Research papers

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 recent 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
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. Laïzé 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, Yangtze 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). For example, Shiau can be well applied to determine the flow regime targets using the RVA (Richter et al., 2006; Kim and Singh, 2014). In addition, although the RVAations in streamflow, but does not consider intra-annual variations of parameter values within the target range, while freqencies 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.

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

(1)

where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_{j-1} \quad (j = 1, 2, \ldots, i) \\ 0 & \text{otherwise} \end{cases}$$

(2)

The definition of the statistic index, $U_{ik}$, is then calculated as

$$U_{ik} = \frac{d_k - E[d_k]}{\sqrt{\text{Var}(d_k)}}$$

(3)

where $E[d_k] = n(n - 1)/4$ is the expected value of $d_k$, and $\text{Var}(d_k) = n(n - 1)(2n + 5)/72$ is the variance of $d_k$, and $U_{ik}$ follows the standard normal distribution. In a two-sided test for trend, if $|U_{ik}| > U_{1-\alpha/2}$, then the null hypothesis is rejected at the significance level of $\alpha$, 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 $U$ indicates an upward trend, and a negative value denotes a downward trend (Gerstengarbe and Werner, 1999; Karabork, 2007). In this paper, $\alpha$ was equal to 0.05 and $U_{1-\alpha/2}$ was equal to 1.96; if $U_{ik} > 1.96$ or $U_{ik} < 1.96$ 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, $UB$ and $U_{ik}$, 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 $\alpha$.

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).

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

(4)

where $x_{i}$ (i = 1, 2, . . . ) is the time series; $x_{i+m}$ is the lag-m time series; and $\bar{x}$ is the mean of the time series. If $-1.96/\sqrt{m} \leq r_m \leq 1.96/\sqrt{m}$, 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):

$$x'_i = x_i - (\bar{x} \times i)$$

(5)
where $\beta = \text{Median}\left(\frac{X_{12} - X_{11}}{X_{11}}\right)$ (1 < j < l < n). The lag-1 autoregressive component was then removed to obtain the residual series,

$$y'_j = X'_j - r_1 \times X'_{j-1} \quad (6)$$

The value of $\beta \times i$ was then added back to the series,

$$y_j = y'_j + (\beta \times i) \quad (7)$$

and the $y_j$ series was then subjected to the MK test to estimate the significance of the trend.

2.2. Indicators of hydrological alteration (IHA)

The IHA statistical package, which was developed by Richter et al. (1996) and supported by The Nature Conservancy (TNC), was used to calculate the hydrological alterations at four control stations within PRD. The IHA computes 33 biologically relevant hydrological parameters to statistically characterize hydrological variation, based on the historic flow or stage records, including five characteristics of flow regimes: magnitude of monthly water conditions, magnitude and duration of annual extreme conditions, timing of annual extreme conditions, frequency and duration of annual extreme conditions, magnitude and duration of annual extreme conditions, frequency and duration of annual extreme conditions, magnitude and duration of annual extreme conditions, magnitude and duration of annual extreme conditions, and the rate and frequency of condition changes. In this study, the Pearl River basin is a large basin. No zero-flow day was ever observed at the study gaging stations during the study period; therefore, the "number of zero flow days" was not considered in this study. The definitions of these 32 parameters and their possible impact on ecosystem are shown in Table 1.

2.3. Indicators of intra-annual variations of streamflow

To comprehensively assess the characteristics of intra-annual streamflow variations, six statistical coefficients were used in this paper, including nonuniformity coefficient ($C_v$), complete accommodation coefficient ($C_C$), concentration degree ($C_d$), concentration period ($C_p$), relative variation range ($C_r$), and absolute variation range ($C_a$).

The nonuniformity coefficient ($C_n$) and complete accommodation coefficient ($C_C$) were adopted to determine the fluctuation of intra-annual streamflow, and their formulas are given as follows:

$$C_n = \frac{\sigma}{Q} \quad \sigma = \sqrt{\frac{1}{12} \sum_{t=1}^{12} (Q(t) - \overline{Q})^2} \quad (8)$$

$$C_C = \frac{\sum_{t=1}^{12} j(t)(Q(t) - \overline{Q})}{\sum_{t=1}^{12} Q(t)} \quad , \quad j(t) = \begin{cases} 0, & Q(t) < \overline{Q} \\ 1, & Q(t) \geq \overline{Q} \end{cases} \quad (9)$$

where $Q(t)$ is the monthly discharge and $\overline{Q}$ is the average of $Q(t)$. Note that when values of $C_n$ and $C_C$ are large they imply a more uneven distribution of monthly discharge.

