Global and Planetary Change 69 (2009) 35–47

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Temporal and spatial variability of annual extreme water level in the Pearl River Delta region, China

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ARTICLE INFO

Article history:
Received 11 November 2008
Accepted 20 July 2009
Available online 3 August 2009

Keyword:
Pearl River Delta
extreme water level
sand excavation
non-parameters test

ABSTRACT

This paper is concerned with identifying the spatial and temporal patterns in the annual maximum and minimum water level in the Pearl River Delta (PRD) region. The Mann–Kendall test and Pettitt test are used to detect trends and abrupt change points, and the Trend Free Pre-Whitening (TFPW) approach then eliminates the effect of serial correlation in data series with significant autocorrelation. Approximately fifty years of the annual hydrological variables from 18 stations in the three major rivers (the West River, the North River, and the East River) are examined. The changing trends of the extremes in water level show different features in different parts of the PRD region. Generally speaking, in the upper part of the delta, the water levels show a decreasing trend while in the middle and lower part there is an increasing trend. This spatial pattern of the extreme water level variation is unlikely to be due to a long-term change in stream flow in the PRD region because the water level changes do not always coincide with the extreme stream flow variations. Sand excavation initiated in the 1980s and continuing for more than 20 years in almost all tributaries around the PRD region is one of the most serious intensive human activities affecting water levels. The result of the Pettitt test indicates that most abrupt change points occurred in 1980s–1990s, which reveals that sand excavation and channel regulation are likely to have been the most significant factors contributing to the change over this period. These anthropogenic activities modify the annual extreme water level dramatically in a way that affects the morphology of river channels and estuaries of the PRD and also the redistribution of discharge. However, there are differences in the geographic locations of significant trends for the water level investigated, which implies that these impacts are not spatially uniform.

1. Introduction

A large number of studies have examined the likely long-term effects of changes in naturally occurring environmental force factors in fluvial systems. These include natural changes such as mean sea level (Ferla et al., 2007), flood frequency (Brath et al., 2006), and precipitation (Ventura, 2002), as well as anthropogenic influences such as dam construction (Yang et al., 2006), channel dredging (Pintera et al., 2004), sand mining (Mas-Pla et al., 1999), and land reclamation(Chen et al., 2005). Trends in water levels, like other hydrological variables in river basins, are a concern in studies that investigate the impacts of variation in climate patterns or human activities over the duration of a particular historical data sequence. In particular, variation in extreme water levels (maximum and minimum water levels) are of increasing concern because of the increased risk of floods and droughts on local or regional scales, as well as an increasing or decreasing water availability at the continental scale that have been observed (Vorosmarty et al., 2000; Milly et al., 2002; Labat et al., 2004). In addition, the maximum water level is an important parameter in the context of construction of levees and the operation of marine facilities. At the same time, a minimum water level is vital for navigation and to support water intakes for human uses (Sobey, 2005).

The vast territory of China experiences frequent natural disasters, including floods, droughts, earthquakes, and heavy snowfalls (Zhang et al., 2002). For example, in 2008, serious snow disasters occurred throughout China and a violent earthquake of 8.0 grade in Sichuan Province caused enormous life and property losses. However, floods and droughts may be more serious due to the high frequency of their occurrence compared to other natural disasters. In the case of the Yangtze River, the longest river in China, its discharge has shown a tendency towards two extremes. Its floods are getting more and more severe, while, in sharp contrast, its water discharges to the sea are getting smaller as more droughts occur (Chen et al., 2001). As reported by Zhang et al. (2006), the annual maximum streamflow and water level of the middle Yangtze River show a significant upward trend. Yin and Li (2001) hold that the main driving force for these changes is not natural environmental phenomena, but rather the intensive human activities, such as destruction of vegetation, land reclamations, and siltation, that have resulted in the reduction of

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0921-8181/$ – see front matter
doi:10.1016/j.gloplacha.2009.07.003

water storage capacity in its fluvial channel. This observation is not unique to the Yangtze River, as many hydrological variations in other drainage basins in China appear to be due not only to natural processes, but also to inappropriate human intervention. For example, this kind of phenomenon has also appeared in the Pearl River, which is ranked as the 13th largest river in the world and the second largest in China (only surpassed by the Yangtze River) in terms of water discharge (336 km^3, (Pearl River water resources committee (PRWRC), 1991)).

The Pearl River has a great number of streams and tributaries which form a complicated watershed called the Pearl River Delta (PRD) (Fig. 1) in the estuary. The PRD is one of the most prosperous areas in China, having experienced rapid economic developments over the past two decades. However, these rapid developments, particularly of municipal infrastructure, have also brought about numerous environmental concerns within the PRD and the intensive human activities have resulted in substantial hydrological deformation (Luo et al., 2002). For this reason, a growing number of Chinese scholars are now studying the variation in hydrologic parameters that reflect these new human impacts in the PRD region (Jia et al., 2002; Chen and Chen, 2002; Han et al., 2005; Jia et al., 2006; Zhang et al., 2008). However, to date, no study has focused on the temporal and spatial variability of the annual extremes in water level over the entire PRD region. In fact, from 1993 to 1998, the PRD region suffered continuous flooding disasters. Estimates rate the largest direct losses caused by the 1994 Pearl River flood at more than 2 billion US dollars (Liu et al., 2003). A strange phenomenon regarding the flood in 1994 (designated as "94.6") at Sanshui station is that the flood height in the upper part of the PRD was lower by 1.28 m compared to that of similar previous flood discharges (Luo et al, 2007). However, in the middle and lower part of the delta, the 94.6 flood waters were significantly elevated. In the current study, the temporal and spatial variability of annual extreme water level in the entire PRD region has been examined. In addition, the relative contribution of major force factors is discussed. The findings presented here are important for assessing the impact of anthropogenic activities on this river system and for designing management and conservation policies for this region.

2. Study area

The Pearl River consists of three main tributaries — the North River, the East River, and the West River, which empty into the Pearl River estuary to form the Pearl River Delta region. This region is located along the southern coastline of China between latitudes 21°40′ N and 23° N, and longitudes 112° E and 113°20′ E (Fig. 1).The PRD occupies an area of approximately 17,200 km^2 and is located in Guangdong province, South China. Benefiting from convenient transportation and rich resources, this region is one of the most developed areas in China, and is surrounded by a number of metropolitan cities, with Guangzhou at the northern apex, Makau in the southwest corner, and Hong Kong in the south-east corner. The PRD covers a region of the subtropical zone with a mean annual temperature ranging from 14 °C to 22 °C and a mean annual precipitation from 1200 mm to 2200 mm (Zhao, 1990). The delta also shows a strong seasonal variation in temperature and precipitation.

