More frequent flooding? Changes in flood frequency in Pearl River basin, China since 1951 and over the past 1000 years

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More frequent flooding? Changes in flood frequency in Pearl River basin, China since 1951 and over the past 1000 years

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Abstract: Flood risks across the Pearl River basin, China, were evaluated using peak flood flow dataset covering a period of 1951-2014 from 78 stations and historical flood records of recent 1000 years. The General Extreme Value (GEV) model and the kernel estimation method were used to evaluate frequencies and risks of hazardous flood events. Results indicated that: (1) no abrupt changes or significant trends could be detected in peak flood flow series at most of the stations, and only 16 out of 78 stations exhibited significant peak flood flow changes with change points around 1990. Peak flood flow in the West River basin was increasing and significant increasing trends were identified during 1981-2010; decreasing peak flood flow was found in coastal regions and significant trends were observed during 1951-2014 and 1966-2014; (2) the largest three flood events were found to cluster in both space and time. Generally, basin-scale flood hazards can be expected in the West and North River basins; (3) the occurrence rate of floods was increasing in middle Pearl River basin but decreasing in the lower Pearl River basin. However, hazardous flood events were observed in the middle and lower Pearl River basin, and it is particularly true in recent 100 years. However, precipitation extremes were subject to moderate variations and human activities, such as building of levees, channelization of river systems and rapid urbanizations were the factors behind the amplification of floods in the middle and lower Pearl River basin, posing serious challenges for developing measures of mitigation of flood hazards in the lower Pearl River basin, particularly the Pearl River Delta (PRD) region.

Key words: Flood frequency; Flood risk; GEV model; Kernel estimation

1. Introduction

Climatic extremes are one of the crucial drivers of meteorological and hydrological hazards, such as floods and droughts (IPCC, 2007; Li et al., 2016). Meanwhile, climate change is expected to intensify the global hydrological cycle which would potentially lead to a general increase in the intensity and frequency of extreme climatic events (Ohmura and Wild, 2002; Alan et al., 2003; Zhang et al., 2013). This will, in turn, have direct implications for hydrological extremes, such as floods and droughts (IPCC, 2013). However, the impacts of climate change on hydrological extremes are expected to vary across different regions over the globe due to the prevailing hydrometeorological regimes and the nature of climate change in specific regions (Beniston and Stephenson, 2004; Burn et al., 2015).

Due to remarkable differences in the hydrometeorological processes that generate floods, climate change can increase or decrease the magnitude, duration, frequency and even nonstationarity of extreme hydrological events, such as floods considered in this study (Gu et al., 2016; Vormoor et al., 2016; Zhang et al., 2016). A very recent study by Zhang et al. (2015a) corroborated the changes in hydrological extremes across China but also found the increasing impact of human activities on fluvial hydrological processes. Changes in hydrometeorological triggers are believed to be the first step to project likely future changes in flood generating processes (Hall et al., 2014; Vormoor et al., 2016). It is particularly the case with flood processes in the Pearl River basin, the second largest river basin in China in terms of flow volume with highly-developed economy, dense population and important megacities, such as Guangdong, Macau and Hong Kong. This constituted the motivation for this study. Hydrometeorological extremes often have disastrous impacts on the society, water resources, agricultural activities, urban infrastructure, and also ecosystems (Das et al., 2013; Li et al., 2016). Floods in particular damage infrastructure, take away many lives and are one of the costliest types of natural disaster in economic and human terms (Bouwer and Vellinga, 2003). It is also true for China where floods tend to have more significant impacts on agriculture than droughts (Zhang et al., 2015b).

Increasing catastrophic losses due to natural hazards have aroused widespread public awareness of extreme events in recent years (e.g. Beniston and Stephenson, 2004; Zolina et al., 2004). By 2100, the mean annual global surface temperature would increase by 1.4-5.8°C, and future climatic and hydrological extremes would tend to increase and intensify correspondingly (Houghton et al., 2001; Beniston et al., 2007; IPCC, 2007). Therefore, it is important to investigate the flood behavior, and related studies can be of practical value in water resources management. It should be noted that precipitation extremes have a predominant effect on floods (Jena et al., 2014). Studies on precipitation extremes across the Pearl River basin have indicated that the amount of rainfall has changed little but the variability has increased over the time interval divided by change points (Zhang et al., 2009). Further, changes in the characteristics of precipitation extremes across the Pearl River basin are similar to those over the globe (Hirsch and Archfield, 2015), i.e. frequencies of precipitation extremes are increasing but magnitudes have moderate changes. However, increasing precipitation extremes are observed mainly in the lower Pearl River basin, including the Pearl River Delta (PRD) region (Zhang et al., 2012), and also partly in the middle Pearl River basin. Therefore, it can be expected that flood risk should be higher in the middle and lower Pearl River basin, or coastal regions (Pino et al., 2016).

In general, extreme floods are rare and hence there is limited opportunity to collect adequate samples of such events in order to make reliable predictions. Therefore, the question is how best to extrapolate to extreme events, when no or only short series of such events are available (Kjeldsen et al., 2014). High quality data and analyses of long historical records of peak extreme events are important to determine whether climate is becoming extreme or variable (Nicholls, 1995). To that end, flood records of 1000 years from Guangdong province (which covers the lower Pearl River basin) and Guangxi province (which covers the middle Pearl River basin) were collected to overcome the limitations of short gauge station-based flood records for analyzing floods, and this is also the significance of this study.

The historical flood records were collected from two books compiled by Wen and Song (2006) and Wen and Yang (2007). These two books included abundant records relevant to various meteorological disasters, such as tropical cyclones, droughts, floods, frosts, and so on. The historical flood records should be screened out from those abundant records and it is a kind of time-consuming job. Therefore, few reports were found concerning flooding changes over long period such as 1000 years in this study based on historical records. Besides, historical flood records in other regions of the globe have been used to analyze the changes in flood frequency (e.g. Mudelsee et al., 2003). Mudelsee et al. (2003) collected flood records from A.D. 1000 to A.D. 2000, and pointed out no upward trends in the occurrence of extreme floods in central Europe. Mudelsee et al. (2004) indicated that the historical flood records can provide reliable and unique information on heavy floods at least since A.D. 1500 in the Elbe and Oder rivers, which further emphasized merits of historical records in the study of flooding frequency from a long-term perspective.

Therefore, the objectives of this study are: (1) to quantify abrupt changes and trends of flood events; (2) to characterize temporal changes of 10 year flood flow and spatial distribution of flood magnitude > 10-year flood magnitude (the flood peak is expected to occur, on average, once every 10 years); and (3) to determine frequency and occurrence rate based on 1000 year flood records. Potential causes of spatiotemporal patterns of floods across the Pearl River basin and related implications are also discussed. This study would provide a clear picture showing the evolution of floods in both space and time in a humid river basin and show the response of hydrological extremes to climate change and human activities.

2. Study region and data

2.1 Study region

The Pearl River (97º39´E- 117º18´E; 3º41´N- 29º15´N) (Fig. 1), with a drainage area of 4.42×10^5km^2, is the second largest river in China in terms of flow volume (PRWRC, 1991). It involves three major tributaries: West River, North River and East River. The West River (Region I) is the largest tributary, accounting for 77.8% of the total drainage area of the basin. The North River (Region II) is the second largest one with a drainage area of 46710 km^2. The East River (Region III) accounts for 6.6% of the total area of the Pearl River. And the Region IV, which is beyond the three major tributaries, locates in the west of the Guangdong province (Fig. 1). The annual mean temperature ranges between 14-22ºC and the precipitation mainly occurs during April-September (Zhang et al., 2009), accounting for 72%-88% of the annual precipitation (PRWRC, 1991).