The concentration degree ($C_d$) usually reflects the degree of concentration of the intra-annual distribution of discharge and the concentration period ($C_p$) indicates the focus of discharge in one year; these are defined as

$$C_d = \frac{Q_{12}}{\sum_{t=1}^{12} Q(t)} \quad (10)$$

$$Q_x = \sum_{t=1}^{12} Q(t) \cos \theta(t), \quad Q_y = \sum_{t=1}^{12} Q(t) \sin \theta(t), \quad Q_{xy} = \sqrt{Q_x^2 + Q_y^2} \quad (11)$$

$$C_p = \arctan \left( \frac{Q_y}{Q_x} \right) \quad (12)$$

where $Q_x$ and $Q_y$ are the two resultant vectors of $Q(t)$ that are decomposed in the x direction and y directions, respectively; $Q_{xy}$ is the module of vector, and $\theta(t) = 2\pi t/12$ is the angle of vector for month (t).

The relative variation range ($C_r$) and the absolute variation range ($C_a$) were employed to analyze the range of monthly discharge distribution, where $C_r$ is the ratio of maximum annual flow

| IHA parameter group | Hydrological parameters | Ecosystem influences |
|---------------------|-------------------------|----------------------|
| Group 1: Magnitude of monthly water conditions | Median value for each calendar month | Habitat availability for aquatic organisms |
| Group 2: Magnitude and duration of annual extreme water conditions | Annual minima 1-day means | Soil moisture availability for plants |
| | Annual minima 3-day means | Availability of water for terrestrial animals |
| | Annual minima 7-day means | Balance of competitive, ruderal and stress tolerant organisms |
| | Annual minima 30-day means | Creation of sites for plant colonization |
| | Annual maxima 1-day means | Structuring of aquatic ecosystems by abiotic vs. biotic factors |
| | Annual maxima 3-day means | Structuring of river channel morphology and physical habitat conditions |
| | Annual maxima 7-day means | |
| | Annual maxima 30-day means | |
| | Annual maxima 90-day means | |
| Group 3: Timing of annual extreme water condition | Julian date of each annual 1 day maximum | Complete accommodation index (Cr) and complete accommodation coefficient (Cc) were adopted to determine the fluctuation of intra-annual streamflow, and their formulas are given as follows: |
| Group 4: Frequency and duration of high and low pulses | Number of high pulse each year | Compatibility with life cycles of organisms |
| | Number of low pulse each year | Predictability/avoidability of stress for organisms |
| | Mean duration of high pulses within each year | Access to special habitats during reproduction or to avoid predation |
| | Mean duration of low pulses within each year | Frequency and magnitude of soil moisture stress for plans |
| Group 5: Rate and frequency of water condition changes | Rise rates: mean of all positive differences | Frequency and duration of anaerobic stress for plans |
| | Fall rate: mean of all negative differences | Nutrient and organic matter exchanges between river and floodplain |
| | magnitude between consecutive daily values | Drought stress on plans |
| | Fall rate: mean of all negative differences | Entrapment of organisms on islands, floodplains |
| | magnitude between consecutive daily values | Desiccation stress on low mobility stream edge (varial zone) |
| | Number of hydrologic reversals | Organisms |

Table 1: Summary of IHA parameters and ecological implications (Richter et al., 1996).
to minimum annual flow, and $C_a$ is the difference between those two values. Their formulas are as follows:

\[
Cr = \frac{Q_{\text{max}}}{Q_{\text{min}}} \quad (13)
\]

\[
C_a = Q_{\text{max}} - Q_{\text{min}} \quad (14)
\]

where $Q_{\text{max}}$ and $Q_{\text{min}}$ are the maximum and minimum annual flows, respectively.

2.4. Range of variability approach (RVA)

The RVA method is used to quantify the degree of alteration for each hydrologic parameter in IHA. This method divides the full range of pre-modification data into three different categories: a low category, middle category, and high category (Lian et al., 2012).

The degree of environmental flow alteration, $D_R$, is defined as

\[
D_R(m) = \frac{N_b - N_e}{N_e} \quad (15)
\]

where $N_b$ and $N_e$ are the expected and observed numbers of years whose IHA values fall in the target ranges (between 25th percentile value and 75th percentile value) during the post-periods, respectively.

2.5. Histogram matching approach (HMA)

Shiau and Wu (2008) presented a histogram matching approach (HMA) for the assessment of flow regime alteration. The HMA uses the degree of histogram dissimilarity as a metric for impact assessment, which is based on the quadratic-form distance between the frequency vectors of the pre- and post-impact histograms weighted by a specified similarity matrix (Huang et al., 2013; Lin et al., 2014b).

The degree of histogram dissimilarity, $D_H$, is defined as

\[
\text{Fig. 1. Map of the river system of the Pearl River Delta.}
\]
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. In addition to being one of the most densely urbanized regions in the world, it is one of the main hubs of economic growth in China. PRD actually consists of two alluvial deltas separated by the core branch of the Pearl River, i.e. the Northwest River delta and the East River delta (Fig. 1). As the fastest developing region in China, the hydrology and morphology of PRD have predominantly been dictated by human activities over the last 20 years, and this has caused a lot of environmental problems, such as floods, salinity intrusion, and storm surges.

