Abrupt behaviors of the streamflow of the Pearl River basin and implications for hydrological alterations across the Pearl River Delta, China

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Introduction

River deltas are heavily populated though contribute much to the socioeconomic development of human society (Ericson et al., 2006; Pont et al., 2002). Accordingly, river deltas receive rising concerns from hydrologists, fluvial geomorphologists, policymakers, ecologists especially during last decades. Various aspects of the river deltas, such as wetland ecological environment, are considerably altered as a result of booming economic development. Intensifying human activities in the river deltas also greatly influenced the morphological properties of the deltas, altered both hydrological processes and ecological environment (e.g. Bott et al., 2006). This is particularly the case for the Pearl River Delta (PRD) (Chen et al., 2008). The Pearl River Delta is characterized by the complicated crisscross river network with density of 0.68–1.07 km/km², being the fastest developing region in China since the country adopted the “open door and market reform” policy in the late 1970s. Because of the booming economy and intensifying human activities, new environmental problems emerged in recent decades in the Pearl River Delta, such as floods, salinity intrusion and storm surge. All these environmental problems could be partly attributed to altered hydrological processes within the river channels across the Pearl River Delta. The altered hydrological conditions are mainly represented by abnormally high flood stage in flooding seasons and more frequent salinity intrusion events in the dry seasons. The hydrological alterations are the integrated consequences of intensive channel dredging, sand mining and levee construction, etc. which took place mainly after 1980s (e.g. Zeng et al., 1992; Chen and Chen, 2002; Liu et al., 2003), and posed new challenges for the regional water resource management.

In this study, we analyze the long streamflow series of three hydrological stations of the lower Pearl River basin and the streamflow ratio between Makou and Sanshui stations by using statistical techniques. Furthermore, we also attempt to address influences of precipitation and human activities (human-induced deepening of river channels) on streamflow ratio. The results indicate that: (1) the streamflow variations show remarkable relations with precipitation changes in West and East River basins, implying tremendous influences of climate changes on hydrological processes. Decreasing precipitation was observed in North River basin. However, the streamflow amount of the Sanshui station largely increased due to enlarged streamflow allocation from the West River to the North River; (2) increasing streamflow ratio of Sanshui/(Makou + Sanshui) is the result of morphological changes (downcut) of river channels in the upper Pearl River Delta. The fast downcut of river channels is mainly due to intensive sand mining. Larger magnitude of increase in streamflow ratio corresponds well to the higher intensity of in-channel sand dredging; (3) after late-1990s, decreasing precipitation of the Pearl River basin abates the streamflow amount and also the streamflow ratio. The influences of human activities and climate changes are varying in different time intervals and in different river basins. Due to tremendous impacts of increased streamflow ratio between Sanshui and Makou station, relations between streamflow and precipitation relations in the North River basin are not statistically good. This study helps to improve understandings of the causes underlying altered streamflow variations in the lower Pearl River basin and the hydrological alterations within the Pearl River Delta region.

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hydrological alteration occurred around 1992. The dynamic balance between scouring and filling processes of the river channel was broken after mid-1980s because of intensive human activities such as in-channel dredging, construction of hydraulic facilities, as the direct results of these human activities are fast down-cutting of riverbeds of the upper Pearl River Delta. Changes of the geometrical shapes of the river channels brought about an altered streamflow ratio between North River and West River. Larger magnitude of cutting-down of the river channel of the lower North River when compared to the lower West River leads to more streamflow transferring from the West River to the North River as measured by the Sanshui/(Makou + Sanshui) streamflow ratio. In general, the Sanshui/(Makou + Sanshui) ratio is increasing, which directly raise the amount of water in the hinterland of the Pearl River Delta and result in higher risk of flood inundation in the flooding season. The changed streamflow ratio was seen as one of the major factors causing alterations of the water levels across the PRD (Zhou et al., 2001; Chen and Chen, 2002; Luo et al., 2007).

