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Flood frequency analysis with consideration of hydrological alterations: Changing properties, causes and implications

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SUMMARY

Under coupled influences of human activities and climate change, hydrological alterations are unavoidable and should be addressed in the evaluation of flood risk. In this study, the flood risk in the Pearl River basin, one of the economically developed regions in China, is investigated, based on long term annual maximum series (AMS) from 28 hydrological stations. Results indicate the following: (1) significant hydrological alterations have been identified and alterations of precipitation extreme regimes are one of the pivotal factors triggering hydrological alterations of AMS, as abrupt changes of precipitation extremes occur is similar to that of the AMS in time and space. In the East River basin, however, massive human withdrawal of freshwater, a number of water reservoirs and other hydraulic facilities combine to reduce the flood risk. (2) High flood risk can be found in the upper and middle West River basin and the North River basin with an increasing magnitude of 0–40% and 10–30%, respectively. Besides, frequencies of flood events with return periods of longer than 20 years are found to be significantly decreasing. In the East River basin, however, the frequency of floods with a return period of 20 years is increasing, but the flood volume is greatly decreasing. (3) Higher flood risk due to alterations of hydrological extremes will pose a threat to the existing hydraulic facilities. Furthermore, the higher flood risk in the West River and North River basins will potentially threaten the Pearl River Delta, a densely populated region with highly developed socio-economy. The results of this study will thus be of great value in developing measures for resilience to natural hazards in high development economic and coastal regions.

1. Introduction

Fluvial hydrological processes are significantly influenced by climate change, such as precipitation and temperature variation (Zhang et al., 2005; Zhu et al., 2012); and human activities, such as construction of water reservoirs, water infrastructure, channel modifications, drainage works, and land-cover and land-use change (Legesse et al., 2003; Zhang et al., 2009a, 2011a; Wijesekara et al., 2012). Under combined influences of climate change, i.e. the well-accepted global warming, and human activities, hydrological series, including extreme series, are not homogeneous and the assumption of stationarity underlying flood frequency analysis methodologies is not satisfied (Milly et al., 2008). This suggests that non-stationarity should be taken into account in flood frequency analysis, and the parameters describing the location, scale and shape properties of the frequency distribution may change over time (Cunderlika and Burn, 2003).

There have been a number of investigations considering non-stationarity in flood frequency analysis due to land use and land cover changes, other human activities and climate changes. Strupczewski et al. (2001) considered trends in the investigation of hydrological non-stationary in flood frequency modeling (FFM) and hydrological design. Cunderlika and Burn (2003) indicated that the presence of significant non-stationarity in a hydrologic time series cannot be ignored when estimating design values for future time horizons, and introduced a second-order non-stationary approach to pooled flood frequency analysis. Villarini et al. (2009) developed a framework for flood frequency analysis based on the Generalized Additive Models for Location, Scale and Shape

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parameters (GAMLSS), a tool for modeling time series under nonstationary conditions. Using the newly-developed GAMLSS, they analyzed annual maximum peak discharge records for Little Sugar Creek, a highly urbanized watershed which drains the urban core of Charlotte, North Carolina. Focusing on the problem that flood frequency analysis (FFA) is often performed with limited hydrological data so the occurrence of an exceptional flood provides valuable data, Brodie (2013) developed a Rational Monte Carlo method (RMC) to provide an independent check of Average Recurrence Interval (ARI) which links observed rainfall intensity at a reference pluviograph to the peak flood discharge.

The Pearl River is the third largest river in terms of drainage area and the second largest river in terms of streamflow in China and has abundant water resources (Zhang et al., 2010a). However, uneven spatial and temporal distribution of water resources, with 80% of the total discharge occurring in the flooding season, i.e. April–September, negatively affects the effective human use of its water resources. Uneven seasonal and spatial distribution of precipitation can easily trigger occurrences of floods and droughts in the Pearl River basin (Zhang et al., 2009a, 2010b). The East River, a tributary of the Pearl River, bears the responsibility of water supply for Shenzhen and Hong Kong, meeting about 80% of Hong Kong's annual water demand. Considering hydrological extremes in the Pearl River basin as a case study, Zhang et al. (2011b) investigated the probability behavior of high and low flows. However, flood risks and flood frequency analysis based on long-term annual maximum streamflow (AMS) series have not been done so far, with particular consideration of hydrological alterations. This kind of research will be of great importance for developing strategies for mitigation of natural hazards within the Pearl River basin, a highly economically developed river basin in China with a large population density in the Pearl River Delta. This constituted the major motivation of this study.