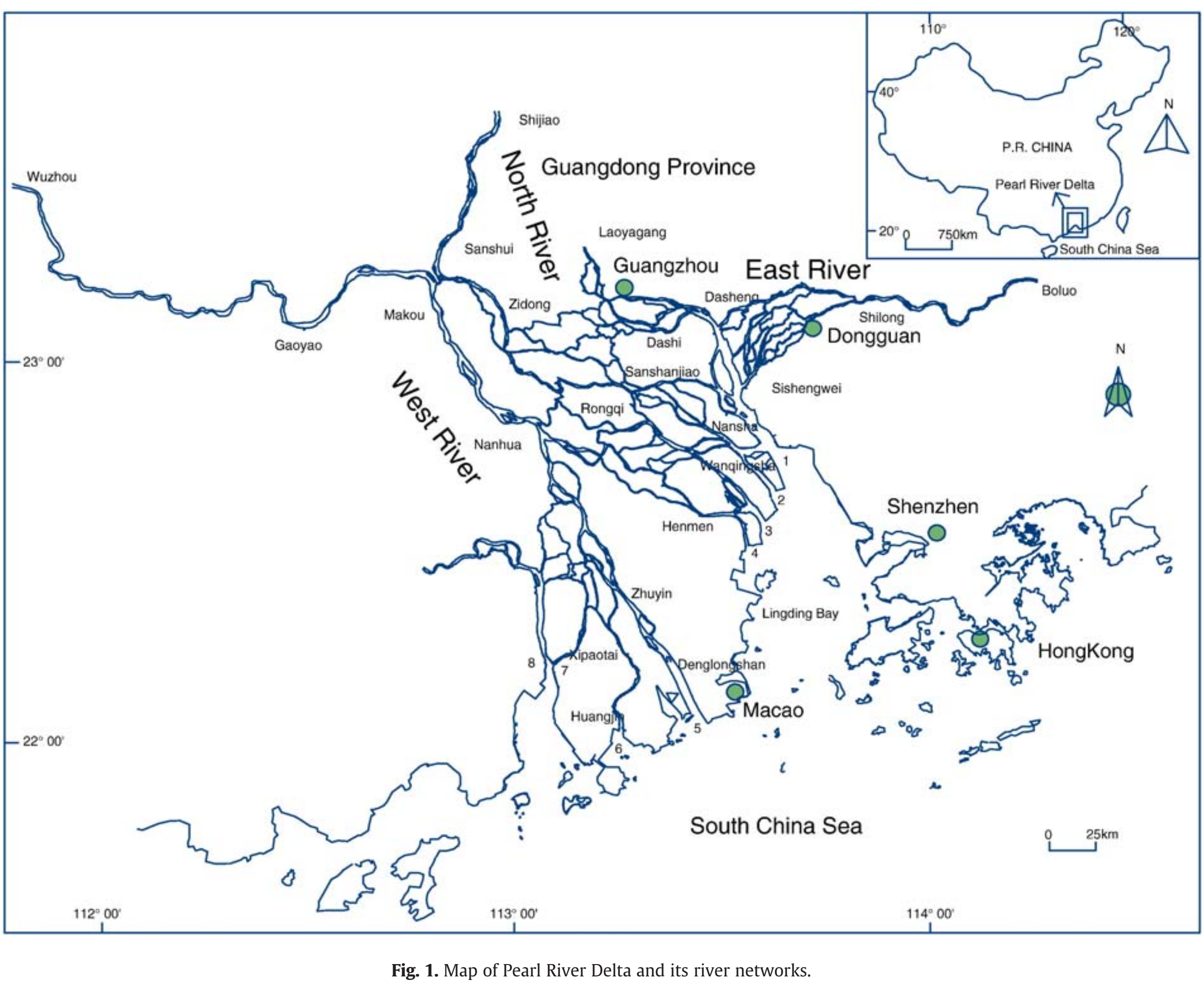

Fig. 1. Map of Pearl River Delta and its river networks.

From April to September period (the wet season), about 95% of the sediment load and 80% of the water are delivered, while only 5% and 20% of these are delivered during the dry season from October to March (Xia et al., 2004). All three tributaries flow into the South China Sea through eight outlets. Four outlets (Yamen, Hutiaomen, Jitimen, and Modaomen) are located in the west, namely the Western outlets, and these collect approximately 45–50% of the total runoff and 60% of the total suspended sediment that is discharged into the South China Sea. The remaining four outlets (Hengmen, Hongqimen, Jiaomen, and Humen) are located in the east, namely the Eastern outlets, and drain into the Lingding Bay.

3. Data and methods

3.1. Data

The selection of observatory stations is one of the most important steps in any investigation of the impacts of natural climate changes and human activities. In this study, a relatively large number of stations, spread fairly evenly throughout the PRD, were chosen and at least 40 years of continuous and complete observations were examined to ensure statistical validity of the trend results (Table 1). These data were collected from the hydrological yearbooks of the People's Republic of China. The reliability and homogeneity of the hydrological data were strictly checked by the authority before they were released.

3.2. Methods

Three statistical methods are used in this study to analyze the spatial variations and temporal trends of the extreme water level series: (1) The Mann–Kendall test. Mann (1945) originally used this test and Kendall (1975) subsequently derived the test statistic distribution. Its advantage is that it is distribution-free and does not assume any special form for the distribution function of the data, including censored and missing data (Yue et al, 2002).Thus, the Mann–Kendall test has been found to be an excellent tool for trend detection by other scholars in similar applications. (2) The Pettitt test is used to identify a change-point in a time series, and assumes that the observations form an ordered sequence (Pettitt, 1979). (3) A simple linear regression method, the parametric *t*-test method, is used to test the long-term linear trends.

Table 1
Results of the Mann–Kendall test and Pettitt test for the annual maximum and minimum water level.

No.	Station name	Parameter	Data period	Mann–Kendall test			Pettitt test			
				Z	Critical value	Trend	Change point	K_T	*P*	Shift
Stations along the tributaries of the West River										
1	Gaoyao	HWL	1951–2001	0.536	(−1.96, 1.96)	Increasing	1991	−152	0.641	Upward
		LWL	1951–2001	3.817	(−1.96, 1.96)	Increasing	1967	−400	1	Upward
2	Makou	HWL	1954–2005	−0.718	(−1.96, 1.96)	Decreasing	1980	164	0.676	Downward
		LWL	1954–2005	−2.628	(−1.96, 1.96)	Decreasing	1989	346	0.993	Downward
3	Nanhua	HWL	1954–2005	−0.039	(−1.96, 1.96)	Decreasing	1983	114	0.420	Downward
		LWL	1954–2005	−1.018	(−1.96, 1.96)	Decreasing	1990	253	0.931	Downward
4	Zhuying	HWL	1958–2005	0.534	(−1.96, 1.96)	Increasing	1990	−75	0.258	Upward
		LWL	1958–2005	−2.835	(−1.96, 1.96)	Decreasing	1990	283	0.986	Downward
5	Xipaotai	HWL	1957–2005	1.962	(−1.96, 1.96)	Increasing	1963	−210	0.890	Upward
		LWL	1957–2005	−1.388	(−1.96, 1.96)	Decreasing	1985	164	0.739	Downward
6	Huangjin	HWL	1964–2005	1.886	(−1.96, 1.96)	Increasing	1983	−162	0.875	Upward
		LWL	1964–2005	6.611	(−1.96, 1.96)	Increasing	1987	−406	1	Upward
7	Denglong shan	HWL	1958–2005	2	(−1.96, 1.96)	Increasing	1988	−209	0.902	Upward
		LWL	1958–2005	−0.560	(−1.96, 1.96)	Decreasing	1997	203	0.888	Downward
Stations along the tributaries of the North River										
8	Shijiao	HWL	1953–2005	−0.591	(−1.96, 1.96)	Decreasing	1998	166	0.664	Downward
		LWL	1953–2005	−1.296	(−1.96, 1.96)	Decreasing	1995	236	0.890	Downward
9	Sanshui	HWL	1954–2005	−1.018	(−1.96, 1.96)	Decreasing	1983	210	0.842	Downward
		LWL	1954–2005	−4.048	(−1.96, 1.96)	Decreasing	1988	471	1	Downward
10	Zidong	HWL	1954–2005	−0.655	(−1.96, 1.96)	Decreasing	1983	194	0.793	Downward
		LWL	1954–2005	−2.517	(−1.96, 1.96)	Decreasing	1985	336	0.991	Downward
11	Dashi	HWL	1965–2005	−0.595	(−1.96, 1.96)	Decreasing	1978	124	0.729	Downward
		LWL	1965–2005	3.291	(−1.96, 1.96)	Increasing	1974	−268	0.998	Upward
12	Rongqi	HWL	1954–2005	1.018	(−1.96, 1.96)	Increasing	1965	−160	0.658	Upward
		LWL	1954–2005	4.34	(−1.96, 1.96)	Increasing	1972	−481	1	Upward
13	Sanshanjiao	HWL	1954–2005	1.997	(−1.96, 1.96)	Increasing	1990	−223	0.875	Upward
		LWL	1954–2005	5.074	(−1.96, 1.96)	Increasing	1977	−538	1	Upward
14	Hengmen	HWL	1954–2005	2.423	(−1.96, 1.96)	Increasing	1988	−289	0.970	Upward
		LWL	1954–2005	5.263	(−1.96, 1.96)	Increasing	1977	−578	1	Upward
15	Wanqingsha	HWL	1954–2005	1.444	(−1.96, 1.96)	Increasing	1962	−271	0.954	Upward
		LWL	1954–2005	6.621	(−1.96, 1.96)	Increasing	1977	−598	1	Upward
16	Nansha	HWL	1963–2005	−0.272	(−1.96, 1.96)	Decreasing	1974	130	0.712	Downward
		LWL	1963–2005	5.777	(−1.96, 1.96)	Increasing	1986	−412	1	Upward
Stations along the tributaries of the East River										
17	Boluo	HWL	1953–2002	−2.861	(−1.96, 1.96)	Decreasing	1987	353	0.997	Downward
		LWL	1953–2002	−4.617	(−1.96, 1.96)	Decreasing	1984	444	1	Downward
18	Shilong	HWL	1957–2001	−4.236	(−1.96, 1.96)	Decreasing	1987	414	1	Downward
		LWL	1957–2001	−6.427	(−1.96, 1.96)	Decreasing	1988	478	1	Downward