Huang and Zhang (2004) also suggested that riverine streamflow from the upper PRD heavily influenced water level behaviors within the river network of the PRD. It should be accepted that former researches benefit a good understanding of the water level changes and associated underlying reasons in the study region. The hydrological series analyzed in the former studies, however, are usually short and cannot reflect hydrological conditions of recent years. Besides, short and intermittent streamflow series can not well reflect dynamic processes of the streamflow variations. Therefore, human influences on streamflow ratio and hydrological alterations are by no means well addressed or understood. Besides, most of former reports attached overwhelming importance to human activities, and less attention has been paid on influences of climate changes on hydrological processes. Furthermore, in recent years, hydrological alterations caused abnormally high water level and more frequent salinity intrusion events in the PRD, posing new challenges for the management of water resource and natural hazards. Knowledge of hydrological processes from the upper Pearl River Delta and the underlying causes in terms of human activities and climate changes will be greatly helpful for the development of improved understanding of water level alterations within the PRD, which has the potential to enhance human mitigation to natural hazards and effective water resource management. In this sense, we will investigate hydrological properties of the upper PRD with updated long hydrological series and improved statistical techniques. This is the major motivation of this study.

Therefore, the objectives of this paper are: (1) to investigate abrupt behaviors and trends of streamflow series of three hydrological stations, i.e. Makou station for the West River basin, Sanshui station for the North River basin and Boluo for the East River basin; (2) to explore the abrupt behaviors of streamflow ratio of the Sanshui station to the total streamflow amount of Sanshui and Makou stations and also the underlying causes; (3) to analyze implications of these hydrological properties for the water resource management and the hydrological alterations within the PRD. The novelty of this study lies in the following points: (1) we will analyze the longest possible monthly hydrological series; (2) we will quantitatively evaluate abrupt behaviors of streamflow variations and relate these changes to human activities and climate changes; (3) besides, we will further improve the simple two-phase linear regression scheme based on the work by Lund and Reeves (2002). The modified method can help to investigate abrupt changes of the considered time series on different time scales, providing the potential to differentiate various factors exerting influences on hydrological processes on different time scales. As such, this study will be helpful to improve our understandings of statistical properties of hydrological processes from the upper PRD under both human activities and climatic changes, to uncover associated implications for the hydrological alterations, water resource management and human mitigation to natural hazards in the study region.

Data

The monthly hydrological data (unit: m³/s) analyzed in this study were extracted from three hydrological stations of the West River basin, the North River basin and the East River basin, i.e. Makou station, Sanshui station and Boluo station. The hydrological data of Makou and Sanshui station cover January 1959 to December 2005 and that of the Boluo station cover January 1954 to December 2002. The hydrologic data before 1989 are extracted
from the Hydrological Year Book (published by the Hydrological Bureau of the Ministry of Water Resources of China) and those after 1989 are provided by the Water Bureau of Guangdong Province. The quality of the hydrological data was firmly controlled before its release. The hydrological series are free of missing data. Our previous studies of the precipitation changes in the Pearl River basin indicated a relatively homogeneous spatial distribution of precipitation variations (e.g. Zhang et al., 2008a). To match the time interval the hydrological data covers, we extracted precipitation data covering the period of 1951–2005 from the 160 rain gauging stations (Gemmer et al., 2004; Zhang et al., 2008b). The data are collected from the National Climatic Centre (NCCC) of the China Meteorological Administration (CMA). Locations of these stations have been indicated in Fig. 1. The quality of the hydro-meteorological dataset used in this study is firmly controlled before its release (see Zhang et al., 2008b).

**Methodology**

First, we will briefly introduce the methodology used in the study (Solow, 1987; Easterling and Peterson, 1995; Vincent, 1998; Lund and Reeves, 2002).

The model is written as:

\[
X_t = \begin{cases} 
\mu_1 + X_t1 + e_t \\
\mu_2 + X_t2 + e_t 
\end{cases}
\]

(1)