PRD has a sub-tropical monsoon climate that is strongly influenced by storms from the South China Sea and the Western Pacific, as well as by southwest monsoons and typhoons. The annual average temperature of the basin is between 21 °C and 23 °C, the annual average evaporation is between 1200–1400 mm, and the annual average precipitation ranges from 1600 to 2300 mm. Since almost 80% of the yearly rainfall occurs from April to September, there is considerable seasonality of precipitation in the basin. The West River, North River and East River currently provide the essential water supply for Guangdong Province and the District of Hong Kong and Macao in China.

In this study, daily streamflow data were used to investigate variations in the flow regime at seven main control hydrological stations, in which, Makou station on the West River, Sanshui station on the North River, Boluo station on the East River, which are three income control stations of PRD (Fig. 1). As shown in Fig. 1, the other four hydrological stations were used for comparative study, in which, Gaoyao and Shijiao stations are the upstream control stations of the Northwest River Delta, and Longchuan and Heyuan stations are the upstream control stations of the East River Delta. Hydrological data used in this study ranges from January 1, 1960 to December 31, 2009, which were obtained from the Bulletins of Chinese River Sediment compiled by the Ministry of Water Resources of China (MWRC) and provided by the Water Bureau of Guangdong Province. The quality of hydrological data is controlled before its release by the Water Bureau of Hydrology of Guangdong Province, and this control included an examination of rationality. Because we have studied the environmental flow alteration in the East River (eg. Lin et al., 2014a,b), this study mainly focuses on the environmental flow alteration in the Northwest River. But the comparative analysis between two river deltas would be also conducted in this study.

3. Study area and data

4. Results of environmental flow alteration

For the Northwest River of PRD, daily streamflow data at Sanshui and Makou stations were used to analyze the variation of flow regime using the Mann-Kendall trend analysis, and results are presented in Fig. 2. It can be seen from Fig. 2 that there was a significant increase in streamflow at Sanshui station, but a non-significant decreasing trend at Makou station. Referring to Fig. 2, it can be also determined that the change point in annual flows at Sanshui and Makou stations was the time period around 1990, which was statistically significant at both Sanshui and Makou stations. Using the time of abrupt change, the streamflow from 1960 to 2009 can be divided into two periods, i.e., the pre-impact period (1960–1989), and the post-impact period (1990–2009), these periods are representative of natural and changed conditions, respectively. It can be also seen from Fig. 2 that the flow magnitude was larger in general at Sanshui station, while it had more fluctuations at Makou station after 1990.

For the East River of PRD, our previous study found that the change point for the annual flow in the East River was identified as the time period from 1970 to 1974 in the East River, this change was mainly due to the construction of Fengshuba and Xinfengjiang reservoirs during this period (Lin et al., 2014a,b). Therefore, the long-term records at Longchuan, Heyuan, and Boluo stations were divided into the pre-impact period of 1951–1969 and the post-impact period of 1975–2010 for the analysis of environmental flow alteration in this study.

4.2. Changes in inter-annual streamflow characteristics

For the Northwest River of PRD, Table 2 summarizes the results obtained by RVA (represented by $D_R$) and HMA (represented by $D_H$) at Sanshui and Makou stations. In comparison with the pre-impact period, in Group 1, the average monthly flow during the post-impact period showed an increasing trend at Sanshui station. When assessed by RVA and HMA, significant variations at monthly scales were observed in four months: January, February, March, and December at Sanshui station. The $D_R$ values for these four months were, respectively, 85%, 100%, 100% and 100%; and the $D_H$ values were 61.08%, 65.93%, 74.94% and 60.36%, respectively. Although the variation in magnitude of monthly flow at Makou station was not considerable but was more complicated. As can be seen from Table 2, there was no evident change in the average monthly flow but there was a decrease in flow during April, May, August, September, October and November. However, in June and July (particularly in July) there was an increase during the
post-impact period compared to the pre-impact period. It is also evident from Table 2, that the main alteration on monthly scales occurred during the dry period at Makou station in January, February, November and December; the DH values for these four months were 55%, 55%, 100% and 55%, respectively.

The parameters of Groups 2, 3 and 4 were used to describe extreme events. In Group 2, the average values of all annual extreme water conditions increased in the post-impact period compared to the pre-impact period. It can be seen from Table 2, that there was a considerable change in the maximum indicators including the 1-, 3-, 7-, 30- and 90-day minimum flows, and that the DH of these exceeded 50%, while there were no obvious changes in the maximum indicators at Sanshui station.

In Group 3, the median Julian date of the annual minima moved ahead by 18 and 23 days, while the median Julian date of the one-day maximum flow was more concentrated during the post-impact period.

In Group 4, there was an evident decrease in the number and duration of low pulses at Sanshui station, while the duration of high pulses increased greatly, although the number of high pulses also decreased. However, for Makou station, there were no obvious changes in the number and duration of low or high pulses.