The MK test considers only the relative values of all terms in the series $X=\{x_1, x_2,\cdots,x_n\}$ to be analyzed. The MK test statistic is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(x_j - x_i) \tag{1}$$

where x_i and x_j are the sequential data values, n is the data set record length, and

$$Sgn(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad \text{if} & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{2}$$

Under the null hypothesis of no trend, and the assumption that the data are independent and identically distributed, the zero mean and variance of the S denoted by σ^2 is computed as:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The standard normal variant is then used for hypothesis testing, and is designated here as the trend test statistic index Z, as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sigma} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sigma} & \text{if} \quad S < 0 \end{cases} \tag{4}$$

Thus, in a two-tailed test for trend, the null hypothesis H_0, that there is no trend in the dataset, is either rejected or accepted depending on whether the calculated Z statistics is more than or less than the critical value of Z-statistics obtained from the normal distribution table at 5% significance level. However, it has been reported many times that the presence of serial correlation may lead to an erroneous rejection of the null hypothesis (Kulkarni and von Stroch, 1995; Yue and Wang, 2002; Yue and Pilon, 2003). Therefore, in this study, a modified pre-whitening method, namely trend free pre-whitening (MK-TFPW), was applied in our dataset with significant autocorrelation to eliminate the effect of serial correlation (data not shown) (Yue et al., 2002).

The Pettitt test (Pettitt, 1979), which is an approximation for a sequence of random variables of the non-parametric method, is used to identify a change-point in a time series and can be briefly described as follows: Once the change point is detected through the test, then the dataset is divided into two intervals. The intervals before and after the change point then form homogeneous groups, which take heterogeneous characteristics from each other.

The two samples $(x_1,x_2,\ldots x_t)$ and $(x_{t+1}, x_{t+2},\ldots,x_T)$ come from the same population. The test statistic $U_{t,T}$ is given by

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} Sgn(x_t - x_j) \tag{5}$$

The most significant change-point is found where the value $|U_{t,T}|$ is max: $K_T = \max|U_{t,T}|$ and the significant level associated with K_T^+ or K_T^- is determined approximately by $\rho = \exp\left(\frac{-6K_T^2}{T^3+T^2}\right)$. If ρ is smaller than the specific significance level, e.g., 0.10 in this study, the null hypothesis is rejected. In other words, if a significant change point exists, the time series is divided into two parts at the location of the change point. The approximate significance probability for a change-point is defined as $P = 1-\rho$.

A simple linear regression method consists of two steps. The first is to use a linear simple regression equation with the time t as an independent variable and the hydrological variable Y, as dependent variable. The second is to test the statistical significance of the slope of the regression equation (Zhang et al, 2006).

4. Results and discussion

4.1. Results

The results of the application of the MK test and the Pettitt test are summarized in Table 1. Variables that have MK results that are significant at the 95% significance level are shown in bold. For the MK test, the gauging stations with more than 40 years of record are applied to the standard normal distribution test with the Z-score. The spatial distributions of trend in the annual maximum and minimum water level for the study period are plotted in Figs. 2 and 3, respectively, which reflect a combined effect of natural condition changes and human activities.

Fig. 2 shows the spatial distribution of MK trends in annual water level maxima events in the PRD region. It is clear that there are no significant trends in annual maximum water level at the upper part of the West River Delta or the North River Delta, while there is a significant decreasing trend at the headwaters of the East River Delta. In the middle part of the PRD region, most stations, especially in the North River Delta, display increasing trends and some of these are significant. At the lower part of the PRD region, a general increasing tendency is detected and most stations at the outlets show a significant upward tendency, except for Nansha station, which displays a slightly downward trend.

The same spatial analysis carried out using annual minimum water level data are shown in Fig. 3. In this case as well, a similar pattern of changes is indicated in the annual maximum water level in some cases. However, the most notable difference is that the changes in the annual minimum water level are much more significant than those seen for the annual maximum water level. As shown in Fig. 3, there are clear decreasing trends prevalent in the upper and middle part of the West River Delta and the East River Delta, except for Gaoyao station at the headwater. Similar results are obtained from trend analysis at the upper part of the North River Delta. However, in the middle part of the North River Delta, a significant upward trend is observed. The trend of the annual minimum water level at the Western and Eastern outlets of PRD region shows a different and somewhat opposing behavior. A majority of stations in the outlets show significant increasing trends exceeding the 95% percentile.

The results of the Pettitt test for an abrupt change in annual extreme water level are also shown in Table 1. At the significance level of 0.10, the annual maximum water level at most stations display no significant abrupt changes throughout the entire PRD region over the study period. However, the stations with significant abrupt changes in annual minimum water level account for 83.3% of the total 18 stations. More specifically, the West River Delta catchments generally exhibit significant abrupt downward changes in their minimum water level and most of these changes appear in the 1980s or 1990s, while the abrupt change in the annual maximum water level appear to be less significant compared to the annual minimum water level. Similar abrupt changing characteristics can also be identified in the extreme water levels in the North River Delta. The difference is that the minimum water level at the Eastern outlets shows a significant abrupt upward change in the 1970s. In the East River Delta, both Boluo and Shilong stations show a significant abrupt downward change, not only in the minimum water level, but also in the maximum water level in the 1980s.

4.2. Discussion

The spatial distribution that results from the application of MK test and Pettitt test for the sites in the PRD region points out a general trend in which the temporal distribution of the annual extremes in water level has been modified. This variation in extreme water level is

