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Evaluation of flood frequency under non-stationarity resulting from climate indices and reservoir indices in the East River basin, China

Qiang Zhang [a,b,c,*], Xihui Gu [a,c], Vijay P. Singh [d], Mingzhong Xiao [a,c], Xiaohong Chen [a,c]

[a] Department of Water Resources and Environment, Sun Yat-sen University, Guangzhou 510275, China
[b] School of Earth Sciences and Engineering, Suzhou University, Anhui 234000, China
[c] Key Laboratory of Water Cycle and Water Security in Southern China of Guangdong High Education Institute, Sun Yat-sen University, Guangzhou 510275, China
[d] Department of Biological and Agricultural Engineering and Zachry Department of Civil Engineering, Texas A&M University, College Station, TX, USA

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SUMMARY

The East River, the major tributary of the Pearl River basin, China, is the major source of water supply for megacities within the Pearl River Delta and also for Hong Kong. In this study, stationary and non-stationary models are used to analyze flood characteristics with time, climate indices, and reservoir index. Results indicate that: (1) the variance of annual maximum stream-flow is constant with time and a linear dependence is detected between annual maximum stream-flow and time at the Longchuan, Heyuan and Lingxia stations and a nonlinear dependence at the Boluo station; (2) Xinfengjiang reservoir is relatively closer to Heyuan station and is believed to exercise a significant influence on the flood process at the gauging station. The Pacific Decadal Oscillation Index (PDO) linearly influences the variance of annual maximum stream-flow at the Lingxia and Boluo stations but nonlinearly at the Longchuan and Heyuan stations. The influences of climate indices on flood processes are significantly distorted by hydrological regulations of water reservoirs, as reflected by a sudden decrease of flood discharge after their construction; (3) in comparison with the stationary model, the non-stationary model with climate indices and reservoir index can better picture changing features of the flood process. This study can serve as a reference for regional planning and management of water resources in the East River basin, and possibly for other river basins on the globe under massive influences of human activities and climate changes.

1. Introduction

Recent years have been witnessing extensive discussions on climate change characterized by increasing temperature due to the considerable impacts of climate change on environment and human society (e.g. Cox et al., 2000; IPCC, 2007; Kurane, 2010). Besides, increasing floods and droughts and accompanying losses are being observed such as Po River, Italian (Coppola et al., 2014) and southern Europe (Vicente-Serrano et al., 2014). Changing characteristics, causes and possible implications behind global warming have been widely reported (e.g., Cox et al., 2000; Mirza, 2002; Zhang et al., 2013a). Nowadays, researchers tend to attribute intensifying hydrological and weather extremes to increasing temperature or global warming (Mirza, 2002; Allan and Soden, 2008), and are pointing out that global warming tends to intensify the hydrological cycle (Allen and Ingram, 2002; Mirza, 2002; Allan and Soden, 2008; Zhang et al., 2013a). Intensifying precipitation extremes tend to trigger increasing hydrological extremes. Chen et al. (2012) detected strong increases in monthly stream-flow of January–April, June and October-December across the Pearl River basin. And stations characterized by significant monthly stream-flow changes are located in the middle and the lower Pearl River basin. Besides, intensifying human activities, such as urbanization (Villarini et al., 2009) and construction of water reservoirs are also being observed (Zhang et al., 2009a, 2009b). Zhang et al. (2014) found increasing/decreasing stream-flow in the East River basin before/after the 1980s. All these factors combine to alter hydrological processes and trigger non-stationarity of hydrological extremes, such as annual peak flood regimes (e.g. Milly et al., 2008; Hattermann et al., 2013).

Flood frequency analysis is conducted as an attempt to predict the possibility of future magnitudes and frequencies, and the assumptions behind flood frequency analyses are that the peak discharge data analyzed are stationary and independent. However,

* Corresponding author at: Department of Water Resources and Environment, Sun Yat-sen University, Guangzhou 510275, China. Tel./fax: +86 20 84113730.
E-mail address: zhangq68@mail.sysu.edu.cn (Q. Zhang).

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the assumptions of stationarity and independence are violated by the existence of non-stationarity of flood series due to climate change and intensifying human activities, such as the construction of water reservoirs and urbanization (Milly et al., 2008; Gilroy and McCuen, 2012). Violation of the stationarity assumption has the potential to impact the accuracy of hydrologic analysis and design (Douglas et al., 2000).

Thus, flood frequency analysis by taking non-stationarity into account has been attracting increasing attention and a number of investigations have been reported addressing flood frequency analysis with consideration of non-stationarity. Generally, to represent the non-stationarity, the parameters of the distributions for flood frequency analysis have often been assumed to be varied as a function of explanatory variables (Coles, 2001; Villarini et al., 2009; Gilroy and McCuen, 2012). Gilroy and McCuen (2012) developed and applied a non-stationary flood frequency analysis method that accounts for multiple non-stationary factors. The proposed method adjusts a measured flood record to urbanization and climate conditions for a future design year to account for the effects of changes in conditions from the year that each flood was measured to a selected design year (Gilroy and McCuen, 2012). Villarini et al. (2009) developed a framework for flood frequency analysis based on the Generalized Additive Models for Location, Scale and Shape parameters (GAMLSS), a tool for modeling time series under non-stationary conditions. Ouarda and El-Adlouni (2011) discussed non-stationary frequency analysis models in hydrology with a focus on the Bayesian approach and the use of non-stationary Generalized Maximum Likelihood Estimation method in hydrologic frequency analysis.