It can be seen from Table 2 that all the indicators of water-condition rate and frequency increased at both Sanshui and Makou stations, and that both \( D_k \) and \( D_h \) of these indicators exceeded 50%, except for the rise rate at Makou station. In particular, the number of reversals changed considerably at both two stations. Fig. 4 shows the number of reversals during the post-impact period at Sanshui and Makou stations. For Sanshui station, the mean value of the number of reversals increased from 104.5 (pre-impact period) to 127.5 (post-impact period); the values of \( D_k \) and \( D_h \) were 100% and 73%, as calculated by the RVA method. Referring to Fig. 4, it can be seen that the frequency of the number of reversals lower than 100 fell from 0.7 to 0, while the frequency higher than 100 grew from 0.3 to 1 during the post-impact period compared to the pre-impact period, and similar changes were be also found at Makou station.

For the East River of PRD, a decrease in maximum flow and an increase in minimum flow were found at the Boluo station in our previous study (Lin et al., 2014a,b). It is also found that the
duration of low pulse was reduced significantly, the median date of the one-day minimum flow moved ahead by about 10.5 days, and rapid changes, including flow reversals increased significantly at the Boluo stations after 1974 (Lin et al., 2014a,b).

4.3. Changes in intra-annual streamflow characteristics

Six additional indicators of intra-annual variation, were calculated and listed in Table 3. For the Northwest River of PRD, through...
a comparison of these indicators during the two periods, it can be seen that there was clear intra-annual variation in streamflow at Sanshui station. The nonuniformity coefficient and the complete accommodation coefficient at Sanshui station decreased by 16.0% and 11.4%, respectively, which indicates that monthly discharges tended to be more even throughout the year after 1990. Meanwhile, the relative variation range sharply decreased by 59.3%, while the absolute relative range increased up to 33.2% during the period 1990–2009. However, the concentration degree slightly decreased, and the concentration periods were both in late July. Unlike at Sanshui station, the intra-annual variations of streamflow at Makou station were in general relatively minor (0.5–6.6%), which indicate that the distribution characteristics of intra-annual streamflow remained consistent to a certain extent in both of the two periods. However, as shown in Fig. 5, the intra-annual variability of streamflow at Makou station was more complex in a seasonal respect, the monthly mean discharge decreased in spring and autumn but increased in June and July during the period 1990–2009, creating a much steeper monthly discharge curve. In addition, annual peak flows at two stations were both observed to occur in July during the post-impact period instead of June during the pre-impact period.

The RVA and HMA methods were also used to estimate the alteration in the intra-annual streamflow, and the results are summarized in Table 3. It can be seen from Table 3 that there was a relatively higher alteration in the intra-annual streamflow at Sanshui station, with average \( D_k \) and \( D_h \) values of 30.0% and 43.26%, respectively. Although there was a significant alteration in the relative variation range, the other indices showed no significant changes. The mean \( D_k \) and \( D_h \) values at Makou station were 18.0% and 24.7%, respectively, which according to Richter’s criteria infer low alteration. It also implies that there were no significant changes in the distribution characteristics of the intra-annual streamflow at Makou station.

For the East River of PRD, refer to Table 3, it can be seen that intra-annual streamflow from Boluo station in the East River Delta showed more evenly distributed from the pre-impact period to the post-impact period. All of these indicators decreased after 1970 s, the relative variation range was the most significant with 65.8% declined, and others indictors were also decreased more than 30% except the concentration period (2.9%). As shown in Fig. 5, the most obvious change at Boluo station was that the monthly discharge curve became flat compared with the curve before 1970. It can be observed that there is a certain reduction (19.3%) in discharge of June, whereas a considerable streamflow increase (15.2–80.3%) of other months except September (decreased by 2.5%).

The result of RVA and HMA at Boluo station is also listed in Table 3, and it can be observed that the mean \( D_h \) value was 13.0%, while the mean \( D_h \) value was 41.1%. The result indicated that there was middle degree alteration in the distribution characteristics of the intra-annual streamflow at Boluo station.

