in the Flood Control Standards (GB50201-2014)^[16]. So it was not suitable to define small and medium floods only on the basis of the flood standard of protection object. In addition, combined with the previous analysis, we could see human activities had a great impact on runoff that result in the definition was not objective according to the runoff frequency. Therefore, based on the characteristics of the annual precipitation in three periods and the study area belonged to small basin, this paper defined small and medium flood as return period of precipitation frequency from 2 to 10 years.

According to the ecological significances of environment flow components proposed by Richter B.D. (Tab.1), combined with the characteristics of morphology and structure of the urban rivers, this paper analyzed that urban rivers provided less habitat and spawning grounds for aquatic organisms, and biodiversity was much less than natural rivers. Thus, there are less refuge sites for living creatures when large flood peak occurred in the river, furthermore, with the existing flood control standards, small and medium flood was still under embankment of channel, so that it would not form floodplain phenomenon, in addition to the canalization and lining, the exchange of material between river and surrounding environment was lost. Therefore, ecological significance of urban rivers in the process of small and medium flood mainly lied in providing signal of water level and flow velocity for fish spawning through flow peak, at the same time, washing away the dirt and providing adequate oxygen and organic matter.

4.3 Parameters analysis of small and medium flood and ecological threshold calculation

By analyzing the hydrological parameters of occurrence time, peak flow, and duration of typical small flood in 1960-1985 and 2008-2014, the results were shown in Table 5 and Table 6.

Table 5. Hydrological parameters of typical small and medium flood from 1960 to 1985

NO.	Precipitation			Flood	
	Timing	Average Precipitation (mm)	Precipitation duration (h)	Peak Flow (m ³ /s)	Flood Duration (d)
1	1978-7-25 02:00	98.3	30	80.1	5
2	1979-7-17 14:00	31.0	12	26.3	4
3	1979-8-3 08:00	29.8	24	28.5	3
...	...	...	...	...	...
...	...	...	...	...	...
18	1985-7-24 01:00	29.8	25	81.5	3
19	1985-8-22 14:00	34.3	30	66.3	4
AVG		50.1	23.8	46.53	3.7
MAX		98.3	30	81.5	7

Table 6. Hydrological parameters of typical small and medium flood from 2008 to 2014

NO.	Precipitation			Flood	
	Timing	Average Precipitation (mm)	Precipitation duration (h)	Peak Flow (m ³ /s)	Flood Duration (d)
1	2008-7-1 05:00	71.5	29	91.9	3
2	2008-7-4 22:00	71.3	20	94.4	6
3	2008-7-17 16:00	73.9	25	111	6
...	...	...	...	...	...
...	...	...	...	...	...
16	2012-7-7 16:00	90.3	16	211	5
17	2013-7-25 17:00	33.4	20	93.2	6
AVG		51.2	19.2	83.78	5.38
MAX		90.3	16	211	14

From Table 5 and Table 6, the average precipitation of small and medium flood events was 50.1mm during 1960 to 1985 compared to 50.2mm during 2008 to 2014, the change was slight, increased by only 2.2%. However, the average peak flow increased from 46.53m³/s to 83.78m³/s, increased by 80.1%. And the extreme value of individual flood peak increased to 211m³/s from 81.5m³/s, the average duration of flood also increased from 3.7d to 5.38d. Thus it could be seen that in spite of the slight change of precipitation, the peak flow and duration small and medium flood increased obviously, which is consistent with the previous result by EFCs. This verified once again that the development of urbanization had caused severe disturbance to small and medium flood in the river, which also had adverse effects on the ecological environment of urban rivers.

Table 5 and Table 6 also indicated that the occurrence time of the small and medium flood of rivers in Ji'nan city was in 6~8 months, it was also the main spawn and grow period for the fish such as crucial carp. Therefore, on the one hand it was necessary to control the peak flow not disturb hydrological regime severely, on the other hand it was needed to ensure that there was certain stimulation of flow velocity and water depth of the small and medium flood. According to the IHA method, the value of 75% and 25% frequency were often to use as the upper and lower limits of parameters [17,18], this paper selected 75% and 25% of peak flow of the small and medium flood in the good ecosystem period (1960-1985) as the upper and lower limits of the hydrological regime restoration flow interval. At the same time, the corresponding flow velocity and water depth were calculated based on the measured section data, and then they were used as control conditions to calculate the ecological suitable threshold for the ecological management period. By calculation the 75% and 25% frequency of peak flow was respectively 52.5m³/s and 27.7m³/s in the good ecosystem period (1960-1985), the corresponding flow velocity was 0.42m/s and 0.30m/s and the water depth was 4.25m and 2.97m. They were consistent with the conclusions of other studies [19,20] about ecological suitable flow velocity of curial carp, which were to say that the induction flow velocity of crucial carp was 0.2m/s and the suitable flow velocity was 0.3~0.6m/s. Therefore, combined with the current status of Huangtai section, the velocity was used as a control indicator, the ecological suitability threshold of small and medium flood was calculated to be [44.5, 96.6] m³/s.

5 Conclusions

- ① This paper analyzed the changes of hydrological regime by EFCs in the three periods of the Xiaoqing River in Ji'nan city, the results showed that except the extreme low flow, the hydrological parameters of the other components had an increasing trend, which rise and fall rates of each component parameters changed significantly in the second period, although the rates had improved in the third period, the occurrence frequency and the peak flow of small and medium flood were still in an increasing trend.
- ② By analyzing the hydrological characteristics of study area, this paper defined the small and medium flood by precipitation frequency. By this method it was avoided the disadvantage of defining by runoff frequency, which was influenced by human activities. The results were consistent with the hydrological characteristics analyzed by EFCs of small and medium flood in small basin.
- ③ Through the statistics of small and medium flood in the good ecosystem period, with the hydrological and hydraulic parameters as the control conditions, river ecological suitable threshold of small and medium flood was calculated under the status section. The result would provide a more rational basis for restoration of hydrological regime and ecological environment of the Xiaoqing River in Ji'nan city.
- ④ Due to the relatively short time series after the comprehensive management of the Xiaoqing River, there might be some deviation in the series of precipitation and runoff. Thus, in the future, we should continue to pay attention to the alteration of hydrological regime in order to provide scientific analysis for the ecological restoration of urban rivers.

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