The Pearl River basin is covered mainly by two provinces, i.e. Guangdong and Guangxi (Fig. 1b). Numerous water reservoirs have been built in northern, eastern and western Guangdong and also central and southern Guangxi (Fig. 1b). In addition, widespread urbanization can be observed in the PRD, eastern Guangdong and coastal regions of Guangdong (Chen et al., 2009) (Fig. 1b) that has a highly-developed economy (Fig. 1c) and dense population settlements (Fig. 1d). Central and southern

Guangxi is dominated by croplands (Fig. 1b). The streamflow variations of the Pearl River basin have a considerable influence on the hydrological processes of the PRD, one of the most complicated deltaic drainage systems in the world (Chen et al., 2009). Flat terrain at low-lying altitude and the downstream location, together with rapid economic development and population growth over the past three decades have made the PRD region more and more vulnerable to natural hazards, such as flood, salinity intrusion, and storm surge. In recent years, engineering facilities and other modifications of the Pearl River network have been designed to strengthen flood protection and to cater for huge requirements of building materials.

2.2 Data

The annual largest 1 day streamflow data (i.e. annual maxima) were collected from 78 hydrological stations across the Pearl River basin (Table 1). Locations of these hydrological stations are shown in Fig. 1a. Besides, daily precipitation data were also collected from 74 stations across the Pearl River basin and their locations are shown in Fig. 1c. All the precipitation and hydrological data cover the period of 1951-2014. Detailed information of these hydrological (Table 1) and precipitation data can be found in Fig. 2. The hydrological data were provided by the Water Conservancy Bureau of the Pearl River Water Conservancy Commission and the precipitation data were collected from National Climate Center. The quality of these data is firmly controlled before release.

There is less than 1% missing values in daily precipitation data (Zhang et al., 2018). The missing precipitation data for 1–2 days were filled by the average precipitation of the neighboring days. Consecutive days with missing data were interpolated by the long-term average of the same days of other years. For the objectives of this study, the gap-fill method did not significantly affect the final results. A similar method had been used by Zhang et al. (2011) to fill daily missing precipitation values. The annual largest 1 day streamflow data from 78 hydrological stations are directly collected from the Water Conservancy Bureau of the Pearl River Water Conservancy Commission. The annual largest 1 day streamflow data have been compiled before release of the data. The missing values of annual largest 1 day streamflow data were filled by the average value of the neighboring years.

Mudelsee et al. (2003) classified floods into three types, based on inundation area and flood-induced losses: (1) floods that occur locally with short duration and small damages; (2) regional floods that have relative longer duration and cause damages to hydraulic infrastructure and also casualties; and (3) fluvial disastrous floods with long lasting duration (usually days or weeks) causing serious and even disastrous damages to hydraulic infrastructure and massive casualties. In this study, historical flood records were collected from documented flood records compiled by Wen and Song (2006) and by Wen and Yang (2007). The documented flood records for Guangdong and Guangxi provinces covered a period of 383-2000 and 107-2000, respectively. The disasters were recorded in history books, local chronicles, water conservancy archives, documents, and so on. For the sake of the study on relations between climate change and disasters, the group was developed to compile the documented nature disaster records spanning almost 2000 years for each province in China based on multisource information. The group selected the recorded flood events with mutual confirmation in different documents as far as possible. In addition, the flood event with more relevant information, such as magnitude, mortality, flood-damaged and flood-affected cropland areas, flood-induced damaged water conservancy facilities, is more likely selected.

The director of the group is Wen who served as director of China meteorological administration, and one of the group is Ding who is an academician of the Chinese academy of sciences. The members of the group coming from senior government authority and famous scientists, can largely ensure the quality of the data. Based on flood types defined by Mudelsee et al. (2003), only disastrous flood events were singled out, since floods occurred almost annually. Meanwhile, flood records before 1000 AD were not complete and contained missing information, thus disastrous flood records during a period of 1000-2000 were singled out and analyzed in this study. One flood event, which caused life losses or submersing more than 10 thousands areas of farmland or destroying important water conservancy facilities, will be classified as disastrous flood events.

3. Methods

3.1 Detection of change points and trends

The Pettitt method (Pettitt, 1979) is a nonparametric test and enables the detection of change in the mean (median) when the change point time is unknown. This method has been widely used in detection of change points (Villarini et al., 2009) and was also used in this study. The test is based on the Mann-Whitney statistic for testing whether the two samples $X_1, \ldots, X_m$ and $X_{m+1}, \ldots, X_n$ come from the same population. The *p* value of test statistic is computed using the limiting distribution approximated by Pettitt (1979), which is valid for continuous variables (e.g. Villarini et al., 2009). The 95% confidence level was used to evaluate the significance of change point in the study.

Trends were tested by non-parametric trend detection methods which are less sensitive to outliers than are parametric statistics. In this study, the modified version of the Mann-Kendall (MMK) trend test method was used which was proposed by Hamed and Rao (1998) based on effective or Equivalent Sample Size (ESS) to eliminate the effect of autocorrelation. MMK has been used in analyzing the effect of global warming on small aquatic ecosystems (Daufresne et al., 2009). In this study MMK was employed to explore trends in flood series, with the significance level set at 5%. For the computation procedure one can refer to Daufresne et al. (2009). The change point and trend detection methods are only applied for the observations during 1951-2014.

3.2 Generalized Extreme Value (GEV) model

The GEV distribution has been widely used in the analysis of hydrometeorological extremes (e.g. Gu et al., 2016) and has three parameters, i.e. the location μ, the scale, α ($\alpha > 0$), and the shape, κ. In this paper, GEV is used to calculate the return period of flood events. The cumulative density function (cdf) of a random variable y drawn from a GEV distribution is given as (Cannon, 2010):

$$F(y;\mu,\alpha,\kappa)=\exp\left[-\left\{1-\kappa\frac{y-\mu}{\alpha}\right\}^{1/\kappa}\right],\qquad \kappa\neq 0,\ 1-\kappa\frac{y-\mu}{\alpha}>0$$
$$F(y;\mu,\alpha,\kappa)=\exp\left[-\exp\left\{1-\frac{y-\mu}{\alpha}\right\}\right],\qquad \kappa=0 \tag{1}$$

3.3 Kernel density estimation of occurrence rates of floods

The kernel density estimation method is used to estimate the occurrence rates of historical floods. The estimation of occurrence rates of time-dependent extreme events can be computed as (Mudelsee et al., 2003; Mudelsee et al., 2004):

$$\lambda(t)=h^{-1}\sum_{i=1}^{m}K\left(\frac{t-T_i}{h}\right) \tag{2}$$

where T_i is the timing of the ith flood event with unit in day; m is the number of floods; $K(\cdot)$ is the kernel function; and h is the width of the kernel function. The Gaussian kernel function is the widely-used kernel function, which can use the Fourier space and produce a smoothed estimation of the occurrence rates of extreme events (Mudelsee et al., 2003; Mudelsee et al., 2004):

$$K(y)=\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{y^2}{2}\right) \tag{3}$$