The objectives of this study therefore were: (1) to detect hydrological alterations and underlying; (2) to evaluate flood risk and flood frequency prior and posterior to the changes, showing changing properties of flood frequency distributions due to hydrological alterations; and (3) to discuss implications of the changes in flood frequencies in the Pearl River basin. Because human activities in the Pearl River basin have been intensifying in recent decades, research on flood frequency by taking into account the hydrological alterations or non-stationarity will help understand flood evolution in a fast changing environment (Zhang et al., 2011c) and regional response of hydrological extremes to climate change.

2. Data and methodologies

2.1. Data

AMS series from 28 hydrological stations were collected and analyzed. Locations of the hydrological stations, marked with numbers, are shown in Fig. 1. The names of the marked stations and time intervals considered in this study are listed in Table 1. There were no missing data within the datasets considered.

2.2. Methodologies

2.2.1. Mann–Whitney U test

Hydrological change points should be detected to split the whole series into different series with various statistical behaviors. A number of techniques for detecting change points in a hydrological series have been proposed, including R/S method (Mandelbrot and Wallis, 1969), Rank–Sum test (R–S test in this paper) (Mann and Whitney, 1947), Sliding *T* test and Sliding *F* test (Patrick and Shlomo, 1999), and Mann–Kendall test (Mann, 1945; Kendall and Gibbons, 1990). Comparing the performance of 10 change-point analysis methods, Lei et al. (2007) found that the R–S test better detects change points. Therefore, in this study the R–S test was employed to analyze abrupt streamflow changes.

The Mann–Whitney *U* test (M–W *U*), an R–S test, is a non-parametric statistical method. The method of computation of the test can be summarized as follows (Patrick and Shlomo, 1999): (1) We assume that the distribution functions of two sub-series posterior and prior to a change-point are $F_{pre}\ (x)$ and $F_{post}\ (x)$. The two samples are extracted from $F_{pre}\ (x)$ and $F_{post}\ (x)$ with sample sizes of n_{pre} and n_{post}, respectively. (2) The series are ranked as $x_1 < x_2 < \cdots < x_n$, where n is the sample size. (3) Sum the ranks and determine the test statistic. If the sample sizes of two sub-series are different, the smaller sample size is n_1 and the related R–S test statistic is T_1; the larger sample size is n_2 and its R–S test statistic is T_2, respectively. When $n_1 = n_2$, take the R–S test statistic in any group as T_1, and another group is T_2. (4) Decision will be made based on the *U* value that can be calculated as:

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - T_1 \tag{1}$$

or $$U = n_1 n_2 + \frac{n_2(n_2+1)}{2} - T_2 \tag{2}$$

If $n_2 \leqslant 8$, Eqs. (1) and (2) can be used to calculate *U* and the smaller *U* value will be taken. Then, the accompanying probability *p* can be obtained based on the *U* accompanying a probability table for the Mann–Whitney *U* test.

If $n_2 > 8$, there is no accompanying probability table. The test statistic can be approximated by the normal distribution as:

$$z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}} \tag{3}$$

When the same ranks occur with high frequency, e.g., more than 25% of the total number, the z value in Eq. (3) should be adjusted based on:

$$z_c = \frac{z}{\sqrt{1 - \frac{\sum(t_j^3 - t_j)}{(n_1+n_2)^3 - (n_1+n_2)}}} \tag{4}$$

where t_j denotes the number of the same ranks.

Generally, two assumptions are made:

Ho: The probability distributions of the two sub-samples are the same and no change point can be detected.

Ha: The probability distributions of the two sub-samples are different and a change point can be detected.

The significance level in this study was $\alpha = 0.05$, $Z_{1-\alpha/2} = 1.96$, and the bilateral sub-median test was used. If $|z| \leqslant Z_{1-\alpha/2}$, then Ho was accept, i.e., there was no significant change point; If $|z| > Z_{1-\alpha/2}$, then Ha would be accepted, i.e., significant change point can be detected, and then the maximum $|z|$ would be accepted as the change point.

It should be noted that there may be different or more than one change points being detected by different methods in a hydrological series. To select the most probable change point, two steps have been done in the paper. Firstly, we try to find all possible change points using the Mann–Whitney *U* test; secondly, the Brown–Forsythe test (Brown and Forsythe, 1974), moving *T* test (Jiang et al., 2002), Sequential Cluster Method (Xiao et al., 2001), and Mann–Kendall test method (Mann, 1945; Kendall and Gibbons, 1990) were used to detect the possible single change point. Then the most probable change point is selected as the most