In the work by Lund and Reeves (2002), \(t_1\) and \(t_2\) are defined as: 1 ≤ \(t_1\) ≤ \(c\) and \(c < t_2\) ≤ \(n\) respectively, where \(c\) is the possible change point to be tested. \(\mu_1\) and \(\mu_2\) are the mean values for the hydrological series defined by \(t_1\) and \(t_2\), respectively. \(\epsilon_t\) is the error term. With this original method, only the time when the abrupt change occurs is decided. The modification we have made in this study mainly lies in the ranges of \(t_1\) and \(t_2\). In our study, \(t_1 = t_2\) is defined as \(t_1 = [j-n,j-1]\), \(t_2 = [j,j+n-1]\) respectively. The sub-sample size \(n\) varies as \(n = 2, 3, ..., N/2\), or may be selected at suitable intervals. The quantity \(j = n + 1, n + 2, ..., N-n + 1\) is the reference time point. \(N\) is the length of the time series. Therefore, \(t_1\) and \(t_2\) are changing. \(t_1\) and \(t_2\) here are the size of the window shifting along the entire time series and are also taken as the time scales as mentioned in the following sections. So, we can see that this modified method behaves in the similar way as the wavelet transform technique does. In this sense, the modification of the method is enlightened by the wavelet transform method. In so doing, a time point when possible abrupt change occurs is decided with respect to a certain time scale, i.e. \(t_1\), \(t_2\). Thus, comparatively, the original method just decides when the change point occurs.

The improved method, however, can both tell the time when the change point occurs and also the related time scales the change point occurs. In this way, mechanisms behind the abrupt behaviors of the streamflow variations are expected to be exposed, as different influencing factors exert their impacts on the streamflow changes on different time scales. The least squares estimates of the trend parameters in (1) are:

\[
\hat{\mu}_1 = \sum_{t = j-n}^{j-1}(t - \bar{t}_1)/(X_t - \bar{X}_1) \quad \text{and} \quad \hat{\mu}_2 = \sum_{t = j}^{j+n-1}(t - \bar{t}_2)/(X_t - \bar{X}_2)
\]

(2)

In (2), \(\bar{X}_1\) and \(\bar{X}_2\) are the average series values before and after time \(j\), respectively. \(\bar{t}_1\) and \(\bar{t}_2\) are the average time observations before and after time \(j\), respectively. Least squares estimates of the location parameters \(\mu_1\) and \(\mu_2\) in equation (1) are:

\[
\hat{\mu}_1 = \bar{X}_1 - \hat{\mu}_{X1} \quad \text{and} \quad \hat{\mu}_2 = \bar{X}_2 - \hat{\mu}_{X2}
\]

(3)

The denominators in (2) can be explicitly evaluated as:

\[
\sum_{t = j-n}^{j-1}(t - \bar{t}_1)^2 = \frac{(j-1)(j-2)}{12} \quad \text{and} \quad \sum_{t = j}^{j+n-1}(t - \bar{t}_2)^2 = \frac{(n-j+1)(n-j)}{12} - \frac{(n-j+1)(n-j+2)(n-j)}{12}
\]

(4)

Under the null hypothesis of no change points, the regression parameters during the two phases must equal, i.e. \(\mu_1 = \mu_2\). If so, \(\hat{\mu}_1 - \hat{\mu}_2\) and \(\hat{\mu}_{X1} - \hat{\mu}_{X2}\) should be close to zero for each sub-sample divided by \(j\).

Rescaling this to a regression \(F\) statistic merely states that (Lund and Reeves, 2002)

\[
F_t = \frac{(SSE_{Red} - SSE_{Full})(n-4)}{2SSE_{Full}}
\]

(5)

In (5), \(SSE_{Full}\) is the ‘full model’ sum of squared errors computed from

\[
SSE_{Full} = \sum_{t = j-n}^{j-1}(X_t - \hat{\mu}_1 - \hat{\mu}_{X1})^2 + \sum_{t = j}^{j+n-1}(X_t - \hat{\mu}_2 - \hat{\mu}_{X2})^2
\]

(6)

\(SSE_{Red}\) is the ‘reduced model’ sum of squared errors, which was formulated as

\[
SSE_{Red} = \sum_{t = j-n}^{j-1}(X_t - \hat{\mu}_{X1} - \hat{\mu}_{Red})^2 + \sum_{t = j}^{j+n-1}(X_t - \hat{\mu}_{X2} - \hat{\mu}_{Red})^2
\]