where $y = (t - T_i)/h$. The occurrence rate of an extreme event, $\lambda(t)$, denotes the number of an extreme event exceeding threshold values given a certain time interval, t. The time interval of time series is $[t_1, t_m]$. Since no data are available outside of the time interval, i.e., $[t_1, t_m]$, $\lambda(t)$ near the boundaries of the time interval is usually underestimated. In this case, a kind of pseudodata is used to reduce the error as a result of underestimated $\lambda(t)$. A mapping technique is used to produce the pseudodata (Mudelsee et al., 2004). pT is the pseudodata outside of the time interval of $[t_1, t_m]$ for the flood series. For $t < t_1$, $pT[i] = t_1 - [T_i - t_1]$; and the same procedure was done for $t > t_m$. The extended series is 1.5 times longer than the original one. The computation of $\lambda(t)$ based on the extended data series was based on:

$$\lambda(t) = h^{-1}\sum_{i=1}^{m*} K\left(\frac{t - T_i^*}{h}\right) \quad (4)$$

where T_i^* is the timing of the *i*th flood event based on the extended data series with a unit of day; m^* is the sample size of the extended data series. Also, the selection of window width, *h*, is important for the estimation of $\lambda(t)$. Too small window width, *h*, selected for computation of $\lambda(t)$ will substantially influence the randomness on $\lambda(t)$; too large window width, *h*, may cause over smoothing of the data series and hence details in information may be excluded. The cross validation method was used to determine the width of window (Mudelsee et al., 2003). The kernel density estimation method is only applied for the historical floods.

3.4 Confidence interval by Bootstrap technique

The bootstrap technique and Equation (4) can be combined to enable uncertainty analysis of the occurrence rate of floods, $\lambda(t)$, using the following procedure (Mudelsee et al., 2004):

(1) Based on the extended data series, T_i^*, the simulated T^+ of the same series length can be obtained using the bootstrap technique;

(2) The occurrence rates, $\lambda^+(t)$, of sample extreme events, T^+, can be computed using Equation (5);

(3) Steps (2) and (3) above will be repeated for 2000 times, and $\lambda^+(t)$ of 2000 samples can be obtained;

(4) The 90% confidence interval for $\lambda^+(t)$ will be obtained using the quantile method.

4. Results

4.1 Change points and trends of peak flood flow

Analyses of change points and trends were only applied in observed flood events (i.e. annual maxima of period of 1951-2014). Fig. 3 illustrates spatial patterns of stations with different change points of peak flood flow. It can be observed from the figure that only 16 out of 78 stations, accounting for 20.5% of the total stations, were characterized by significant change points of peak flood flow changes and most of these stations are found in the middle and lower Pearl River basin. In the coastal regions of the lower Pearl River basin, 10 out of 16 stations with significant change points were observed, accounting for 62.5% of the total stations characterized by significant change points of peak flood flow. Generally, flooding in the Pearl River basin is mainly attributed to precipitation extremes which were observed mainly in the middle and lower Pearl River basin and particularly in the lower Pearl River basin (Zhang et al., 2012). Results of change points of precipitation maxima by Zhang et al. (2009) indicated that precipitation maxima were dominated by significant change points during 1980-1993, and significant change points of peak flood flow series detected in this study were during 1986-1995, showing significant impacts of precipitation extremes on flooding. These results showed that significant change points of flood processes were found mainly in the middle Pearl River basin and particularly in the lower Pearl River basin. Besides, human impacts on flood processes cannot be ignored and it is particularly the case for the East River basin (Zhang et al., 2015c), where 3 large water reservoirs were built that controlled 11700 km^2 of drainage area.

Significant increasing peak flood flow was observed mainly in northeastern West River basin, mainstream of the Pearl River basin, northern North River basin, southeastern West River basin, and southern North River. Significant decreasing peak flood flow was observed mainly in southeastern West River, southern North River basin, and also parts of rivers along the coastal regions of the lower Pearl River basin (Fig. 4a). Most of stations show decreases in flood peaks both before and after change point, especially in Regions I and IV (Figs. 4b, 4c). However, the flood peaks in Region III turned decreasing trend before change point to increasing trend after change point, suggesting shifted and/or modified physical mechanisms behind flood generation processes. Significant increasing precipitation extremes were found in northeastern West River basin and northern North River basin, and significant decreasing precipitation extremes were detected in East River basin. Hence, spatial patterns of peak flood flow matched those of precipitation extremes (Figs. 4a, 4d), implying that floods in these regions were impacted mainly by precipitation extremes. The southeastern West River basin and rivers in the west parts of region III were dominated by significant increasing precipitation extremes but significant decreasing peak flood flow (Fig. 4). Human activities exerted considerable impacts on flood processes in these regions. Crop land in the Guangxi province was found mainly in the southeastern Jiangxi province (Fig. 1b) and irrigated cropland had a significant increase (Zhang et al., 2015b). The volume of water withdrawal for agricultural irrigation during 2014 only reached $2.09\times10^{10}m^3$. Meanwhile, the total water storage capacity of water reservoirs of the Guangxi Province reached 6.74×10^{10} m^3, and more than half of the reservoirs were built in the southeastern West River basin (Fig. 1b). The western parts of the region III were also dominated by croplands and large-scale reservoirs (Fig. 1b), and agricultural water consumption reached 2.24×10^{10} m^3, and the total storage capacity of reservoirs reached 4.48×10^{10} m^3 during 2014. These human activities greatly decreased peak flood flow volume in these regions. Therefore, increasing human impacts on flood processes should arouse considerable concerns for the management of water resources and mitigation of flood hazards (Zhang et al., 2015a).

To determine trends of peak flood flow during specific time intervals, multi-scale trend analysis was done (Fig. 5). Trends were identified by changing the time interval by shifting the beginning and ending time of the interval with a time step of 5 years. The shortest time interval was 15 years to ensure the validity of statistical analysis. Besides, the percentages of stations with significant trends were also analyzed (Fig. 5). The percentage of stations with significant trends in almost all time intervals, was relatively low, being about 15% and even lower. However, stations with significant decreasing trends of peak flood flow during 1966-2005 accounted for 20-25% of the total stations considered in the study (Figs. 5). Significant increasing peak flood flow was identified during 1981-2010 in the West River basin, and stations with significant increasing peak flood flow during 1981-2010 accounted for 25-35% of the total stations. Stations with significant decreasing peak flood flow during 1966-1990 accounted for 25-30% of the total stations (Figs. 5). Peak flows in the North River basin had moderate changes without statistically detectable trends (Figs. 5). Significant decreasing peak flood flow can be observed at the stations in the East River basin or eastern parts of the region III, and stations with significant decreasing peak flood flow during 1951-1980 and 1951-2014 accounted for 20-25% and 25-30% of the total stations (Figs. 5). Stations with significant decreasing peak flood flow were fewer after 1981 (Fig. 5), implying amplifying flooding regimes after 1981 in the eastern parts of the region III. Larger changing variability of peak flood flow in the western parts of the region III were observed. Stations with significant increasing peak flood flow during 1951-1975 accounted for 30-35% and less stations were characterized by significant increasing peak flood flow after 1966, and peak flood flow after 1966 turned out to be significantly decreasing after 1966 (Figs. 5), stations with significant decreasing peak flood flow accounted for 35-50% of the total stations.

The detailed information of flood events occurred in recent 60 years can be used to verify the observed results in Fig. 5. For example, we observed significant increasing peak flood flow during 1981-2010 in the West River basin. The recorded flood events also showed the floods with high magnitude intensively occurred in this period (i.e. 1981-2010). During 20 years from 1981 to 2000 only, the West River basin was hit by five floods with return periods larger than 20 year: (1) flood in June 18-23, 1983, caused 147 deaths; (2) flood in August 21 to September 4, 1988, caused 58 deaths; (3) flood in June 12-17, 1994, caused 224 deaths; (4) flood in July 16-19, 1996, caused 252 deaths; and (5) flood in June 16-26, 1998, caused 81 deaths.