### Table 3

| Location | Indicator | Nonuniform coefficient (Cn) | Complete accommodation coefficient (Cc) | Concentration degree (Cd) | Concentration period (Cp) | Relative variation range (Cr) | Absolute variation range (Ca) |
|----------|-----------|-------------------------------|----------------------------------------|----------------------------|-----------------------------|--------------------------------|--------------------------------|
| Upstream of the Northwest River Delta | Gaoyao Medians Pre-impact | 0.45 | 6.87 | 0.77 | 0.31 | 11.14 | 16170.33 |
|          | Post-impact | 0.48 | 7.12 | 0.80 | 0.33 | 11.28 | 16661.75 |
|          | Shijiao Dn (%) | 39.05 | 30.00 | 10.00 | 30.00 | 30.00 | 20.00 |
|          | Post-impact | 0.43 | 6.04 | 0.79 | 0.31 | 12.28 | 2946.95 |
|          | Dn (%) | 10.00 | 40.00 | 40.00 | 40.00 | 40.00 | 40.00 |
|          | Post-impact | 20.60 | 26.75 | 26.06 | 19.14 | 16.91 | 15.74 |
| Income of the Northwest River Delta | Makou station Dn (%) | 21.96 | 15.82 | 17.02 | 42.77 | 28.46 | 22.00 |
|          | Post-impact | 1.06 | 0.41 | 0.58 | 7.62 | 39.58 | 3740.00 |
|          | Dn (%) | 0.29 | 0.42 | 7.79 | 3.10 | 16.10 | 4980.00 |
|          | Post-impact | 0.74 | 0.30 | 0.45 | 7.83 | 0.80 | 15281.00 |
|          | Dn (%) | 0.77 | 0.29 | 0.39 | 6.27 | 10.96 | 416.38 |
|          | Post-impact | 0.51 | 0.21 | 0.28 | 6.06 | 6.61 | 346.12 |
|          | Dn (%) | 50.49 | 71.51 | 31.73 | 24.75 | 56.66 | 22.79 |
|          | Post-impact | 0.89 | 0.37 | 0.54 | 7.89 | 16.10 | 4980.00 |
|          | Dn (%) | 10.00 | 20.00 | 20.00 | 20.00 | 90.00 | 20.00 |
|          | Post-impact | 0.78 | 0.29 | 0.39 | 6.27 | 10.96 | 416.38 |
|          | Dn (%) | 0.51 | 0.21 | 0.28 | 6.06 | 6.61 | 346.12 |
|          | Post-impact | 50.30 | 21.36 | 58.63 | 48.20 | 44.71 | 37.43 |
|          | Dn (%) | 72.22 | 11.11 | 55.56 | 55.56 | 55.56 | 33.33 |
|          | Post-impact | 0.66 | 0.25 | 0.35 | 6.36 | 8.96 | 868.03 |
|          | Dn (%) | 0.36 | 0.15 | 0.20 | 5.79 | 3.36 | 553.96 |
|          | Post-impact | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|          | Dn (%) | 48.30 | 23.86 | 53.02 | 48.12 | 55.56 | 33.33 |
|          | Post-impact | 16.67 | 16.67 | 0.00 | 5.56 | 5.56 | 33.33 |
|          | Dn (%) | 48.31 | 35.65 | 48.78 | 43.26 | 47.96 | 22.79 |
and downward bias in the post-impact period, respectively. However, HMA can give a global assess which eliminates shortcomings of the RVA. Referring to Fig. 6(b) and (d)), it can be seen that the degree of hydrological alteration were 34% and 31% by using HMA method, but there is little difference in the measurement of variation degree for HMA. Therefore, these results indicated that combination with RVA and HMA can give a more comprehensive evaluation of IHA parameters alteration.

5.2. Impact of discharge diversion

An analysis of the above results shows that there was an alteration in the discharge processes at the two control stations in PRD after 1990. One of the most important reasons for this is considered to be the practice of uneven sand dredging, which began in the late 1980s (Chen and Chen, 2002; Luo et al., 2007; Liu et al., 2014). Fig. 7 shows the geometric shapes of river cross sections at Sanshui station from the year 1984–2009, where little change in the depth of channel bed elevation was observed between 1984 and 1988. However, after this date, large-scale sand excavation became commonplace and the depth of the channel bed elevation dropped by more than 7 m between 1988 and 2005. There were obvious trends in the variation of the depth of the channel bed elevation after 2005. An analysis of the divided flow ratio between Sanshui and Makou stations (the annual flow at Sanshui station is divided by the total annual flow at Sanshui and Makou stations) was also been conducted, and the results are shown in Fig. 7. It is evident that there was little change in the divided flow ratio from the 1960s to the 1980s, and that the values at Sanshui station varied between 0.11 and 0.16 in most cases. However, this situation altered drastically in relation to excessive mining that took place after the end of the 1980s, where, as shown in Fig. 7, the divided flow ratio increased by about 0.07 up to an average of 0.21 (with the maximum of approximately 0.26 in 1996).

To quantitatively analyze how the diversion ratio affects the inter-annual streamflow, further research was conducted by real-locating annual streamflow at Makou and Sanshui stations during 1990–2009, using the average diversion ratio during the period 1960–1989. From the results shown in Fig. 8 and Table 4, it can be observed that without the impact of change in the diversion ratio.
ratio, the annual discharge in the pre- and post- periods would be more similar, particularly at Sanshui station. Referring to Table 4, it can be found that the change in the diversion ratio is considered to be the main factor affecting the inter-annual streamflow alteration at Sanshui and Makou stations, whose contributions were 90.08% and 122.35%, respectively. Although the contribution of the diversion ratio to the variation of annual streamflow at Makou station was great, the decline was not very obvious because of the large base flow, which mostly depends on streamflow from the control station in the upper stream (Gaoyao station). On the other hand, other factors, mainly human activities and climate change in the upper stream, resulted in changes in streamflow at Gaoyao and Shijiao stations (as the control stations for these two main tributaries that drain into PRD), also had some influences on Sanshui and Makou station, whose contributions were 9.92% and -22.35%, respectively, and the effect of these factors tended to increase annual streamflow. These results indicate that the main factor causing inter-annual streamflow alteration at Sanshui and Makou station was a change of the diversion ratio due to changes in river channel geometry.