(7)

where \(\hat{\mu}_{Red}\) and \(\hat{\mu}_{Red}\) are estimated under the constraints \(\mu_1 = \hat{\mu}_{Red}\) and \(\mu_2 = \hat{\mu}_{Red}\) (Lund and Reeves, 2002). If a change point is present at time \(j - 1\), \(F_t\) should be statistically larger when compared to the threshold value by \(F\) test. The effective degree of freedom \(\text{(Eff}F)\) after the correction of dependence and in a normalized distribution for the time series (Storch and Zwiens, 1999; Jiang et al., 2007) can be estimated by

\[
\text{Eff}F = \frac{2n}{\text{INT}(1 + 2\sum_{t = 1}^{\text{INT}(\sqrt{\frac{n}{t}})}r_t(t))}
\]

(8)

where \(\text{INT}\) denotes the integer part of the number, \(r(t)\) is the autocorrelation with time lag of \(t\), \(r(t)\) is the autocorrelation function of the entire hydrological series and \(\text{INT}(\sqrt{\frac{n}{t}})\) is the autocorrelation function of the hydrological series considered. After the effective degree of freedom is known, the threshold value \((F)\) can be obtained via the \(F\) test table (Lund and Reeves, 2002). If \(F_t > F_{\text{th}}\), then we can say that the change point is statistically significant. This method is used to detect significant change points and linear trends between the change points in time series. The figures in this study were made by using the Surfer software package.

**Results and discussion**

Hydrological variations of the Pearl River basin

Fig. 2 illustrates the abrupt behaviors of streamflow series of the Makou station (the upper panel) and trends of sub-series between change points (the lower panel). X axis shows the time scales, i.e. \(t\) \((t_1\) or \(t_2\), because \(t_1 = t_2\)). Dashed contours denote turning points from upward to downward trends and vice versa. Thick dashed or solid contours indicate significant change points at >95% confidence level. More detailed descriptions can be found in the caption of Fig. 2. The upper panel of Fig. 2 shows the shifts of change points on different time scales. At time scales of <32 months, there are many upward and downward trends interrupted by change points. Only two change points are significant at >95% confidence level. One change point occurs in about 1962, followed by downward trend. Another significant change point occurs in about 1964,
followed by upward trend. For the sake of better understanding of abrupt changes (change points and trends between change points) of stream series, we also plotted the standardized streamflow series and trends interrupted by change points in the lower panel of Fig. 2. Slight increasing trend can be identified between 1959 and 1962. After a decreasing trend in a shorter time interval, increasing trend was observed between 1964 and 1966. On time scales of >64 months, more than two change points with centers circled by thick lines can be found.

The upper panel of Fig. 2 indicates that after 1983, the streamflow of the Makou station turns to be decreasing and increasing trend can be detected after about 1990. The streamflow series come to be decreasing after about 1994. To clearly demonstrate these statistical properties, we illustrate the standardized streamflow series and also the trends between change points (see lower panel of Fig. 2). After about 1966, the streamflow is increasing and then turns into decreasing trend in 1983. After 1990, the streamflow is increasing, and is decreasing after 1994. Therefore, four time intervals were identified marked by increasing streamflow trends, while two time intervals by decreasing trends. These time intervals can be observed from lower panel of Fig. 2.

As for abrupt changes of streamflow of the Sanshui station (Fig. 4), on time scales of <32 months, only one significant change point is found. On time scales of >32 months, two regions are characterized mainly by decreasing trends (lower panel of Fig. 2). In addition, it can be found in the lower panel of Fig. 2 that an abnormally high streamflow occurred in 1983 which was due to heavy rainfall induced by strong typhoon activity. The flood event caused by this typhoon affected 67,000 ha of agricultural land.

To demonstrate the influence of precipitation variations on streamflow changes, herein we will also analyze statistical properties of standardized areal average precipitation changes of the West River basin. Spatial patterns of change points of precipitation in the ‘time scale vs. time’ space (upper panel of Fig. 3) show similar characteristics to those of the streamflow variations of the Makou station (upper panel of Fig. 2). F test results show no significant changes within the standardized areal average precipitation series of the West River basin. Moreover, we also analyzed the trends between time points identified by relatively higher threshold values for the sake of an easy comparison between streamflow and precipitation changes. The visual comparison of the lower panels of Figs. 2 and 3 indicates that the streamflow variations largely follow the precipitation changes during the last decades. Particularly the abnormally high precipitation in 1983 (lower panel of Fig. 3) well corresponds to the high streamflow in 1983 observed in the lower panel of Fig. 2. Thereby, the variations of streamflow amount in Makou station are mainly influenced by precipitation changes. Quantitative evaluation of relations between precipitation and streamflow for three river basins considered in this study is conducted in the following section.
Fig. 3. Trends estimation of precipitation variations of the West River basin. The upper panel shows change points on different time scales; and lower panel shows linear trends of time intervals separated by change points.