4.2 GEV-based flood frequency

The GEV model was used to fit peak flood flow series (i.e. annual maxima of period of 1951-2014) and the Kolmogorov Smirnov (K-S) statistic D was used to evaluate the goodness-of-fit of GEV-based fitting performance (Fig. 6). Fig. 6 indicated that peak flood flow series at almost all stations, except two stations, was well modelled by GEV at 0.05 significance level. The peak flood flow series at these two stations were also modelled by GEV at the 0.1 significance level. Therefore, GEV was used for flood frequency analysis across the Pearl River basin. Return periods of floods at all hydrological stations were estimated and spatial patterns were also characterized across the basin. It can be observed from Fig. 7 that floods of > 10-year flood magnitude occurred with high frequency. However, large floods occurred in a clustering manner at the annual time scale. About 40% of total number in the three largest flood events of all stations occurred during two time intervals, i.e. 1965-1970 and 1993-2002 (i.e. 90 of total 236) (Fig. 7). This is particular true in Region I where there occurred 38 out of 66 three largest floods at 22 stations during these two time intervals (region I in Fig. 7). There was no temporal clustering observed for the three largest floods that occurred in the North River basin, but the spatial concentration was identified (region II in Fig. 7). Taking the great floods that occurred during May 1982 across the entire North River basin as an example, flood events of > 10 year flood were observed at 9 out of 20 stations and the measured largest three floods were observed at 7 stations.

Survey of floods across the West and North River basins indicated that higher probability was expected for the simultaneous occurrence of floods in both North and West River basins. For example, 1994 was a serious flooding year and floods that occurred in the West River basin at 11 stations were larger than 10 year flood and 7 out of 11 stations were dominated by the largest three floods of the recorded floods. Meanwhile, peak flood flows at 8 stations in the North River basin were larger than 10 year flood and 6 out of 8 stations were dominated by the recorded largest three floods. The occurrence of large floods in the east parts of region III was evidently uneven in time and the measured largest three floods occurred mainly during 1958-1969, and decreased occurrence rates was observed for large floods after 2005.

However, floods of > 10 year flood were amplifying after 2005. Besides, the occurrence of large floods in the east parts of the region III was also subject to spatial clustering, and floods of > 10 year flood were observed usually at numerous stations at the same time (region III in Fig. 7). Moreover, large floods occurred in a clustering manner during 1966-1974 and occurrence rates of large floods after 1980 exhibited moderate changes (region IV in Fig. 7).

The percentage of stations with flood regimes of > 10 year flood to the total stations for each region was counted and trends were evaluated by the 11-year moving average method (Fig. 8), with the aim to determine the occurrences of large floods in both space and time. It can be seen from Fig. 8a that the percentage of stations dominated by the occurrence of large floods in West River basin had moderate changes with a slight increasing tendency (Fig. 8a), and particularly after 1990. The percentage of stations dominated by the occurrence of large floods had an increasing tendency and this increasing tendency was maintained during the entire time interval considered in this study (Fig. 8b). The percentage of stations with the occurrence of large floods followed similar changing patterns, i.e. increase and then decrease, implying enhancing risks of floods across the entire region (Figs. 8c and 8d).

4.3 Flood risks based on historical flood records

Based on historical flood records, the occurrence rates of floods during the last 1000 years in the Guangdong and Guangxi provinces were analyzed and local polynomial regression fitting technique was used to smooth the series. It can be observed from Fig. 9a that the occurrences of floods had increasing trends before 1600 AD and reached the peak value during about 1600 AD in Guangdong province. The occurrences of floods had moderate variations during 1600-1900 with moderate variability. These results would be further evaluated using the kernel density estimation method in the next section. However, the occurrence of floods in Guangxi province told another story when compared to those in Guangdong province (Fig. 9b). A moderate increasing tendency of occurrence rates of floods was observed before 1800 AD and the time interval after 1800 AD witnessed abruptly elevating occurrence rates of floods and it is particularly the case during recent 100 years, i.e. 1900-2000 (Fig. 9b).

Basin-scale hazardous flood events were identified based on flood criterion defined by Mudelsee et al. (2003, 2004). Meanwhile, flood risks of recent 1000 years were evaluated using the kernel estimation method (Fig. 10). The width of the time window was 56 years and 41 years for hazardous floods in the Guangdong and Guangxi provinces based on the cross validation method (Figs. 10b and 10d). Moreover, the time window of 30 years was used to have a closer look at the occurrence rates of hazardous floods (Figs. 10a and 10c). It can be seen from Fig. 10 that hazardous floods had an increasing tendency in general, except the time interval of 1400-1800 which was characterized by decreasing occurrence rates. Recent 200 years witnessed a sharp amplification of floods in the Guangxi and Guangdong provinces. Remarkable amplification of floods in the middle and lower Pearl River basin, and particularly in recent 200 years, should arouse a considerable concern.

Because the period of recent 60 years is a segment in the past 1000 years, analyzing the historical flood records is beneficial for understanding the changes in flooding during recent 60 years. For example, we observed increasing trends in floods in Region I (most parts in Guangxi province) during recent 60 years. Actually, basin-scale hazardous flood events show a sharp amplification since recent 200 years in Guangxi province. As we all know, the influences of human activities on flood generations are considerable smaller in recent 200 year (except for recent 60 year) than in recent 60 years and even neglected. However, human-induced climate change is enhanced continually since the recent 200 year when the world conducted the industrial revolution. Therefore, the increasing flooding in recent 60 year beginning from recent 200 years in Guangxi province is very likely caused by climate change.

5. Discussions

Change points and trends analyses showed that only a few stations showed a change point or significant trend in the flood peaks. In other words, the flood peaks are stationary in most of the stations considered in this study. Our previous study has also detected the trends in flood peaks before and after the change points, indicating that no significant trends have been found (e.g. Zhang et al., 2014). Taking change points in the West River as example, Change points of flood peaks in the mainstream of the West River occurred approximately in 1990 in spite of a few difference. The flood peaks of the West River basin are heavily influenced by the confluences of tributaries on the upstream of the West River and the factors causing abrupt changes in mean are complicated and blurry. The influence of hydraulic facilities is considerable. However, after the 1990s a few hydraulic facilities have been constructed and their influence can be ignored. Analysis of precipitation extremes in the Pearl River basin indicated that the amount of rainfall had changed little but its variability had increased over the time interval divided by change points. Abrupt changes of precipitation maxima were shifting in different seasons. However, change points of precipitation maxima in summer occurred in 1990, 1988 and 1991, which are in line with changes points of flood peaks of the West River basin. It should be noted that floods occur mainly during the summer season. Therefore, it can be tentatively stated that abrupt changes of flood peaks of the West River basin are mainly the result of abrupt behavior of precipitation maxima. However, due to spatiotemporal patterns of precipitation maxima in the Pearl River basin and the production and confluence of flood streamflow, the abrupt behavior of flood peaks usually does not match that of precipitation maxima. Moreover, human interferences also introduce considerable uncertainty and cause obscure relations between abrupt changes of flood peaks and precipitation maxima. This analysis implies abrupt changes of flood peaks due to various influencing factors.

