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Inter- and intra- annual environmental flow alteration and its implication in the Pearl River Delta, South China

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ABSTRACT

Environmental flow is fundamental to ecological health and integrity of a riverine environment. River delta systems have become more and more complicated due to climate change and human activities and these have made a significant impact on significant changes in hydrological processes and the ecological environment. Highly intense human activities and most economically developed regions in the Pearl River Delta (PRD), China, was selected as case study. Based on observed daily flow data with a length of 50 years from seven control stations, inter-annual and intra-annual streamflow alterations in this region were analyzed by using the indicators of hydrologic alteration (IHA) method, the range of variability approach (RVA), and the histogram matching approach (HMA), and quantitative impact of main factors on inter- and intra-annual streamflow alterations were derived. Results showed the following: (1) Combination of RVA and HMA can better reveal changes of IHAs, so as to more comprehensively evaluate environmental flow alteration of river systems. (2) Discharge diversion due to changes in river channel geometry is the main factor causing inter-annual streamflow alteration in the Northwest River of PRD, whose contributions were 122.35% and 90.08% at Makou and Sanshui stations, respectively. (3) Change in upstream flow is the main factor causing intra-annual streamflow alteration in the Northwest River of PRD, while reservoir operation is the main factor causing intra-annual streamflow alteration in the East River of PRD. (4) Climate change and reservoir operation can make intra-annual distribution of monthly discharge more concentrate and even, respectively. This study contributes to an improved understanding of environmental flow alteration and associated underlying causes of flow regime variations in the river delta region.

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1. Introduction

As a primary link between land and ocean, a river delta serves as the source of delivering terrigenous materials into the sea, such as fresh water, sediment and nutrients (Liu et al., 2014). Though heavily populated in most cases, the deltas contribute much to the socioeconomic development of China (Ericson et al., 2006). However, in recent decades the processes occurring in river delta systems have become more and more complicated due to climate change and human activities, and these have not only made a significant impact on the geomorphology of river channels but have caused significant changes in hydrological processes and the ecological environment (e.g. Bott et al., 2006). Syvitski's research shows that more than two-thirds of the world's 33 major deltas are sinking and the vast majority of those have experienced flooding in recent years, primarily as a result of human activity (University of Colorado at Boulder, 2016). Restrepo and Kettner (2013) studied human induced discharge diversion and its environmental implications in a tropical delta of Colombia, and results indicated that relative resent anthropogenic influences on the Patía River drainage basin have altered the deltaic environment and beyond significantly.

The indicators of hydrologic alteration (IHA), developed by The Nature Conservancy in the USA (Richter et al., 1996), is one of the most widely used tools to evaluate hydrological alterations and their impact on ecosystems. To quantify the degree of alteration

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for each hydrologic parameter in the IHA, the range of variability approach (RVA) was developed by Richter et al. (1996). The impact of climate-induced change and socio-economics on hydrological alterations has also been quantified by IHA and RVA (e.g. Laizé et al., 2014; Lee et al., 2014). Monk et al. (2011) quantified trends in indicator hydroecological variables for regime-based groups of Canadian rivers by IHA. Puig et al. (2016) also studied recent changes in the flow regime of the Lower Paraná River and current fluvial pollution warnings in its Delta Biosphere Reserve by IHA. Song et al. (2016) used IHA and RVA to evaluate water level alteration induced by urbanization in the Lower Qinhuai river basin, Yangtz River delta in the last half century, which showed that the Lower Qinhuai river basin was changed with moderate intensity by the urbanization process.

However, the IHA mainly includes indices of inter-annual variations in streamflow, but does not consider intra-annual variations of streamflow, which are also known to affect riverine ecosystems (Richter et al., 1996; Li et al., 2014). In addition, although the RVA can be well applied to determine the flow regime targets using the IHA (Babel et al., 2012), it is subject to potential limitations (Richter et al., 2006; Kim and Singh, 2014). For example, Shiau and Wu (2008) determined that this method mainly considers variations of parameter values within the target range, while frequencies of hydrologic parameters falling beyond the target range (the interval between the 25th- and 75th-percentile values) are not explicitly taken into account. To solve this problem, Shiau and Wu (2008) adopted the histogram matching approach (HMA) to assess the flow regime alteration. The HMA uses the degree of histogram dissimilarity, which employs the quadratic-form distance between frequency vectors of the pre- and post-impact histograms based on the IHA, to describe the whole variance of hydrologic alterations (Yang et al., 2012).

