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The long-term water level dynamics during urbanization in plain catchment in Yangtze River Delta

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ABSTRACT

Numerous aquatic problems have been produced by the extensive urbanization especially in last decades in eastern China. This paper presents an evaluation of water level alteration induced by urbanization in the Lower Qinhuai river basin, Yangtz River delta in the last half century. Analyses were conducted using Range of Variability Approach, based on the indicator system of hydrologic alteration including 31 water level related parameters. By contrasting the overall alteration range and that of each parameter in 1960–1979 (pre-impact period) and 1980–2008 (post-impact period) the hydrological impact of urbanization was revealed. The results indicate that, 1 the urbanization in 1980s-2010s lead to an expansion of impervious area by 8 times and a sever simplification of river network structure; 2 the average monthly water level increased considerably from the pre-impact to post-impact period due to the urbanization; 3 the low water level is more sensitive to the interference of urbanization, both the magnitude of water level in dry season and minimum low water pulse increased distinctly; 4the Lower Qinhuai river basin was changed with moderate intensity by the urbanization process, with and overall change degree of 42.5%. In conclusion, water level is a remarkable indicator of the river regime response to urbanization in plain river network area. The results of the study would provide support in water resources management in urban development, opening new perspective of the hydrological process evaluation in high urbanized plain catchment.

1. Introduction

Hydrological deterioration and environment degradation caused by urbanization have been recognized as one of the most important factors for global environmental change (Braud et al., 2013). Aquatic system in plain river network is confronted with more critical and tremendous threaten, due to the barrier free expansion of urban construction and the underlying surface dominated hydrological environment provided by the broad flat geomorphology (Chen, 2007; Wang et al., 2008). The regulation of aquatic systems by impervious area and hydraulic constructions during urbanization is necessary to support key human activities including hydropower production, agricultural production, industrial and civil uses, and flood risk mitigation (Bizzi et al., 2012; Nilsson et al., 2005).

Hydrological impacts of the alteration of underlying surface and river networks together with countermeasures are primarily studied (Burns et al., 2012; Chung et al., 2011; Hibbs and Sharp, 2012). The expansion of impervious area such as roads, buildings, and other paved area, can reduce the filtration rate and leads to more efficient runoff processes (Burns et al., 2015; Valtanen et al., 2014). The alteration of river networks, such as river landfill, channelization, curve cut-off, accelerates the flood process by shortening and smoothening the flood routes. The majority research focused on the rainfall runoff process and flood process demonstrated the higher frequency, magnitude and peak flow of the flood event in the urbanized catchment than the less or non urbanized catchment (Miller et al., 2014; Rose and Peters, 2001; Sheng and Wilson, 2008; Suriya and Mudgal, 2012). However, the hydrological alteration of river regime under normal condition, such as daily river discharge, flow velocity and water depth were seldom addressed in hydrological effects study.

The range of variability approach (RVA), which considers the alteration of frequency distributions of relevant indicators during the pre-impact and post-impact periods (Richter et al., 1996, 1997, 1998), is the most widely used approach to evaluate the long-term river regime alteration. In the RVA, two sets of flow data, representing pre-impact and post-impact conditions, are examined using 31 hydrologically relevant indicators known as indicators of hydrological alteration (IHAs) to assess the alteration of flow. Each IHA

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has one range of variability, which is determined by the 25th and 75th percentiles of the pre-impact IHA annual values. As soon as this range is established, the frequency (or ratio) of pre-impact and post-impact IHA values that fall into this range is calculated separately. Then, the relative change of the post-impact frequency to the pre-impact frequency will be considered as the hydrological alteration in the RVA (Yang et al., 2014).

In this study, we took the highly urbanized catchment in plain river network area-Lower Qinhuai river catchment, Yangtze River Delta—as a case area. The main objectives of this research were to analyze the underlying surface and river structure variations during the urbanization process based on multi-period satellite images, to extensively discuss and set up appropriate IHAs system to evaluate hydrological alteration between a more-natural reference condition and post-urbanized conditions with real measured gauge data, and to reveal the water level alteration due to the rapid urbanization. The results would help improve the understanding of the controlling mechanisms of river system and their mutual influence on each other and on catchment storage capacity.