The Guangdong province is dominated by high urbanization, highly-developed socio-economy and dense population density and it is particularly the case for the PRD region (Figs. 1b, 1c and 1d). Intensifying human activities, such as in-channel sand dredging, building of levees and fast urbanization, have greatly altered physical and geographical features of underlying surfaces and hence modified the flooding processes. The volume of sand dredged during the 1990s in the North and East River basins was respectively 3.38×10^6 m^3/year and 1.50×10^6 m^3/year, causing deepening of river channel (e.g. Luo et al., 2007). Massive building of levees and simplification of river channel systems have caused wide-spread gathering of flood waters and hence amplification of floods.

Taking the PRD as an example, during recent 60 years, more than 20000 levees were combined with 400 levees and the length of river channel was reduced from 10000 km to 5000 km. Besides, the construction of large-scale reservoirs greatly reduced the occurrence rates and magnitude of floods (Figs. 11a, 11b and 11c). However, fast and massive urbanization, such as the urbanization rate of the Guangdong province reaching 67.67% caused fast production of floods and hence enhanced flood risk (Fig. 10a). Increasing flood magnitudes in the recent 60 years

(Fig. 3a) and increasing occurrence rates of floods in the recent 100 years (Fig. 9b) caused increasing losses of agricultural production and increasing casualty (Figs. 11c, 11d, and 11f). However, when compared to Guangdong province, Guangxi province was dominated by lower urbanization and less dense population density (Fig. 1d), human activities did not exert significant impacts on floods. Increasing precipitation extremes and particularly increasing precipitation concentration (Zhang et al., 2012, 2013) triggered discernable amplification of floods in the Guangxi Province. Therefore, recent 200 years also witnessed the intensification of hazardous floods which undoubtedly posed a challenge for mitigation of flood hazards in the lower Pearl River basin, particularly the PRD region. Although the fluvial disastrous floods may be ignored in the early time, the increasing numbers of extreme floods are significant and sharp. The no reported flood events in the early time may be one of the reasons of sharp increases. However, we think it is not enough to explain this. Taking Guangxi province as an example, the significant increase is continual, especially for recent 200 years (Fig. 9b). In recent 200 years, no reported extreme floods did not have so much difference that number of floods is still significantly increasing. When historical flood records are tried to use, the no reported flood events are the problem that the users must face not only for us but also for Mudelsee et al. (2003). In addition, the spanning time is larger, the problem is more difficult to solve. Nevertheless, the historical flood information can definitely provide valuable information to improve our understanding of the changes in flood frequency.

6. Conclusions

Evaluation of flood risks was done in both space and time across the Pearl River basin, China, based on peak flood flow data from 78 hydrological stations during the period of 1951-2014 and 1000-year flood hazard records. The following conclusions can be drawn from this study:

(1) No statistically significant changes can be detected in the peak flood flow series at most of the stations, but significant changes were observed at 16 out of 78 stations. Stations with significant peak flood flow changes were found in mainstream of the West River basin, the East River basin and rivers in western parts of the coastal regions and the change points were mainly during the 1990s. Abrupt changes of peak flood flow in the West River basin were attributed to the abrupt behavior of precipitation extremes. Construction of large-scale hydraulic facilities and reservoirs was the major cause behind abrupt behavior of peak flood flow in the coastal region.

(2) The northern parts and mainstream of the West River basin and northern North River basin were dominated by significant increasing peak flood flow, implying amplification of floods. Peak flood flow in the East River basin however had significant decreasing trends which were attributed to the changes in precipitation extremes. It should be emphasized that precipitation extremes were increasing in southeastern West River basin and west parts of the coastal regions, and peak flood flow in these regions was decreasing. Expanding agricultural irrigation and hydrological regulation of reservoirs were the causes of decreasing peak flood flow in these regions. A closer look at the abrupt behavior of peak flood flow indicated that significant increasing peak flood flow was identified during 1981-2010 at 25-35% of the stations in the West River basin; significant

decreasing peak flood flow was observed during 1951-2014 at 25-30% of the stations in the East River basin; and 30-35% of the stations in the western parts of the coastal region were dominated by significant increasing peak flood flow during 1951-1975, and 35-50% of the stations were dominated by significant decreasing peak flood flow.

(3) The largest three flood events were concentrated during two time intervals, i.e. 1965-1970 and 1993-2002. The percentage of stations characterized by floods of > 10-year flood was increasing after 1975. The East River basin was dominated by the concentrated occurrence of the three largest flood events during 1958-1969 and the percentage of stations with > 10-year flood was increasing after 2000. Results indicated temporal and spatial clustering of flood hazards. This point should arouse considerable concern for the mitigation to flood hazards.

(4) Historical flood records of recent 1000 years told an interesting story about flood risks in basin-scale hazardous flood events from a long term perspective. Flood risks of the middle and lower Pearl River basin were enhancing and it is particularly the case in the recent 100 years. Particularly, the flood risks in the middle and lower Pearl River basin in terms of disastrous flood regimes were increasing, posing serious challenges for mitigation of flood hazards in the PRD region.

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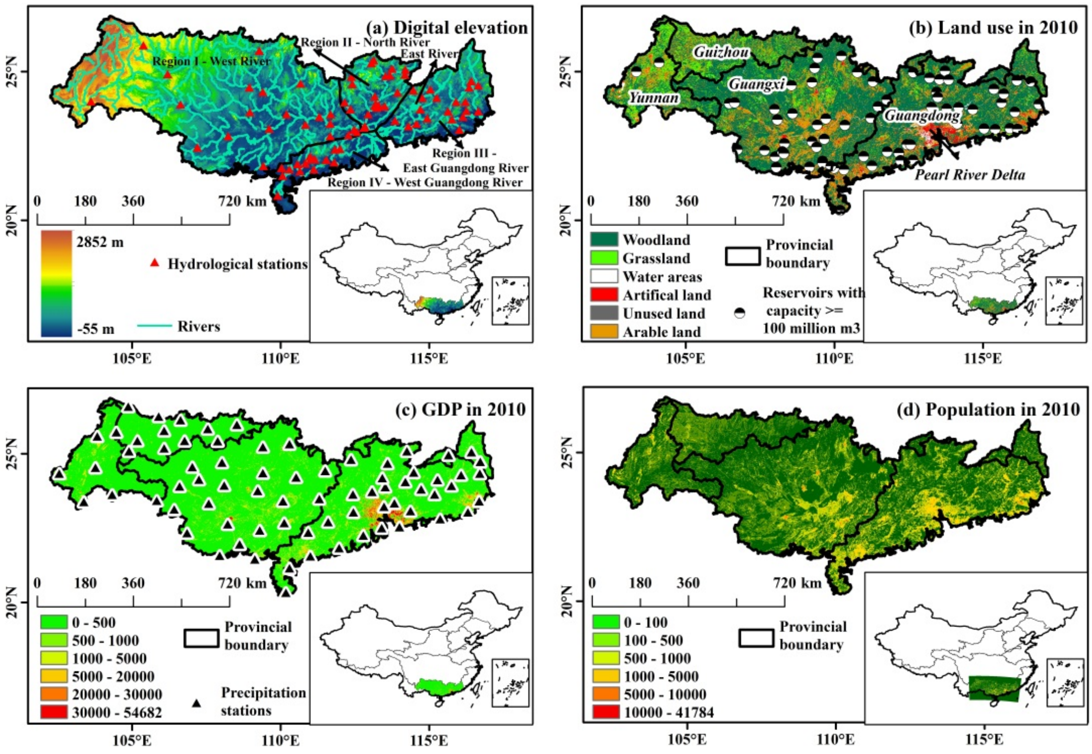

Fig. 1 Locations of hydrological stations, precipitation gauging stations, and water reservoirs, and spatial patterns of land use, socio-economy and population across the Pearl River basin.