Fig. 4. Trends estimation of streamflow variations of the Sanshui station. The upper panel shows change points on different time scales; and lower panel shows linear trends of time intervals separated by change points.

late 1990s. Fig. 5 illustrates different changing patterns when compared to streamflow variations of the Sanshui station. The upper panel of Fig. 5 indicates two significant change points on time scales of <32 months, i.e. 1983 and 1992, followed by decreasing precipitation. The lower panel of Fig. 5 clearly indicates general decreasing trends of areal average precipitation of the North River.
Two changes points occur in early 1980s and early 1990s. Anti-phase relations between streamflow of the Sanshui station and the precipitation amount in the North River basin were further elucidated in the next sections.

Fig. 6 shows abrupt behaviors of streamflow of the Boluo station on different time scales. At time scales of <32 months, the streamflow series is subdivided mostly by short intervals of decreasing trends (the upper panel of Fig. 6). Four significant change points are identified in mid-1960s, 1975, early 1980s, 1997 and 1999. On time scales of >32 months, 1975–1985 can be taken as the transitional time interval between increasing and decreasing streamflow. After early 1990s, the streamflow changes are characterized by increasing trends. The standardized streamflow series is subdivided into seven segments by significant change points (the lower panel of Fig. 6). It can be observed from the lower panel of Fig. 6 that the streamflow variations before mid-1980s are characterized mainly by increasing trends, and decreasing trends can be found during two time intervals, i.e. mid-1980s–early 1990s and 2000–2005. From the perspective of large time scales of >64 months, the streamflow variations of the Boluo station are featured by increasing trends. As for the precipitation changes of the East River basin, no abrupt changes are identified on the time scales of >64 months. Two significant change points occur in early 1980s and late 1990s (upper panel of Fig. 7). It can be seen from lower panel of Fig. 7 that general increasing trends are found during 1990–1997. After 1997, the precipitation turns to be decreasing. More complicated changing properties of streamflow variations when compared to those of precipitation changes might be the result of intensifying human interferences with the hydrological processes besides the influences of climatic changes (Chen et al., 2008; Zhang et al., 2009a). To further understand the influences of human activities and climate changes on the streamflow changes, we analyze the statistical relations between areal average precipitation of the West River (Fig. 8A), the North River (Fig. 8B) and the East River (Fig. 8C). Fig. 8 demonstrates the good correlations between precipitation and streamflow for the West River basin and East River basin when compared to the East River basin. Bad precipitation vs. streamflow relations in the North River basin could be attributed mainly to the increasing streamflow ratio between Sanshui and Makou station as a result of human activities. Therefore, the streamflow changes of the Makou station and the Boluo station are mainly controlled by climate changes; streamflow changes of the Sanshui stations are mainly influenced by altered streamflow ratio as a result of deepened river channel induced by intensive sand dredging.

**Streamflow ratio between Makou and Sanshui stations**

Changes of streamflow ratio between Makou and Sanshui station (Sanshui/Makou + Sanshui) have exerted tremendous influences on hydrological processes and were seen as an important factor causing hydrological alteration across the PRD (Chen et al., 2004, 2008). The upper panel of Fig. 9 indicates abrupt changes of streamflow ratio on different time scales. Only one significant change point is identified in 1960s on time scales of <32 months. On time scales of >32 months, four time intervals can be seen as transitional periods when the streamflow ratio changes from one pattern to another: late 1970s, mid-1980s, mid-1990s and after 2000. We analyzed trends of streamflow ratio between change points and the results are shown in the lower panel of Fig. 9. Decreasing streamflow ratio can be found during 1959–1964, 1980–1983 and 1986–1999. Increasing streamflow ratio occurred to the rest time segments within the study period. It can be observed that, during the time intervals considered in this study,
Fig. 6. Trends estimation of streamflow variations of the Boluo station. The upper panel shows change points on different time scales; and lower panel shows linear trends of time intervals separated by change points.