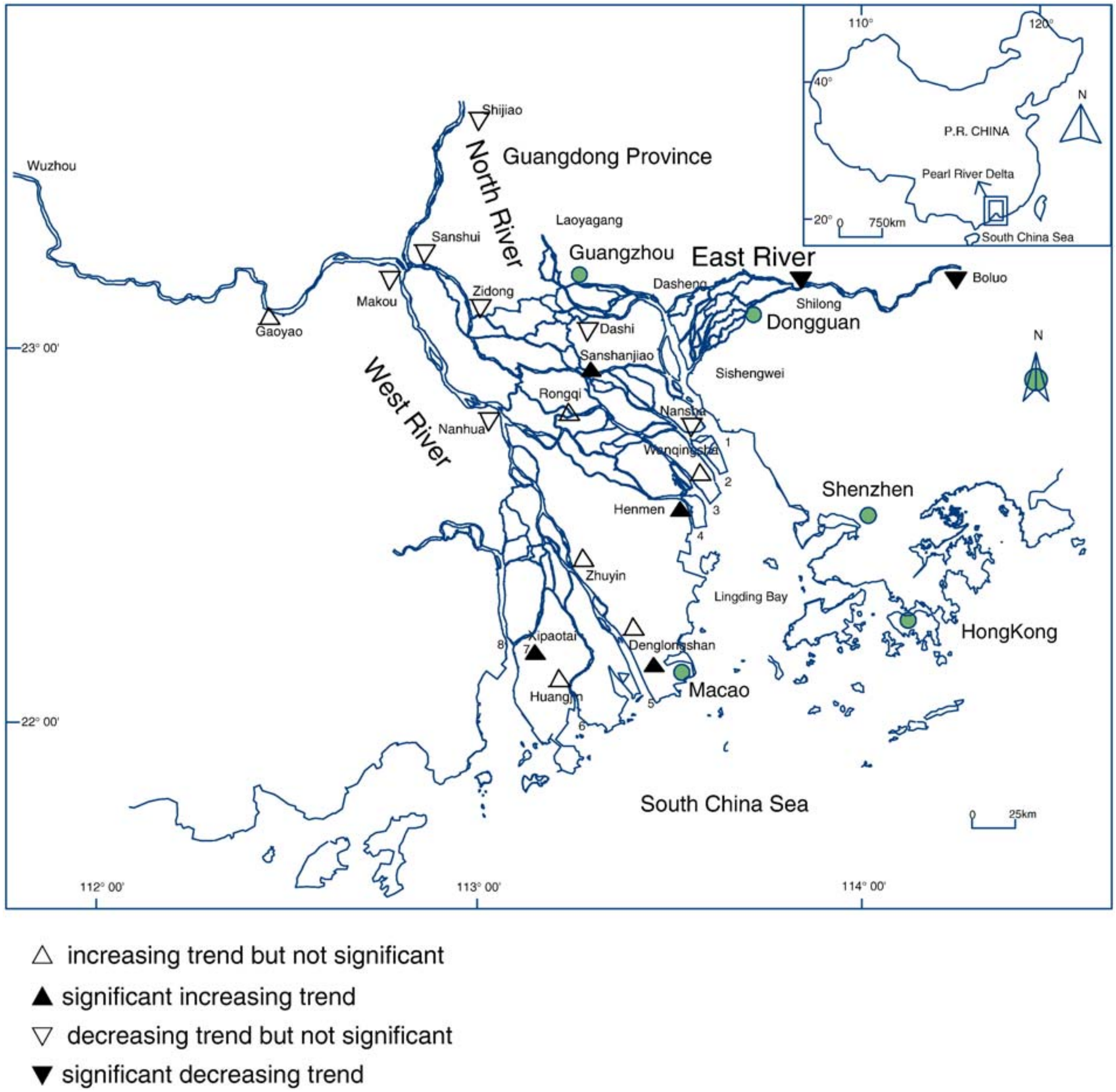

Fig. 2. Trend results for the annual maximum water level during the study period.

a result of catchment processes and is affected by many factors, including natural climate changes and human activities. The potential impacts of natural climate changes have received much attention from scholars in a variety of fields. A comprehensive report provided by IPCC (1996) indicates that climatic change is likely to increase the runoff in the upper regions because of increased precipitation. Meanwhile, the global sea level is continuously rising due to the upward trend in worldwide air temperatures. These runoff and sea level variations may affect the annual extreme water level in the PRD region. On the other hand, the intensive human activities, including sand excavation, reservoir construction, and water abstraction, have become more serious from the upper to the lower part of the PRD region, and these too have substantially changed the hydrology of the delta. However, the impacts of climate change (particularly precipitation variation) on water levels are difficult to detect at most stations in the Pearl River Basin due to other potential anthropogenic impacts, such as reservoir construction and water diversion. Therefore, in this paper, the influence of water discharge and terrain are selectively analyzed because they are the most two direct factors resulting in the variation of water level. The impacts of other factors, such as precipitation variation and ENSO, will finally be reflected through the change of discharge.

4.2.1. Impacts of the flow condition

In general, the water levels correspond to a great extent to the freshwater flow in the fluvial basin. For this reason, the variations in the annual extreme runoff in the upper part of the PRD that are analyzed in this paper are taken from the five main gauge stations of the delta. These include Gaoyao station in the West River Delta, Shijiao station in the North River Delta, Boluo station in the East River Delta, and Sanshui and Makou station. These latter two stations are two of the most important stations in the PRD, because a portion of the flow from the upper stream goes into the North River networks via the Sanshui station and the rest enters the West River networks through the Makou station. The annual minimum runoffs are not investigated at Gaoyao, Makou, and Sanshui station because these three stations are located in the areas affected by the tidal current in the dry season.

Gaoyao station is an important reference station for the flood controlling activities and flood mitigation in the upper part of the West River Delta. Fig. 4a shows a significant upward trend for the maximum

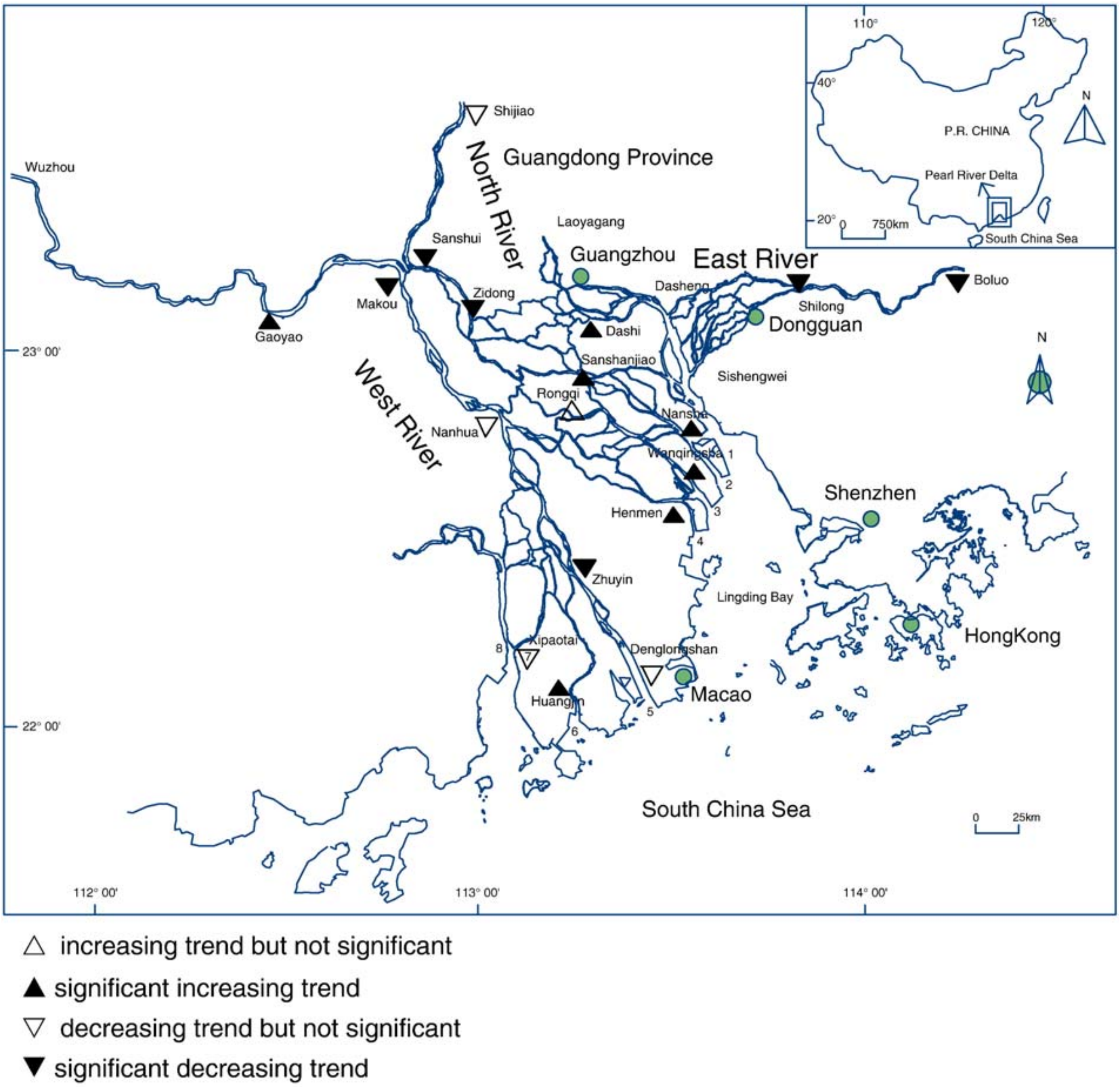

Fig. 3. Trend results for the annual minimum water level during the study period.