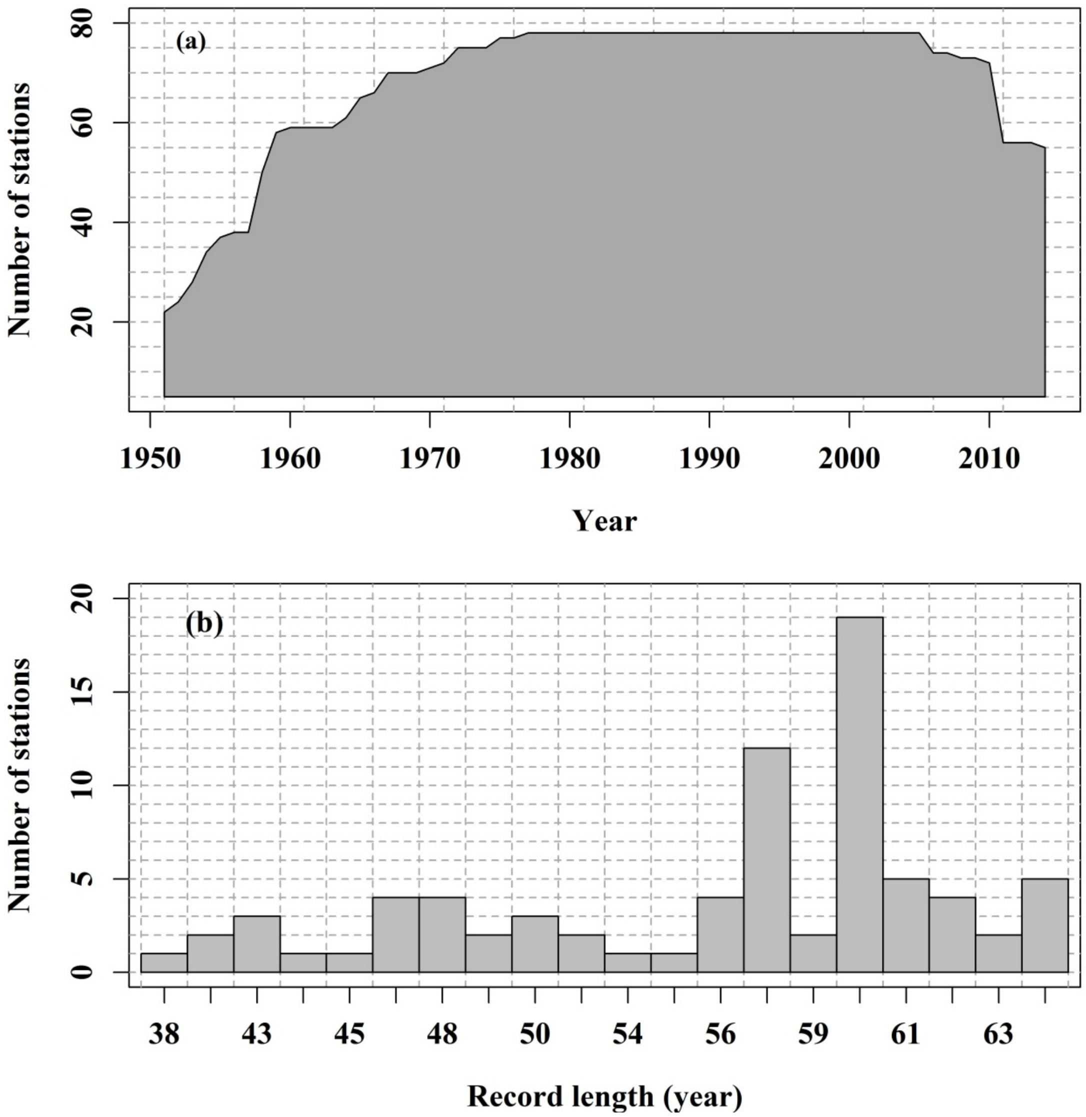

Fig. 2 Information on peak flood flow dataset.

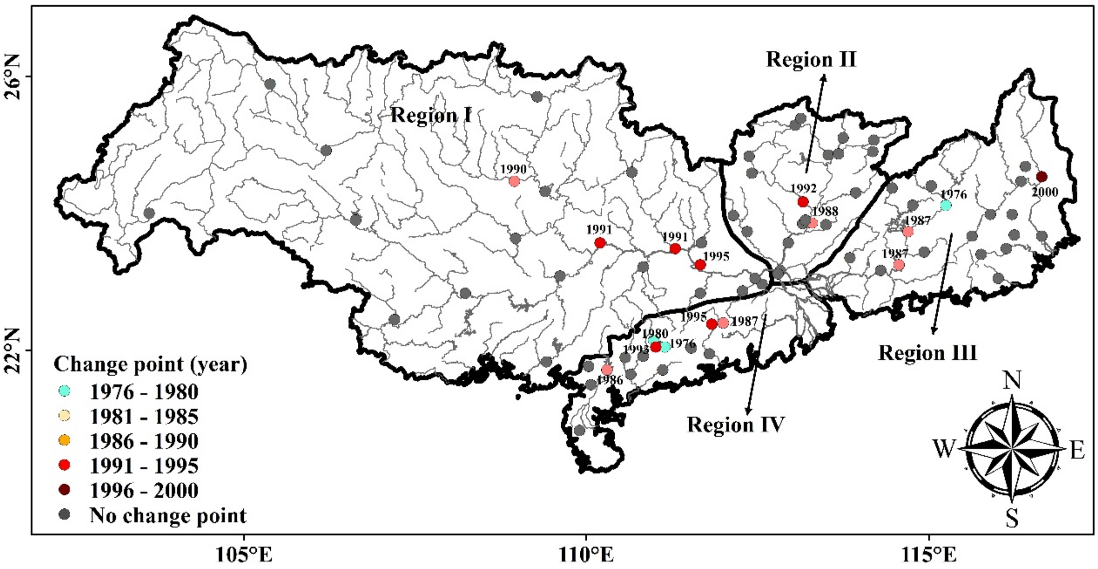

Fig. 3 Spatial distribution of change points by Pettitt test for peak flood flow changes

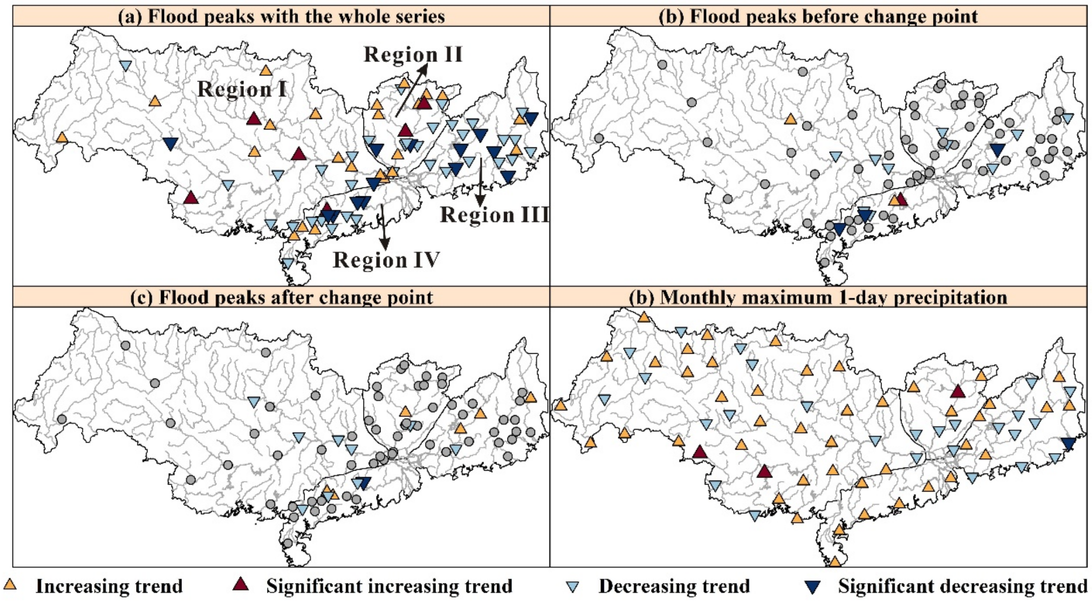

Fig. 4 Trends in (a) flood peaks with the whole series, (b) flood peaks before change point, (c) flood peaks after change point, and (d) precipitation extremes. The gray dots in (b) and (c) indicate the stations without change point.