Fig. 7. Trends estimation of precipitation variations of the East River basin. The upper panel shows change points on different time scales; and lower panel shows linear trends of time intervals separated by change points.

Thereby, increasing streamflow of Sanshui station (the lower panel of Fig. 4) can be largely attributed to the increasing streamflow ratio between Sanshui and Makou, causing anti-phase relations between precipitation changes in the North River basin (Fig. 5) and the streamflow changes of the Sanshui station (Fig. 4). Decreasing streamflow of Makou station is the result of increasing streamflow ratio after mid-1990s (Fig. 2). Increasing streamflow flow ratio is largely attributed to down-cutting behaviors of riverbed in the upper PRD. Research results (Chen and Chen, 2002) indicated that fast and intensive down-cutting processes of the river channels in the upper PRD occurred after mid-1980s. Since 1985, the sand sediments dredged annually are about 0.05–0.06 billion cubic meters, which is the direct cause for the intensive downcut of riverbed of the upper PRD (Chen and Chen, 2002). However, the amount of sediments dredged during 1990–1993 accounted for more than half of the total sediment mined during recent decades, which heavily influenced morphological properties of the river channels of the upper PRD.

Study by Luo et al. (2007) indicated that, from 1986 to 2003, about 0.87 billion cubic meters of sand were excavated, which caused average down-cutting depths of 0.59 – 1.73 m, 0.34 – 4.43 m, and 1.77 – 6.48 m in the main channels of the West River, North River and East River, the major water systems in the PRD. Before mid-1980s however, the scouring and filling processes of the river channels are in dynamic balances or in slight deposition processes. Sediment load dredged during 1980–1998 accounts for total net sedimentation within 70 – 125 years (Huang and Zhang, 2006). The river channel in the upper PRD was greatly altered due to in-channel dredging and levee construction after about mid-1980s, resulting in decreasing water level (Lu et al., 2007), which can be seen as the major reason for a significant increasing streamflow ratio during early 1980s and mid-1990s (Fig. 9). The lower panel of Fig. 9 indicates moderate variations of streamflow ratio before mid-1980s. Larger magnitude of increase of streamflow ratio was observed after mid-1980s as a result of fast and intensive downcut of river channels, showing considerable influences of human activities, such as sand dredging, upon hydrological processes. Even larger magnitude of increase in streamflow
ratio changes was observed after 1993. After 1996, the amount of sand sediments dredged was decreasing. Fig. 9 also indicates decreasing streamflow ratio after 1996. Therefore, these results and observations imply the influences of riverbed downcut on streamflow ratio between Sanshui and Makou stations. It should be noted that, after late-1990s, the streamflow amount from the Pearl River basin is decreasing, which is largely because of decreasing precipitation of the Pearl River basin in the period (Figs. 3 and 5).

The streamflow ratio of Sanshui/(Sanshui + Makou) is also decreasing, partly for the reasons of the reduced sand sediment dredged from the river channel and partly because of the decreasing streamflow of the West River basin. Changed streamflow ratio between Sanshui and Makou greatly altered the water allocation between hinterland of the Pearl River basin and West River channel. Our previous studies (e.g. Chen et al., 2009) indicated that the time when the change points of water level changes occur match well those of the streamflow ratio revealed in this study, i.e. early 1980s and early 1990s. Lower panel of Fig. 9 shows larger changing magnitude of streamflow after early 1990s, which can well explain the hydrological alterations starting at early 1990s. With 'range of variability approach' (RVA) approach, we also advocated the considerable influences of changed streamflow ratio on hydrological processes, particularly the water level variations across the Pearl River Delta (Zhang et al., 2009b).

Generally, human activities such as in-channel sand dredging and climatic changes work together to trigger altered streamflow allocation between Sanshui and Makou station by changing hypsographical properties of the river channel, and the changed streamflow ratio or water allocation further lead to or intensify the hydrological alterations across the Pearl River Delta region (Chen et al., 2008; Zhang et al., 2009b). This is the ripple effect in terms of the influences of human activities and climate changes on the hydrological processes. The aforementioned analyses can be seen as the implication of the changing streamflow ratio between Sanshui and Makou station for the hydrological alterations within the Pearl River Delta region.