5.3. Impact of upstream flow

In addition to the human-induced deepening of the river channel, which has resulted in a change in the divided flow ratio between Makou and Sanshui stations, it is also acknowledged that upstream flow alteration due to climate change and human activities can also affect the streamflow in PRD. By the late 1990s, in the Pearl River basin alone, there are over 8936 reservoirs, with a total storage capacity of 518 x 10^8 m^3, representing 15.9% of Pearl River’s annual water discharge (Liu et al., 2014). Fig. 1 shows the location of large reservoirs situated upstream of the two tributaries. Zhang et al. (2009) found that streamflow variations were related to precipitation changes in the West River basin, implying the tremendous influence of climate change on hydrological processes in the West River basin. However, as can be seen from Fig. 9, there
were no significant changes in streamflow at Gaoyao and Shijiao stations, which are the control stations for these two main tributaries that drain into PRD. This result implies that human activities (including reservoir operation) and climate changes in the upper stream had less combined influence on the inter-annual streamflow alteration of the Northwest River Delta.

In relation to the intra-annual variations of streamflow, we also analyzed correlations between the indices of intra-annual variations of the diversion ratio, and streamflow at Makou and Sanshui stations, and those obtained from upstream (Gaoyao and Shijiao stations). The correlation coefficients are shown in Table 5, and it can be seen that there were strong correlations between the indices of intra-annual variations of streamflow at Sanshui and Makou stations and those at Gaoyao station (Figs. 10 and 11), which shows that distribution characteristics of intra-annual streamflow at Sanshui and Makou stations were affected mainly...
by the streamflow at the upstream control station. To some extent, this reflects the influence of climate change and human activities in the upper stream, and Zhang et al. (2009) found that the streamflow variations show remarkable relations with precipitation changes in West River basins, which implies climate change make more contribution to the streamflow variation in West River. It can be also seen from Table 3 that concentration degree and non-uniformity coefficient increased from pre-impact period to post-impact period at Gaoyao and Makou station, which indicated that climate change make intra-annual distribution of monthly discharge more uneven. While the intra-annual environmental flow alteration at Shijiao station was more complicated due to climate change and human activities, especially reservoir operation. These results indicate that the main factor causing intra-annual streamflow alteration at Sanshui and Makou station was a change of upstream flow due to environment change, especially climate change.

5.4. Impact of reservoir operation

From the above analysis, reservoir operation can also affect the environmental flow alteration, especially the intra-annual variation. Our previous study (Lin et al., 2014a,b) has been shown that the runoff has been changed significantly after 1974 in a positive trend in the East River, and it is apparent that the Fengshuba reservoir construction from 1970 to 1974 had a major impact on its downstream flows. It can be seen from Fig. 5, the average monthly flow decreased during the flood period, but increased greatly during the dry period from pre-impact period to post-impact period at Heyuan, and Boluo stations. This is due to the reservoirs usually operate to store flow in the flood period but release flow in the dry period, but the impact of upstream reservoirs diminished with the distance downstream. Referring to Table 3, it can be seen that concentration degree and non-uniformity coefficient decreased from pre-impact period to post-impact period at Longchuan, Heyuan, and Boluo stations. These results all indicated that reservoirs operation can make intra-annual distribution of monthly discharge more even.

5.5. Possible impact of environmental alteration

Environmental flow alteration, such as changes in magnitude, timing, low and high pulses, can directly affect the hydrological processes and riverine ecosystem (Lytle and Poff, 2004). According to the above analysis of environmental flow alteration in PRD, there could be three possible impacts on the ecosystem in this area. For example, according to this study, changes in monthly flows and annual extreme conditions have occurred in this area.

![Scatter plots between indicators of intra-annual variations of streamflow at Gaoyao and Makou stations.](image-url)
As a result of these changes, there will be a reduction in biodiversity, a decrease in aquatic macrophytes, and an increase in fine sediment deposition (Richards and Bacon, 1994). In addition, the occurrence time of the annual minimum and maximum water conditions has changed (Table 2 and Fig. 3), which disrupts the spawning of fish with pelagic eggs, because the spawning activity for many fish is triggered by both the rising water and the rising temperature in spring (Lian et al., 2012). Finally, rapid changes, especially flow reversals (Fig. 4), have been observed in the PRD region (Table 2), which disrupt the biological life cycle and result in the disappearance of native species and the invasion of alien species (Lin et al., 2014a). Besides, changes in the characteristics of intra-annual streamflow have also been observed in the PRD region (Table 3), especially at Sanshui station, which can influence water resources regulation and the growth of aquatic organisms (Zheng and Liu, 2003).