streamflow series ($p = 0.028 < 0.05$) at Gaoyao station, while the increasing trend of the annual maximum water level is relatively mild ($p = 0.529 > 0.05$ and the slope of simple linear regression is 0.012). Fig. 4b also shows that a slight reduction in the maximum water level in the cumulative double mass plot has occurred in recent years. Shijiao station is the monitoring station for the North River Delta. Although the extremes in streamflow show slightly increasing trends, the extreme water levels show decreasing trend and this trend is relatively clear for the minimum water level (Fig. 5a and b). At the same time, the minimum water level does show more obvious changes than are seen for the maximum water level in the cumulative double mass plot (Fig. 5c and d). The annual extreme streamflow and water level of Boluo station are plotted in Fig. 6a and b. It can be seen that the annual maximum streamflow displays a clear downward trend, while the annual minimum streamflow exhibits a strong upward trend. The probable reason for this is that East River is the most regulated river among the three main rivers and has experienced large scale multipurpose water resource development since 1960 (Zhang et al., 2008). The Pearl River Water Resources Committee (PRWRC) reports that a total number of 387 large and medium reservoirs, with a total storage capacity of 46.7 billion m^3, have been constructed as of 2005 in the Pearl River Basin (including the delta region). However, there are great spatial variations in reservoir construction in the West River, North River, and East River (Table 2). The water storage index is as high as 0.78 in the East River, but is only around 0.10 in the West and North Rivers (Zhang et al., 2008). The two largest reservoirs in Guangdong Province, namely Xinfengjiang Reservoir and Fengshuba Reservoir located in the upper reaches of the East River, are used to help flood resistance in the wet season and drought resistance in the dry season. Although the maximum water level and streamflow show consistent variation trends (Fig. 6a), the minimum water level and discharge display opposite trends (Fig. 6b). Similar results can also be seen in the double mass plot (Fig. 6c and d). Geographically, streamflows from the West River networks and the North River networks enter the delta via the Gaoyao station and Shijiao station, respectively. The annual maximum streamflow shows an upward trend due to the increasing runoff from the upper region (Figs. 7a and 8a), and this upward trend is much more evident at Sanshui station (Fig. 8a). However, the overall annual maximum water level is decreasing at these two stations (Figs. 7b and 8b) and this water level reduction can be clearly detected

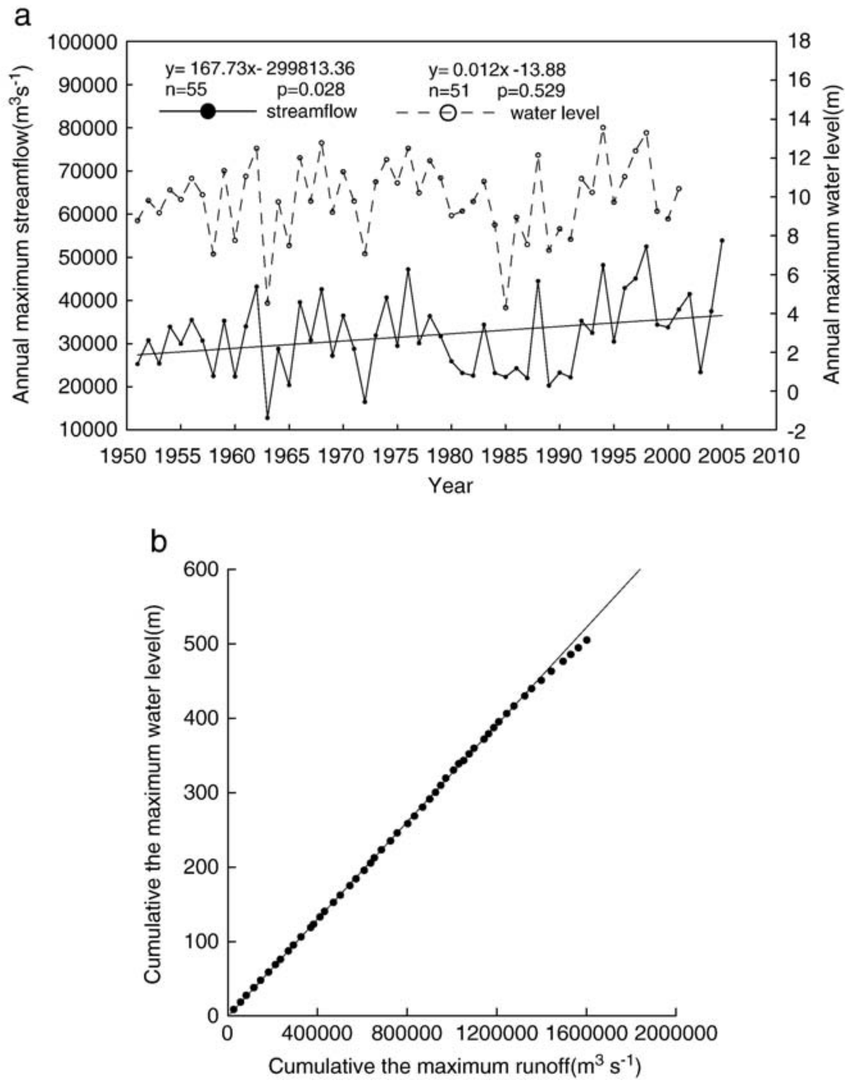

Fig. 4. a. *t*-test trends for the annual maximum streamflow and water level at Gaoyao. b. Cumulative double mass plot of the maximum streamflow and water level at Gaoyao.

in the cumulative double mass plots obtained for Sanshui. The inconsistency of trends between annual extreme discharge and water level indicates that the variation in water level is not primarily controlled by the flow coming from the upper region. Therefore, the present research results suggest that there must be other controlling mechanisms that are influencing the annual extreme water level rather than the flow change.

4.2.2. Impacts of the terrain condition

Over the last two decades, the demand for sand has been sharply increasing with the rapid economic development, urban construction, and land reclamation in the PRD region. This demand has resulted in indiscriminate digging of sediment throughout the entire Pearl River networks. Luo et al. (2007) carry out a more systematic survey of the sand excavation activities in the PRD region. They estimate that over 8.7×10^8 m^3 of sand was excavated from 1986 to 2003, based on field surveys of excavating activities and the river hypsography. This has resulted in an average downcutting of the 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 Delta, North River Delta, and East River Delta, respectively. As a consequence, the morphology of the river channels within the PRD region and related geomorphic processes have changed substantially, which in turn now affects the variation in the temporal and spatial distribution of annual extremes in water level in the PRD region.

However, sand excavation activities are distributed unevenly over the PRD region, as they depend on the sand quality and area transportation conditions. In general, the quantity of sand extraction in the upper part of the PRD is much larger than it is in the lower part. Therefore, the channel volume has increased more in the upper part. In the case of the East River Delta, the average riverbed descent is 6.5 m in the upper part from Boluo to Shilong, while it is 4.8 m in the middle part and it is only 2.4 m in the lower part of the East River Delta. In addition, in the upper part of the PRD, the fluvial dynamics is much stronger than the tidal dynamics; hence, the water level is not mainly controlled by the tide, but rather by the runoff. As mentioned previously, although the annual extreme streamflows of most stations at the headwater of the PRD region have changed in recent years, and although some of these show significantly increasing trends, the increasing discharge is unable to fill up the extra channel volumes caused by sand excavation. Therefore, the water levels during low flows, as well as during flood stages, have decreased with riverbed downcutting in the upper part of the PRD.