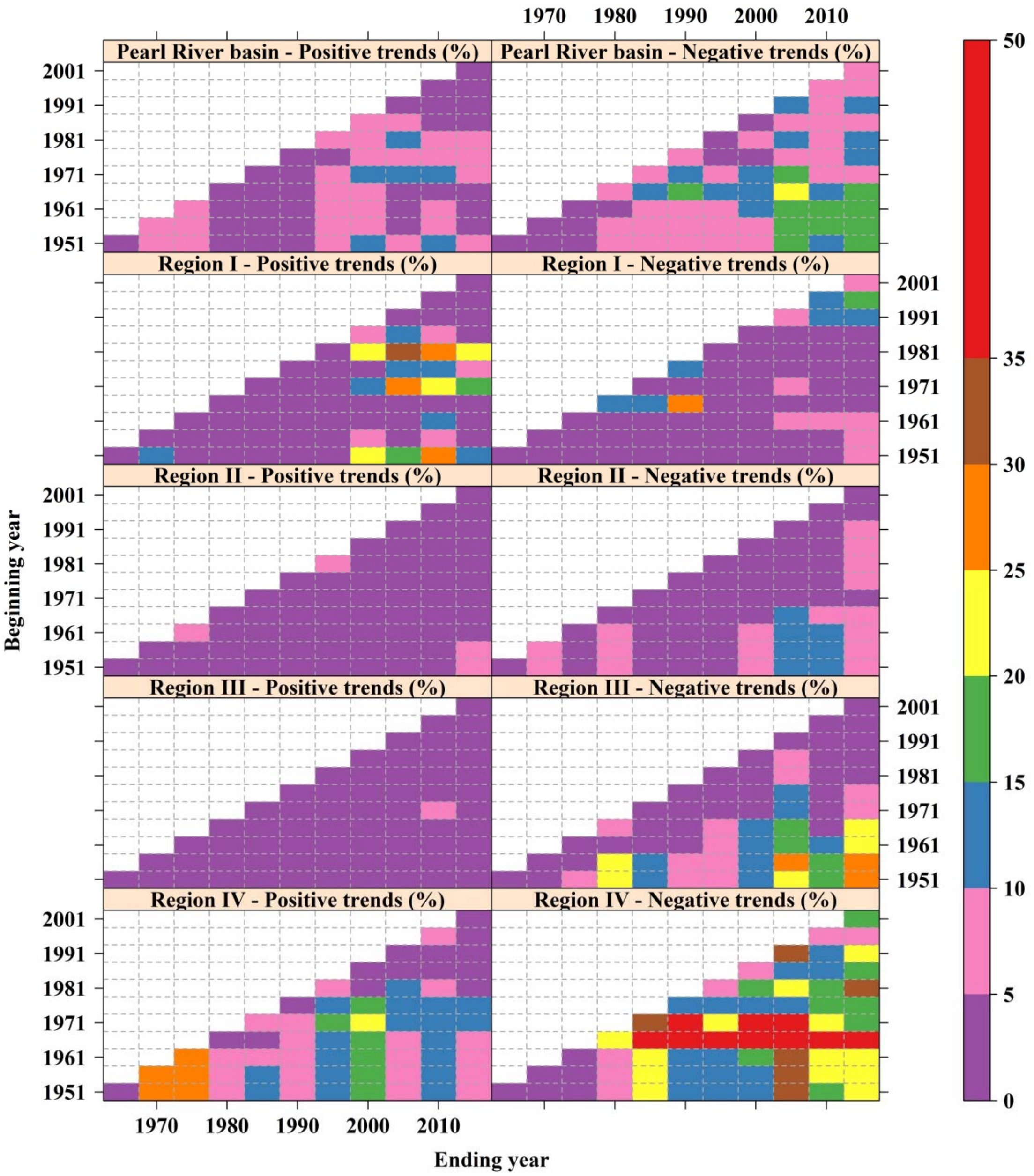

Fig. 5 Percentage of stations with significant trends in peak flood flow

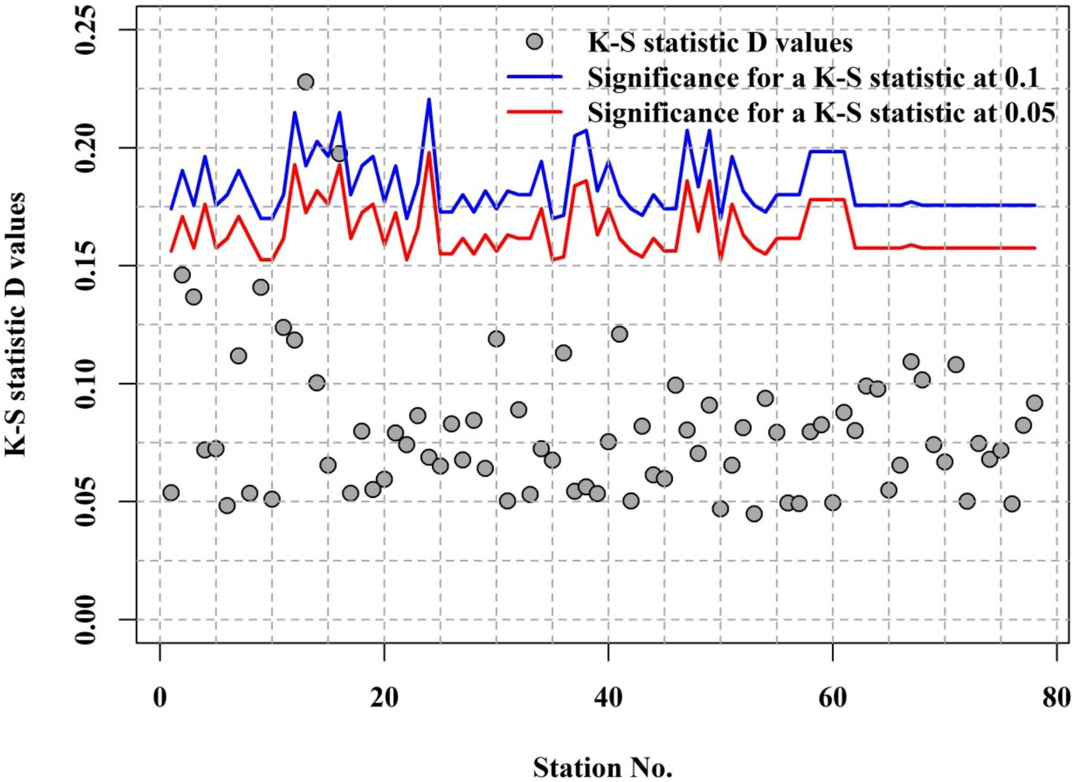

Fig. 6 K-S test results of performance of GEV fitting of peak flood flow of the Pearl River basin