The East River is one of the main tributaries of the Pearl River basin in China (Fig. 1). As the availability and variability of water resources in the East River is of great importance for sustainable social and economic development in the Pearl River Delta, one of the economically developed regions in China, hydrologists have tried to identify the fundamental statistical features of the hydrological series, such as frequency distribution (Zhang et al., 2009b), and have also tried to explore possible impacts of human activities and climatic changes on hydrological regimes in the East River basin using statistical methods and hydrological models (e.g. Chen et al., 2010; Zhang et al., 2013b). Besides, the availability and variability of water resources of the East River basin are also closely related to changes in flood regimes. Due to the impacts of human activities (Zhou et al., 2012; Chen et al., 2013) and climate changes (Zhang et al., 2013b), the non-stationarity should be taken into account in flood frequency analysis in the river basin. However, such reports are not available so far and related studies will be of great value to water resources management and human mitigation to natural hazards in the East River basin, and this constitutes the motivation of this study. The objectives of this study were to investigate the influence of climate changes and construction of water reservoirs on flood series using non-stationary statistical models and to evaluate flood frequencies with the consideration of non-stationarity. This study attempts to provide technical framework for flood frequency analysis by considering non-stationarity in a river basin whose flood processes are heavily influenced by the combined influences of human activities and climate change.

2. Study region and data

2.1. Study region

The East River, one of the main tributaries of the Pearl River basin (Fig. 1), is 562 km long and has a drainage area of 27,040 km^2, accounting for about 5.96% of the Pearl River basin area. Water resources in the East River basin have been highly developed and heavily committed for a variety of uses, such as water supply, hydropower, navigation, irrigation, and suppression of seawater invasion. The East River provides water supply satisfying about 80% of Hong Kong's annual water demands. Up to 2006, 896 water reservoirs have been constructed with a total storage capacity of 1.90×10^{10} m^3. Fig. 1 shows five major water reservoirs, i.e., Xinfengjiang, Fengshuba, Baipenzhu, Tiantangshan and Xiangang, with a total storage capacity of 1.74×10^{10} m^3. Detailed information on these water reservoirs was given in Table 1.

2.2. Data

Daily stream flow data covering the period of 1954–2009 were collected from four hydrological stations in this study. Locations of

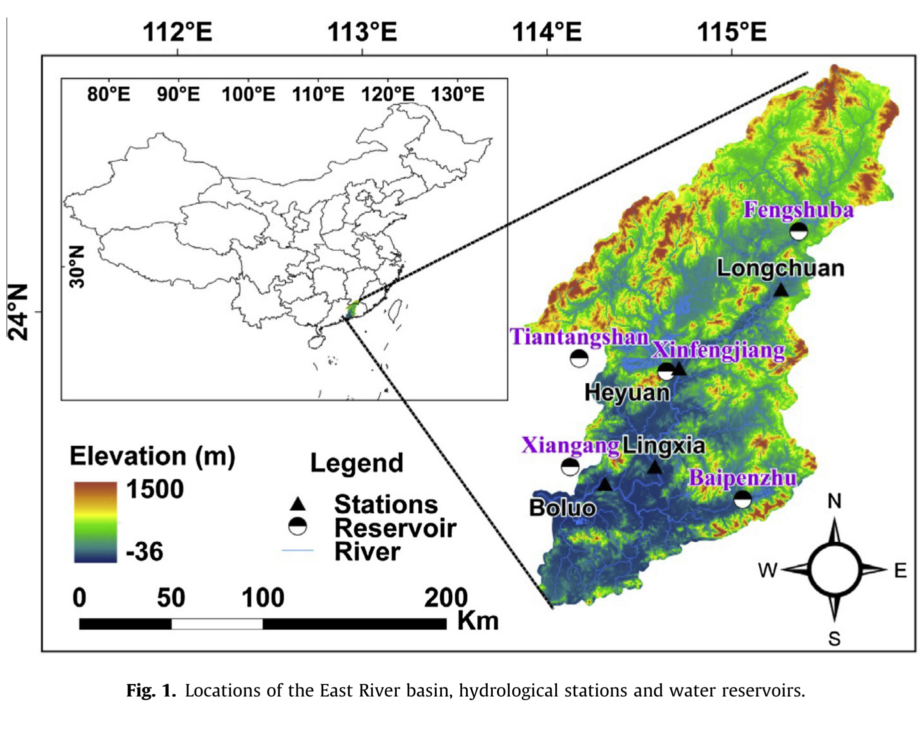

Fig. 1. Locations of the East River basin, hydrological stations and water reservoirs.