The temporal and spatial variability of water level caused by sand excavation display different trends in different parts of the PRD region. In the middle part of the entire PRD region, the water level of some stations show abnormal increases, and this phenomenon is more obvious in the North River Delta. For example, a huge 50-year return period flood occurred in June of 1994 (designated as “94.6”) at Makou

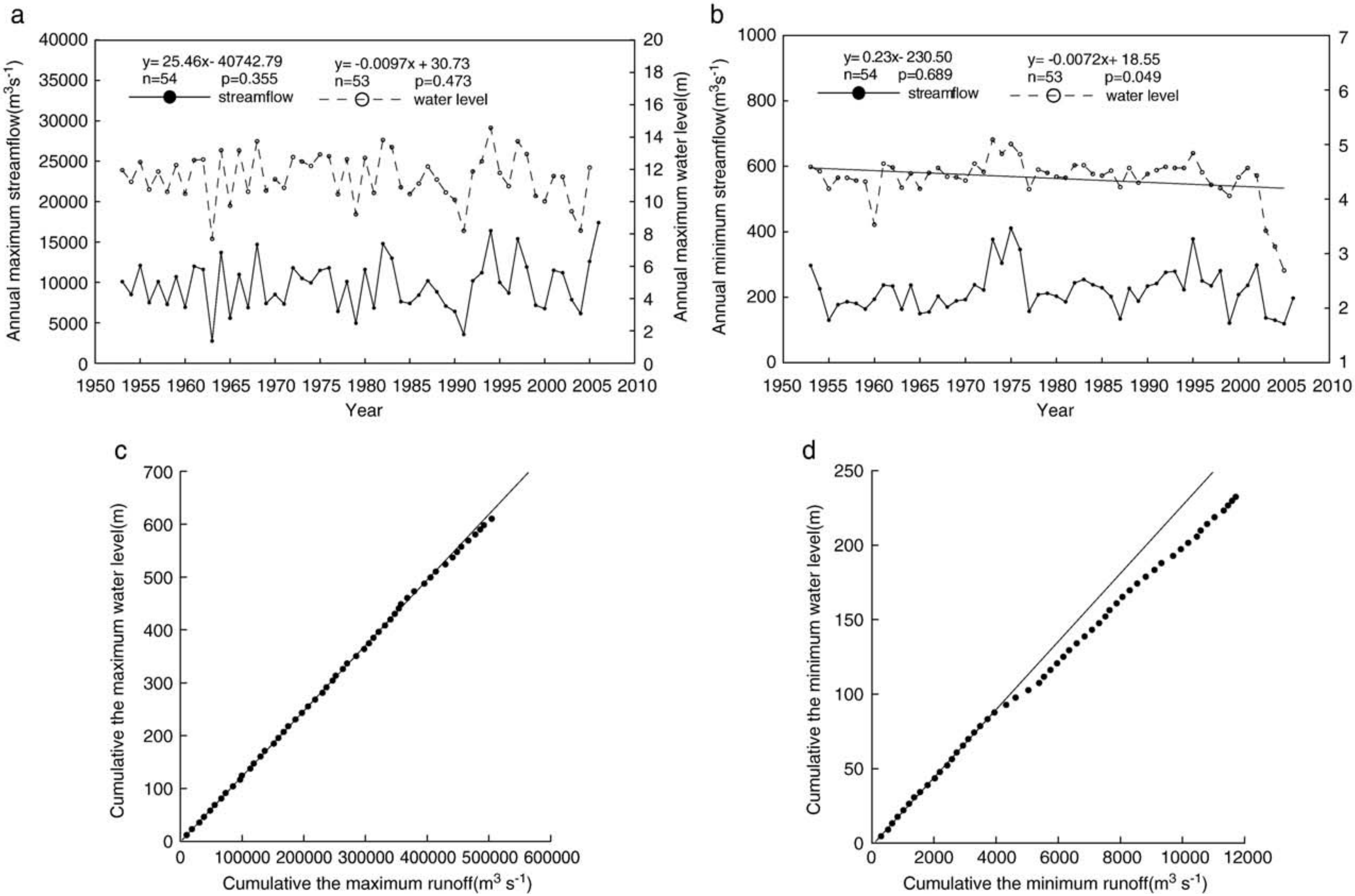

Fig. 5. a. *t*-test trends for the annual maximum streamflow and water level at Shijiao. b. *t*-test trends for the annual minimum streamflow and water level at Shijiao. c. Cumulative double mass plot of the maximum streamflow and water level at Shijiao. d. Cumulative double mass plot of the minimum streamflow and water level at Shijiao.

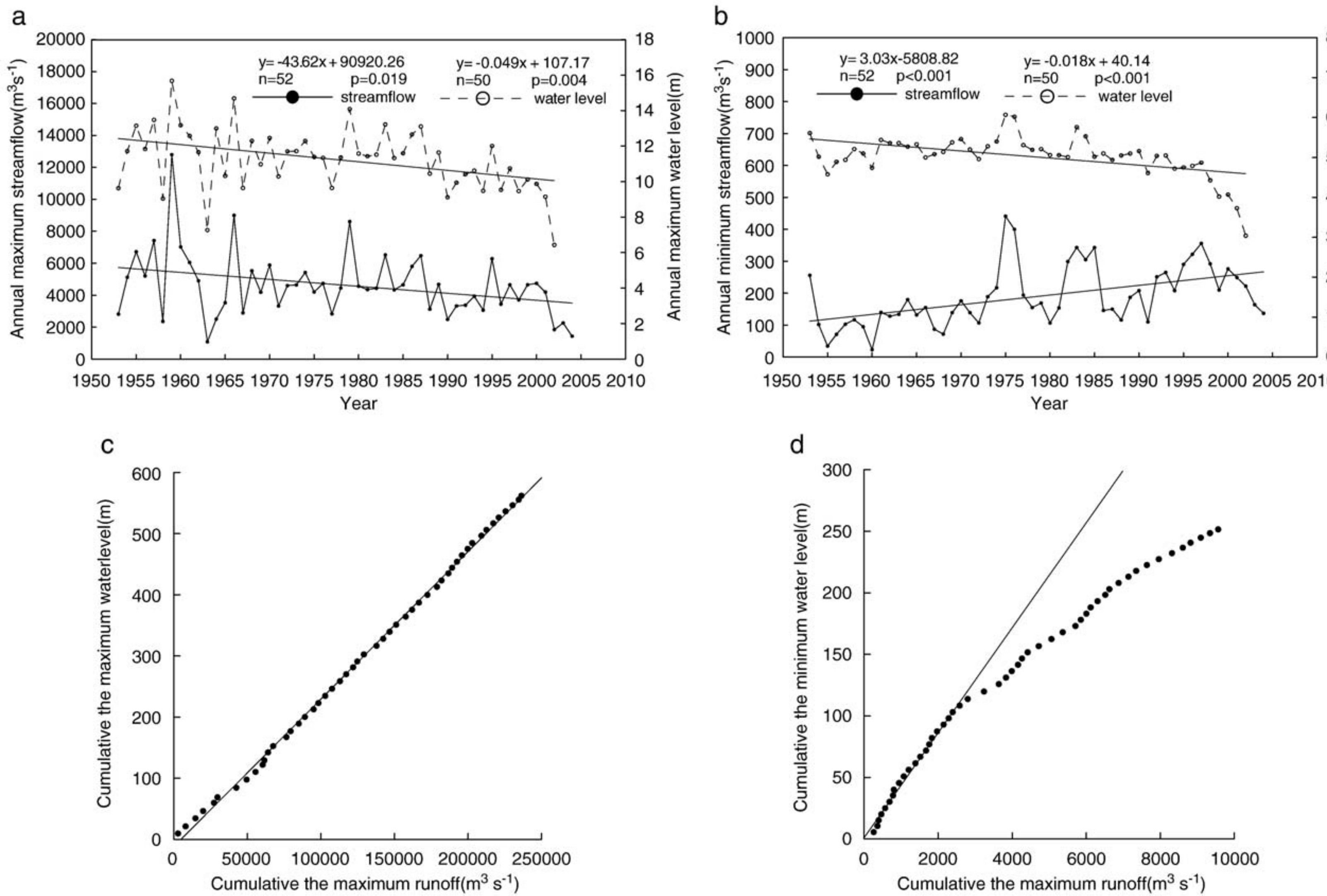

Fig. 6. a. *t*-test trends for the annual maximum streamflow and water level at Boluo. b. *t*-test trends for the annual minimum streamflow and water level at Boluo. c. Cumulative double mass plot of the maximum streamflow and water level at Boluo. d. Cumulative double mass plot of the minimum streamflow and water level at Boluo.