2. Material and methods

2.1. Study area

Lower Qinhuai River basin located between 118°39′ to 119 19′E and 31 34′ to 32 10′N, in south-west of Jiangsu province in China (Fig. 1). Draining an area of 410 km^2, the main Qinhuai River flows across the urban area of Nanjing before emptying into Yangtze River. The basin is dominated by the humid climatic region, with an annual averaged precipitation approximately 1047 mm and averaged temperature around 15.4 °C. The rainy season extends from April to September, while the precipitation intensively concentrates in summer (June to August) due to the affection of southeast monsoon. Lower Qinhuai catchment is a typical flat terrain. The lowland polders cover the wide bank of the Lower Qinhuai river with the elevation varied from 6 to 8 m.a.s.l. The altitude of the 80% of the catchment was lower than 40 m.a.s.l., while the rest 20% was occupied by the low hills and mountains lower than 300 m.a.s.l. Due to the low topography, serious flood and waterlogging problem especially during summer threaten this area, which is then intensified by the urbanization process. The main soil types consist of yellow-brown soil, purple soil, limestone soil, paddy soil, and gray fluvo-aquic soil. The land use pattern mainly includes paddy field, woodland, impervious surface, water, and dry land. Associated with the expanding of the impervious area, the water area shrunk severely due to the dramatic urbanization over the past decades. The water storage capacity and the regulation capacity are, therefore, severely affected by the decline of the infiltration rate and the simplification of the river system.

2.2. Methodology

2.2.1. River network structure

Urban expansion significantly altered the river network structure. The linear river network were extracted and its structure variation were analyzed. We selected 5 parameters, including river length (L), river density (Rd), water surface ratio (WSr), river complexity (CR) and river structure stability (SR), to represent the river network spatial distribution in the catchment. The meaning and the calculation formulas of each parameter are as follows,

River length (L): the totally length of the line river network;

River density (Rd): the length of the river network on unit basin area (S),

$$\mathrm{Rd} = \frac{L}{S} \tag{1}$$

Water surface ratio (WSr): the water surface area (S_w) on unit basin area,

$$\mathrm{WSr} = \frac{S_\mathrm{w}}{S} \tag{2}$$

River complexity (CR): the ration of total river length (L) and main stream length (L_m),

$$\mathrm{CR} = N_\mathrm{c} \times \left(\frac{L}{L_\mathrm{m}}\right) \tag{3}$$

River stability (SR):

$$\mathrm{SR} = \frac{L_{\mathrm{i}+n}/\mathrm{RA}_{\mathrm{i}+n}}{(L_\mathrm{i}/\mathrm{RA}_\mathrm{i})} \tag{4}$$

Here, N_c is the maximum channel order; L and L_m refer to the total river length and the length of the main river individually; $L_{\mathrm{i}+n}$ and L_i present the total river length of the $(\mathrm{i}+n)$th year and the ith year; $\mathrm{RA}_{\mathrm{i}+n}$ and RA_i refer to the water surface of the river in the $(\mathrm{i}+n)^{\mathrm{th}}$ year and the ith year.

2.2.2. Indicators of hydrologic alteration (IHAs)

IHA compares water regime such as discharge, water level, flow velocity etc., before and after the impact from human activities. Due to the low gradients of Lower Qinhuai catchment and the widespread river regulating gate, the flow velocity and discharge of most rivers are quite low except during flood time. Based on such fact, we set up IHAs systems including 31 indicators using long term water level elevation, to perform integrated calculation before and after urbanization. According to the basic characteristics of hydrological condition, such as quantity, occurrence time, occurrence frequency, time duration, and rate of variation, these 31 indicators were then divided into 5 groups (Table 1).

The following Eq. (5) was used to quantify the alteration degree of IHA affected by urbanization.

$$D = \frac{N_0 - N_\mathrm{e}}{N_\mathrm{e}} \times 100\% \tag{5}$$

Here, D is the change degree of each IHA indicator;

N_0 is the observed number of years in post-impacted period with IHA values fall within the RVA target;

N_e is expected number of years in post-impacted period whose IHA values are anticipated within the RVA target; may use r^*N_T to assess;

r is the ratio of IHA values within the RVA target before urbanization. When the threshold of the range are set to 75% and 25%, r can be valued at 50%;

N_T is the total years of flow series in pre-impacted period.

When D valued from 0 to 33%, the hydrological indicator was altered with low intensity, and when D ranged from 34% to 66% and 67% to 100%, the indicator was considered to be altered with moderate and high intensity.

The total alteration degree of the river system in the post-impact period due to the urbanization were also calculated in this research,

$$D_0 = \left(\frac{1}{32}\sum_{1}^{32} {D_i}^2\right)^{1/2} \tag{6}$$

Here, D_0 is the total alteration degree of the post-impact period; D_i is the alteration degree of the indicator i.

2.2.3. Range of variability approach (RVA)

The range of variability approach (RVA) was proposed by Richter et al. (1997). The central insight of RVA lies in the comparison of the IHAs values within the RVA target in the pre-impact period and post-impact period. A similar frequency in pre and post impact period indicate a low impact from urbanization. Higher or lower