6. Conclusions

Environmental flow alteration is a current and important topic in hydrology. The Pearl River Delta, located in south China, was selected as case study. Seven main gauging stations were used to investigate the variation of hydrological processes in PRD. The methodologies used for analysis in this paper were the Mann-Kendall test, IHA, RVA and HMA. The main conclusions are summarized as follows.

The results indicated that combination with RVA and HMA can give a more comprehensive evaluation of environmental flow alteration. Environmental flow alteration has changed a lot in PRD during the past 50 years. Correlation analysis was used to further analyze the underlying factors causing environmental flow alteration in PRD. It is also found that 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, while change in upstream flow is the main factor causing intra-annual streamflow alteration in the Northwest River of PRD, especially due to climate change. And reservoir operation is the main factor causing intra-annual streamflow alteration in the East River of PRD. The results also indicated that climate change make intra-annual distribution of monthly discharge more concentrate, while reservoir operation can make it more even.

Flow regime alteration is one of primary drivers for a number of fundamental ecological processes in river ecosystems, and environmental flow alteration has possible impacts on ecosystems and water supply within the PRD region. The results will assist in...
improving water resources management and ecosystem sustain-
ability in the PRD region.

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References

Babel, M.S., Dinh, C.N., Mullick, M.R.A., Nanduri, U.V., 2012. Operation of a hydropower system considering environmental flow requirements: a case study in La Ngua river basin, Vietnam. J. Hydro-environ. Res. 6, 63–73.

Toll, B.T., Montgomery, D.S., Newbold, J.D., Arscott, D.B., Dow, C.L., Auffdenkampe, A. K., Jackson, J.K., Kaplan, L.A., 2006. Ecosystem metabolism in stream of the Catskill Mountains (Delaware and Hudson River watersheds) and Lower Hudson Valley. J. North Am. Benthol. Soc. 25, 1018–1044.

Chen, X.H., Chen, Y.D., 2002. Hydrological change and its causes in the river network of the Pearl River Delta. Acta Geogr. Sin. 57 (4), 430–436 (in Chinese).

Chen, Y.D., Zhang, Q., Chen, X.H., Wang, P., 2012. Multiscale variability of streamflow changes in the Pearl River basin, China. Stoch. Environ. Res. Risk A 26, 235–246.

Dai, S.B., Yang, S.L., Cai, A.M., 2008. Impacts of dams on the sediment flux of the Pearl river, southern China. Catena 76, 36–43.

Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. Global Planet. Change 50, 63–82.

Gerstengarbe, F., Werner, P., 1999. Estimation of the beginning and end of recurrent events within a climate regime. Clim. Res. 11, 97–107.

He, Y., Lin, K., Chen, X., Ye, C., Cheng, L., 2014. Classification-based spatiotemporal variations of Pan evaporation across the Guangdong Province, South China. Water Res. Manag. http://dx.doi.org/10.1111/j.1126-9404.00810.5.

Huang, F., Xia, Z., Li, F., Wu, T., 2013. Assessing sediment regime alteration of the upper Yangtze River. Environ. Earth Sci. 70, 2349–2357.

Karabork, M.C., 2007. Trends in drought patterns of Turkey. J. Environ. Eng. Sci. 6, 45–52.

Kendall, M.G., 1975. Rank Correlation Measures. Charles Griffin, London.

Kim, Z., Singh, V.P., 2014. Assessment of Environmental Flow Requirements by Entropy-Based Multi-Criteria Decision. Water Res. Manag. 28, 459–474.

Kumar, S., Merwade, V., Kam, J., Thurner, K., 2009. Streamflow trends in Indiana: effects of long-term persistence, precipitation and subsurface drains. J. Hydrology 374 (1–2), 171–183.

Laize, C.L., Acreman, M.C., Schneider, C., Dunbar, M.J., Houghton-carr, H.A., Florke, M., Hannah, D.M., 2014. Projected flow alteration and ecological risk for Pan-European Rivers. River Res. Appl. 30, 299–314.

Lee, A., Cho, S., Kang, D.K., Kim, S., 2014. Analysis of the effect of climate change on the Nakdong river stream flow using indicators of hydrological alteration. J. Hydro-environ. Res. 8, 234–247.

Li, F., Zhang, G., Xu, Y.J., 2014. Spatiotemporal variability of climate and streamflow in the Songhua River Basin, northeast China. J. Hydrol. 514, 53–64.

Lian, Y., You, J., Sparks, R., Demissie, M., 2012. Impact of human activities to hydrologic alterations on the Illinois River. J. Hydrol. Eng. 17, 537–546.

Lin, K., Lian, Y., Chen, X., Lu, F., 2014a. Changes in runoffs and eco-flows in the Dongjiang River of the Pearl River Basin, China. Front. Earth Sci. 8 (4), 547–557.