In this study, we took the highly intense human activities and most economically developed regions in China, Pearl River Delta—as a case area. The Pearl River flows into the South China Sea (SCS). The Pearl River Delta (PRD) is the low-lying area surrounding the Pearl River estuary. A number of studies have previously been conducted to investigate the impact of climate change and human activities on water resources in the Pearl River basin (e.g. Dai et al., 2008; Niu and Chen, 2010; Chen et al., 2012; Wu and Chen, 2013; He et al., 2014; Niu and Sivakumar, 2014). However, less attention has been paid to the alterations in environmental flow in PRD, including changes in relation to the magnitude, frequency, duration, timing of flow regime, and rate of change, which are well recognized by ecologists as primary drivers for a number of fundamental ecological processes in riverine ecosystems (Poff and Zimmerman, 2010).

Therefore, in this study, we not only analyze inter-annual variations of streamflow, but also study the intra-annual variations of streamflow in PRD. What's more, to undertake a more comprehensive evaluation, in this study we employ the IHA, RVA and HMA methods together to evaluate environmental flow alteration in PRD. More importantly, we derive the quantitative impacts of main factors on inter- and intra-annual streamflow alterations, which are useful in assessing environmental flow alteration and gaining an understanding of the reasons of its occurrence in river delta area.

2. Methodology

2.1. Trend and abrupt change analysis method

A number of trend analysis methods have been proposed for the detection of monotonic trends within hydrologic time series (e.g., linear regression trend test, cumulative anomaly method, Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) and Spearman rank correlation test). The MK test method has been widely used in the word (e.g., Shi and Wang, 2015; Shi et al., 2016a, 2016b). Therefore, the MK test method is used to analyze trends and detect abrupt changes within the time series in this study.

The MK test method first defines a test statistic, d_k, that is calculated, based on the rank series, r_i, as in the following equation.

$$d_k = \sum_{i=1}^{k} r_i (2 \leqslant k \leqslant n) \tag{1}$$

where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{others} \end{cases} (j = 1, 2, \ldots, i) \tag{2}$$

The definition of the statistic index, UF_K, is then calculated as

$$UF_k = \frac{d_k - E[d_k]}{\sqrt{Var[d_k]}} \tag{3}$$

where $E[d_k] = n(n-1)/4$ is the expected value of d_k, and $Var[d_k] = n(n-1)(2n+5)/72$ is the variance of d_k, and UF follows the standard normal distribution. In a two-sided test for trend, if $|UF| > U_{1-\alpha/2}$, then the null hypothesis is rejected at the significance level of α, where $U_{1-\alpha/2}$ is the critical value of the standard normal distribution. A corresponding rank series is then obtained by arranging the time series in reverse order, and the same processes are performed to obtain the other statistical index, UB. A positive value of UF indicates an upward trend, and a negative value denotes a downward trend (Gerstengarbe and Werner, 1999; Karabork, 2007). In this paper, α was equal to 0.05 and $U_{1-\alpha/2}$was equal to 1.96; if $UF > 1.96$ or $UF < 1.96$ in a time series then it shows a significant increasing or decreasing trend at the level of 0.05. In addition, if the two lines, UF and UB, have an intersection point within the significance level, then the intersection point is regarded as an abrupt point in the time series with a significance value of α.

The research of Von Storch (1995) and Yue et al. (2002) determined that the influence of serial correlation may cause uncertainty in the MK test, and therefore in this study, the "pre-whitening" method proposed by Von Storch (1995) was applied to eliminate this effect. This was achieved by removing the lag-1 serial correlation from the time series before applying it to the MK test.

The serial correlation should first be calculated using the following formula (Yue et al., 2002).

$$r_m = \frac{Cov(x_i, x_{i+m})}{Var(x_i)} = \frac{\frac{1}{n-m}\sum_{i=1}^{n-m}(x_i - \bar{x})(x_{i+m} - \bar{x})}{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{4}$$

where x_i ($i = 1, 2, \ldots$) is the time series; x_{i+m} is the lag-m time series; and $\bar{x}$ is the mean of the time series. If $\frac{-1-1.96\sqrt{n-2}}{n-1} \leqslant r_m \leqslant \frac{-1+1.96\sqrt{n-2}}{n-1}$, the time series is assumed to be an independent series at the 0.05 confidence level. In this case, the original time series was appropriate for the MK test; if this had not been the case, it would require pre-whitening. The annual runoff series of all the stations in this paper were all tested using this serial correlation analysis, and the results indicated that only the series at Sanshui station had a significant serial correlation at lag-1. Therefore, the effect of serial correlation needed to be limited using the pre-whitening method, and therefore a new series was then obtained as follows (Kumar et al., 2009):

$$x'_i = x_i - (\beta \times i) \tag{5}$$

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