Table 2
Summary information of large and medium reservoirs in the Pearl River (from Pearl River Water Resources Committee website http://www.pearlwater.gov.cn (in Chinese)).

Rivers	Large and medium reservoir [a]		Storage index [b]
	Number	Storage (10^9 m^3)	
West River	236	20.6	0.09
North River	47	5	0.12
East River	39	18	0.78

[a] The capacity of large reservoirs and medium reservoirs are over 10^8 m^3 and from 10^7 to 10^8 m^3, respectively.
[b] Storage index is defined as the ratio of the reservoir water storage capacity and water discharge, source from Zhang et al. (2008).

and Sanshui station in the upper part of the delta. This flood decreased to a 20-year one at Nanhua station in the middle part of the West River delta and Zidong station in the middle part of the North River Delta, and then changed again to a 50-year one at Dashi station, which is lower than a 200-year flood at Sansanjiao station in the middle part of the North River Delta. By the time the floodwaters had arrived in the estuary, the water level had again decreased to a 50-year flood level. The main reason for the rising water level in the middle reach is that the runoff is hindered by the tidal backwater. Although intensive sand excavation can cause riverbed down-cutting in the middle, as well as in the upper part, it also increases channel volume at the same time, which makes the sea water enter the delta more easily than previously. The effect of the increased tidal prism cannot only prevent the water level from decreasing with the riverbed descent, but also can slow down the runoff velocity, which leads to the occurrence of anomalous water levels. It is evident that the rise in the minimum water level is more substantial, because stations in the middle are all in the scope of tidal ranges in the dry season. At the same time, the dense sluices, docks, and bridges along the river and the change of land use in the middle stream all contribute to the rise in water level.

Compared to the West River Delta, the North River Delta shows more significant changes in the annual extremes of water level, which is also related to the sand mining. In the last two decades, the amount of sand excavation in the North River Delta has been much larger than in the West River Delta, which has led to the redistribution of discharge. Luo et al. (2007) analyze the divided annual averaged runoff ratio at Makou and Sanshui station and indicates that the divided flow ratio (DFR) between these two stations has changed. Similar changing characteristics are identified in the annual maximum runoff in the present paper. The result of Pettitt test at Sanshui station shows that the change point is the year 1991 and the average divided maximum

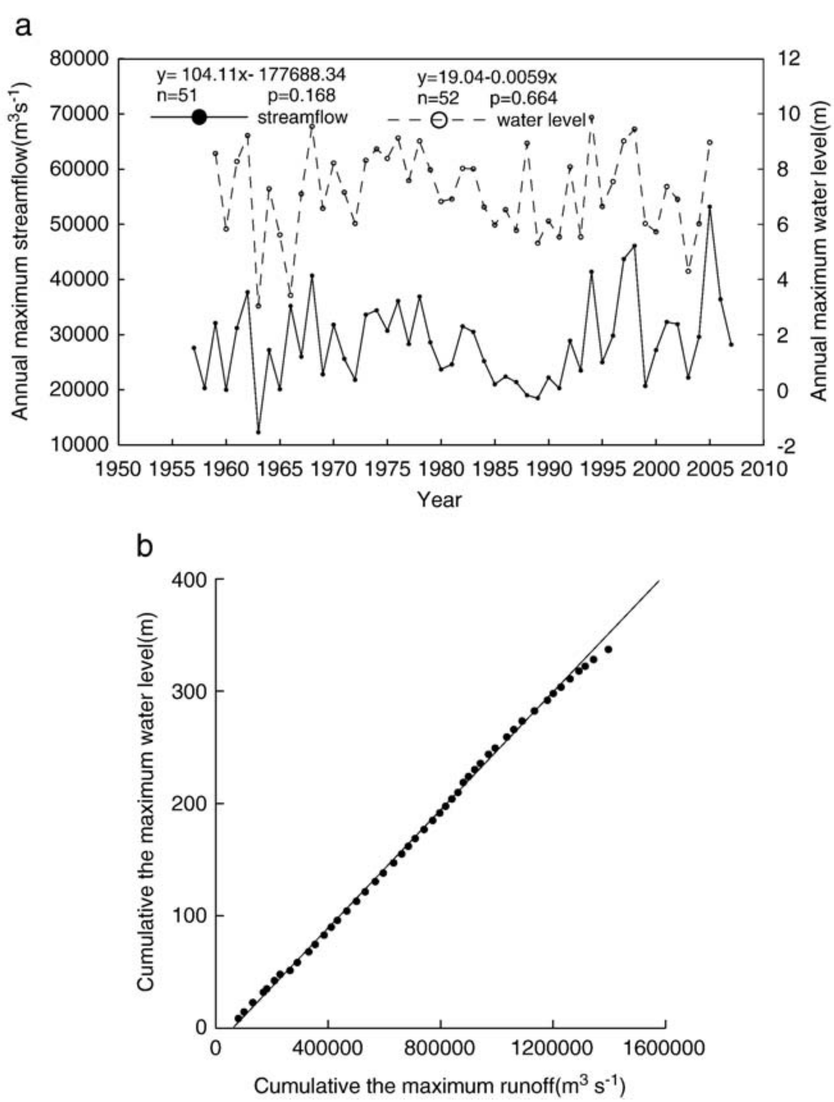

Fig. 7. a. *t*-test trends for the annual maximum streamflow and water level at Makou. b. Cumulative double mass plot of the maximum streamflow and water level at Makou.