Lin, K., Lv, F., Chen, L., Singh, V.P., Zhang, Q., Chen, X., 2014b. Xianjiang model combined with Curve Number to simulate the effect of land use change on environmental flow. J. Hydrol. 519, 3142–3152.

Liu, F., Yuan, L., Yang, Q., Ou, S., Xie, L., Cui, X., 2014. Hydrological responses to the combined influence of diverse human activities in the Pearl River Delta, China. Catena 113, 41–55.

Luo, X.L., Zeng, E.Y., J.R.Y., Wang, C.P., 2007. Effects of in-channel sand excavation on the hydrology of the Pearl River Delta, China. J. Hydrol. 343, 230–239.

Lytle, D.A., Poff, N.L., 2004. Adaptation to natural flow regimes. Trends Ecol. Evol. 19, 94–100.

Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 13, 245–259.

Monk, W.A., Peters, D.L., Curry, A., Baird, D., 2011. Quantifying trends in indicator hydroecological variables for regime-based groups of Canadian rivers. Hydrol. Process. 25, 3086–3100.

Niu, J., Chen, J., 2010. Terrestrial hydrological features of the Pearl River basin in South China. J. Hydro-environ. Res. 4 (4), 279–288.

Niu, J., Sivakumar, B., 2014. Study of runoff response to land use change in the East River basin in South China. Stoch. Environ. Res. Risk A 28 (4), 857–865.

Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biol. 55, 194–205.

Puig, A., Olguín Salinas, H.F., Borús, J.A., 2016. Recent changes (1973–2014 versus 1903–1972) in the flow regime of the Lower Paraná River and current fluvial pollution warnings in its Delta Biosphere Reserve. Environ. Sci. Pollut. Res. 23, 11471–11492.

Restrepo, J.D., Cantero, J.R., 2013. Discharge diversion in the Patía River delta, the Colombian Pacific: geomorphic and ecological consequences for mangrove ecosystems. J. S. Am. Earth Sci. 46, 183–198.

Richards, C., Bacon, K.L., 1994. Influence of fine sediment on macroinvertebrate colonization of surface and hyporheic stream substrates. Great Basin Naturalist 54, 106–113.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10 (4), 1163–1174.

Richter, B.D., Warner, A.T., Meyer, J.L., Lutz, K., 2006. A collaborative and adaptive process for developing environmental flow recommendations. River Res. Appl. 22, 297–318.

Shi, H.Y., Wang, G.Q., 2015. Impacts of climate change and hydraulic structures on runoff and sediment discharge in the middle Yellow River. Hydrol. Process. 29 (14), 3236–3246.

Shi, H.Y., Li, T.J., Wang, K., Zhang, A., Wang, G.Q., Fu, X.D., 2016a. Physically based simulation of the streamflow decrease caused by sediment-trapping dams in the middle Yellow River. Hydrol. Process. 30 (5), 783–794.

Shi, H.Y., Li, T.J., Wei, J.H., Fu, W., Wang, G.Q., 2016b. Spatial and temporal characteristics of precipitation over the Three-River Headwaters region during 1961–2014. J. Hydrol. Regional Stud. 6, 52–65.

Shiau, J.T., Wu, F.C., 2008. A histogram matching approach for assessment of flow regime alteration: application to environmental flow optimization. River Res. Appl. 24, 914–928.

Song, S., Xu, Y.P., Zhang, J.X., Li, C., Wang, Y.F., 2016. The long-term water level dynamics during urbanization in plain catchment in Yangtze River Delta. Agric. Water Manage. 174, 93–102.

University of Colorado at Boulder, 2016. World’s large river deltas continue to degrade from human activity. News, Marine Pollution Bulletin 106, 4–7.

Von Storch, V.H. (Ed.), 1995. Misuses of statistical analysis in climate researchvon Storch, H., Navarra, A. (Eds.). Analysis of Climate Variability: Applications of Statistical Techniques. Springer-Verlag, Berlin, pp. 11–26.

Wu, Y.P., Chen, J., 2013. Analyzing the water budget and hydrological characteristics and responses to land use in a monsoonal Climate River Basin in South China. Environ. Manage. 51 (6), 1174–1186.

Yang, Z.F., Yan, Y., Liu, Q., 2012. Assessment of the flow regime alterations in the Lower Yellow River, China. Ecol. Inform. 10, 56–64.

Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol. Process. 16, 1807–1829.

Zhang, Q., Xu, C.Y., Chen, Y.D., 2009. Abrupt behaviors of the streamflow of the Pearl River basin and implications for hydrological alterations across the Pearl River Delta, China. J. Hydrol. 377, 274–283.

Zheng, H.X., Liu, C.M., 2003. Changes of annual runoff distribution in the headwater of the Yellow River Basin. Process Geogr. 22 (6), 585–590 (In Chinese).