Conclusions

In recent years, altered hydrological processes across the Pearl River Delta were observed which are represented by abnormal high water level in the hinterland in flooding season and lower water level in winters. The direct consequences of these hydrological alterations are higher risk of flood inundation in flooding seasons and more difficult human withdrawal of fresh water resource due to more frequent salinity intrusion in the dry seasons. Changed streamflow ratio between Sanshui and Makou stations could be seen as the major cause for the hydrological alterations. In this study, we quantitatively evaluated abrupt changes and trends of streamflow variations and also those of streamflow ratio of Sanshui/(Sanshui + Makou) based on long monthly hydrological data at the Makou, Sanshui and Boluo stations. We obtained some interesting and important conclusions based on the aforementioned analysis:

1. The modified simple two-phase linear regression scheme in this study can well reveal abrupt changes of hydrological series on different time scales. The hydrological processes are influenced by more than one factor and these influencing factors tend to alter the changing properties of hydrological series in terms of trend and abrupt behaviors. The improved method, when compared to the original two-phase linear regression scheme, is greatly helpful to deeply investigate mechanisms behind hydrological alterations, holding the potential to differentiate various influencing factors having impacts on hydrological changes. This point is also one of the main contributions of this study.

2. Generally, the streamflow changes are heavily controlled by the precipitation variations except the North River basin. The precipitation of the North River basin is decreasing and the streamflow of the Sanshui station is increasing. This is mainly due to changed allocation of water between Sanshui and Makou stations. Therefore, in the lower Pearl River basin, intensifying human activities have more influences, to a certain degree, on streamflow changes than the climate changes do. This conclusion comes up with challenges for the water resource management under the fast changing environment, and it is particularly the case for the lower Pearl River Delta, one of the highly developed regions in China.

3. Massive sand sediments dredged from the river channels resulted in considerable downcut of riverbed, leading to increased streamflow ratio of Sanshui/(Makou and Sanshui), and it is particularly true for the period of 1980–1998. Intensity of sand dredging in different periods is in good line with changing properties of streamflow ratio. Before mid-1980s, the scouring and filling processes are nearly in balance. The streamflow ratio is in moderate variations. Larger magnitude of increase of streamflow ratio occurred after mid-1980 when compared to that before mid-1980s which is mainly due to intensified sand mining, and this is particularly the case after 1993. After mid-1990s, reduced sand mining caused decreasing streamflow ratio. Decreasing streamflow of Makou station and Sanshui station may also be due to the reduced streamflow ratio. Therefore, we can conclude that the hydrological alterations within the Pearl River basin are mostly the results of human activities such as sand mining, hydraulic facilities and so on. Precipitation changes may also make its contribution to the hydrological alterations.

Even so, our study implies that influences of human activities on changing properties of streamflow series in the lower Pearl River basin are larger.

4. The precipitation of the Pearl River basin is decreasing after late 1990s, so does the streamflow amount and streamflow allocation between the West River and the North River. Altered streamflow allocation was seen as a major cause for the hydrological alterations across the Pearl River Delta, and alteration of streamflow allocation was the integrated consequence of human activities and climate variations. These two factors exerted varying influences in different time intervals and on different time scales. Altered streamflow allocation between Sanshui and Makou intensifies the hydrological alterations of water level within the Pearl River Delta. Furthermore, the impacts various influencing factors have on hydrological processes in the lower Pearl River basin, including the Pearl River Delta region, are varying in different river channels because of extremely complicated hydrological dynamic processes in the river networks in the Pearl River Delta. Our previous studies (Chen et al., 2008; Zhang et al., 2009b) investigated hydrological alterations in terms of water level changes and associated relations to hydrological processes from the upper Pearl River Delta and human activities (mainly the in-channel sand dredging). This study further addressed the changing properties of streamflow allocation between North River and the West River and underlying causes such as climate changes and human activities, which greatly helps to deeply understand the mechanisms behind the hydrological alterations within the Pearl River Delta. This posed a new challenge for policy-making aiming to enhance human...
mitigation to water hazards and water resource management within the Pearl River Delta. Thus, reasonable adjustments of human activities were in urgent need to satisfy natural evolution of environment, and the final objective is to satisfy the sustainable socioeconomic development of the Pearl River Delta.

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