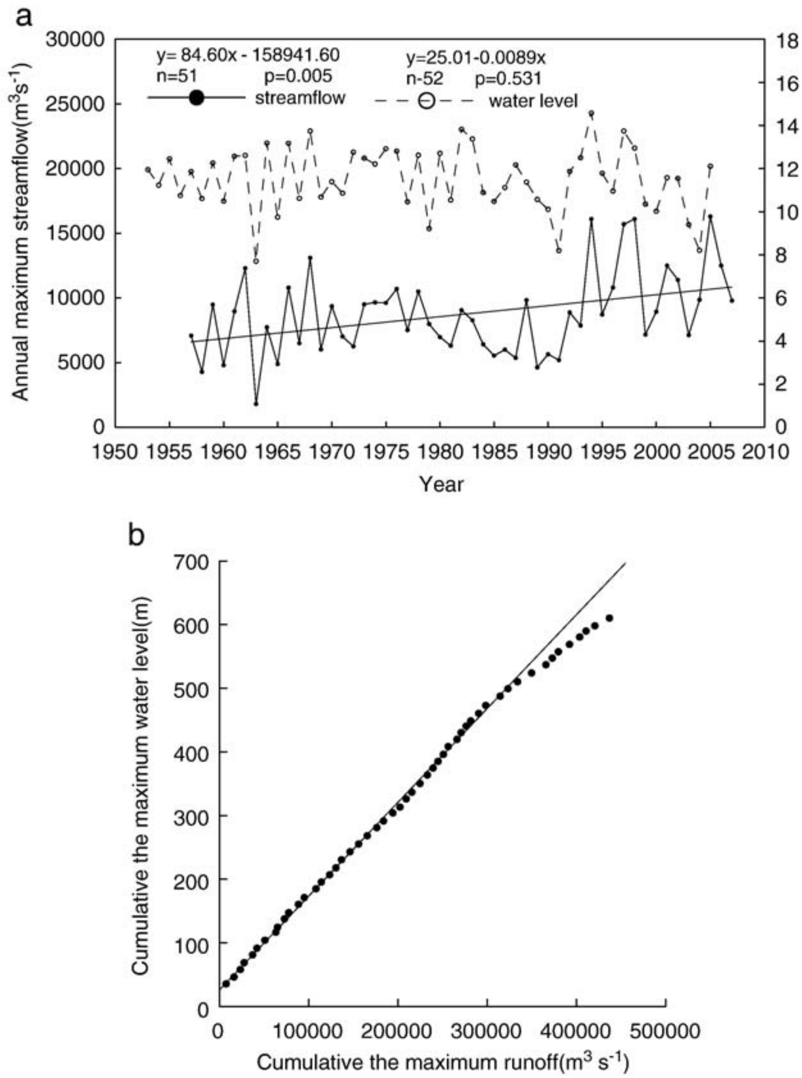

Fig. 8. a. t-test trends for the annual maximum streamflow and water level at Sanshui. b. Cumulative double mass plot of the maximum streamflow and water level at Sanshui.

runoff ratio was 21.3% pre-1991 and 25.6% post-1991(Fig. 9). The mean level of annual maximum runoff was shifted upward by more than 20% at Sanshui station, with significant abrupt changes. Changes in the DFR have taken place not only at the upper part of the PRD, but also in almost all of the channels, due to unbalanced digging depths. That means that more runoff will enter the North river networks, mainly through Sanshui station, and the increased flow is then hindered in the middle part of the North River Delta by the tidal

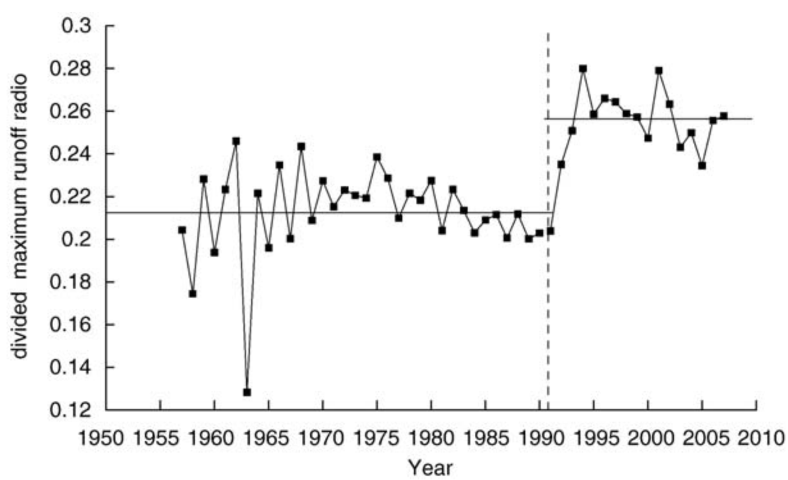

Fig. 9. The shift of mean level of the divided maximum runoff ration at Sanshui station in the North River with significant change point at the significance level of 0.10.

backwater from the lower part. This is likely to be the primary reason why the annual extreme water levels increase in some stations in the North River networks, such as Sansanjiao and Rongqi. This result confirms that the middle parts of the North River Delta are experiencing more rapid increases in the annual extreme water level and have therefore higher risk of flood hazards.

Figs. 2 and 3 also indicate that most stations are exhibiting increasing trends for the annual extreme water levels in the lower part of the PRD region. In addition, the increasing trend for the annual minimum water level is more significant than that for the annual maximum water level. Sand mining is not the main factor modifying the water level characteristic near the estuaries, because the annual water level there is dominated by the tidal level. Chen et al. (2005) analyze the coastal changes near the PRD during the period 1978–1998, based on satellite remote sensing and GIS, and point out that the coastline had moved noticeably seaward during the study period. Although there are some factors, such as siltation, which may explain this extensive rate of change in coastline, these extensions can be better perceived with regard to another kind of human activity, namely land reclamation (Weng, 2007). The Eastern outlets of the North River, for example, extended seaward 8–10 km during the period from 1980s to 2005. The stations which originally located near estuaries before land reclamation now belong to the river course environment and the water level is affected by the runoff after land reclamation. In addition, the modifications of morphology near the estuaries by land reclamation lead to the narrowing of the cross section and reduction in the wetlands, which in turn directly result in rising water levels near the estuaries. The annual minimum water level shows a more significant increasing trend than the maximum water level does because the tidal dynamics is stronger than the fluvial dynamics in the dry season. This leads to more tidal discharge entering the delta through the outlets of the PRD and hence substantially raises the water level.

5. Conclusions

Of 18 gauging stations in the PRD region, 9 are found to have decreasing annual maximum water levels while 10 are found to have decreasing minimum water levels. The temporal water level trends show a spatial tendency: for the West River Delta, there is no obvious trend for the annual maximum water level in the upper region, while the stations in the middle region exhibit an increasing trend and this upward trend is significant in the lower region. The minimum water levels display an obvious downward trend in the upper and middle regions of the West River Delta, with the exception of Gaoyao station. In the North River Delta, all stations in the upper part show a slightly downward trend for the annual maximum water level. However, almost all of the stations in the middle and downstream areas show increasing trends and some of these are significant. The annual minimum water level in the North River Delta follows a similar trend pattern as the maximum water level. The difference is that the increasing trend at stations near the estuary is much more significant; for the East River Delta, the two gauges, Boluo and Shilong, both show decreasing maximum and minimum water levels.

As indicated in this paper, although some stations in the upper part of the delta show an increasing trend for the annual extreme runoff, the variation in the extreme water level is not always consistent with the extreme streamflow, which indicates that the effect of runoff is limited to some extent. Apart from the climate changes, human activities are also responsible for the temporal and spatial variability of annual extreme water levels. The results of the Pettitt test indicate that the abrupt change of most stations occurred in the period 1980s–1990s, which also corresponds to the period of most intensive human activity in this region. Long-term and large-scale sand excavation initiated in the 1980s around the entire PRD region plays the most important role in directly affecting the hydrological variables, including the annual extreme water level. In general, the extreme water level decreases substantially with the riverbed downcutting in the upper part of the PRD. However, increases in the extreme water levels are also evident in the middle part, primarily due to the backwater. This phenomenon is more obvious in the North River Delta as a result of redistribution of discharge by sand excavation. Land reclamation is likely to have a relatively greater effect on increasing the extreme water levels of the stations near estuary.

The research results indicate that the middle and lower part of the PRD region, particularly in the North River Delta, may experience increased risk of flooding. It should be mentioned that Pearl River is an important water resource for the metropolitan cities around it. For example, the East River–Shenzhen water supply project is designed as a solution to the water demand from Hong Kong. However, the continuously decreasing minimum water levels in the East River will have negative impacts on water intake by cities. In addition, the middle and lower part of the PRD region is heavily populated and economically developed, which makes the increased flood risk, especially in the North River Delta, now more serious in terms of potential human and property losses. Therefore, corresponding measures should be taken to reduce the water level reductions that are currently due to the intensive human activities in the entire PRD region.

Acknowledgements

This research was financially supported by “National Science & Technology Pillar Program during the Eleventh Five-year Plan” (Project Number 2008BAB29B09), “Commonweal Program of Chinese Ministry of Water Resources” (Project Number 200701026), “Special grade of the financial support from China Postdoctoral Science Foundation” (Project Number 200801360) and “Natural Science Foundation of Hohai University” (Project Number 2008427111). Thanks should be extended to two anonymous reviewers and Dr. Sierd Cloetingh for their invaluable and constructive suggestions which greatly improved the quality of this paper.

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