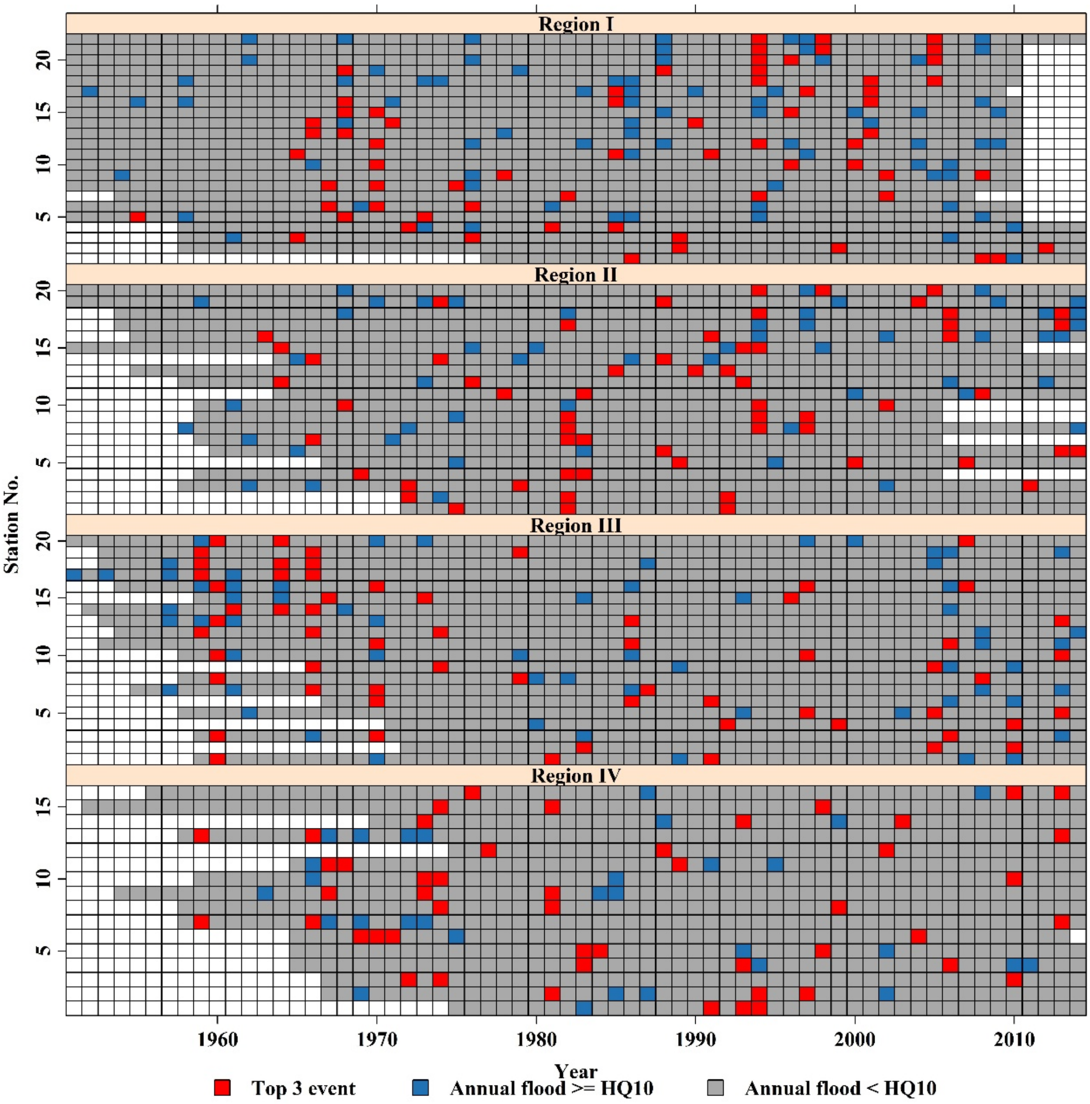

Fig. 7 GEV model based estimated return periods of peak flood flow at hydrological stations considered in this study across the Pearl River basin.

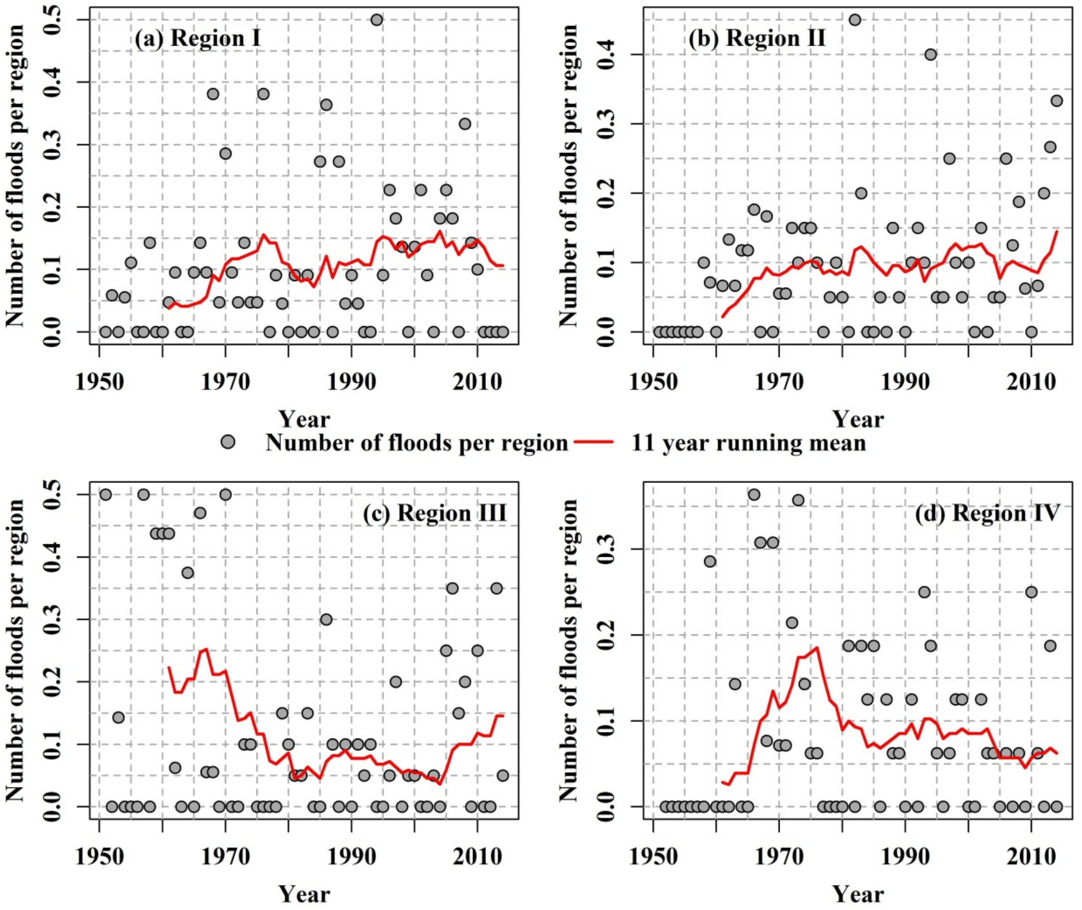

Fig. 8 Temporal changes of percentage of stations with flood events of magnitude of > 10-year flood magnitude

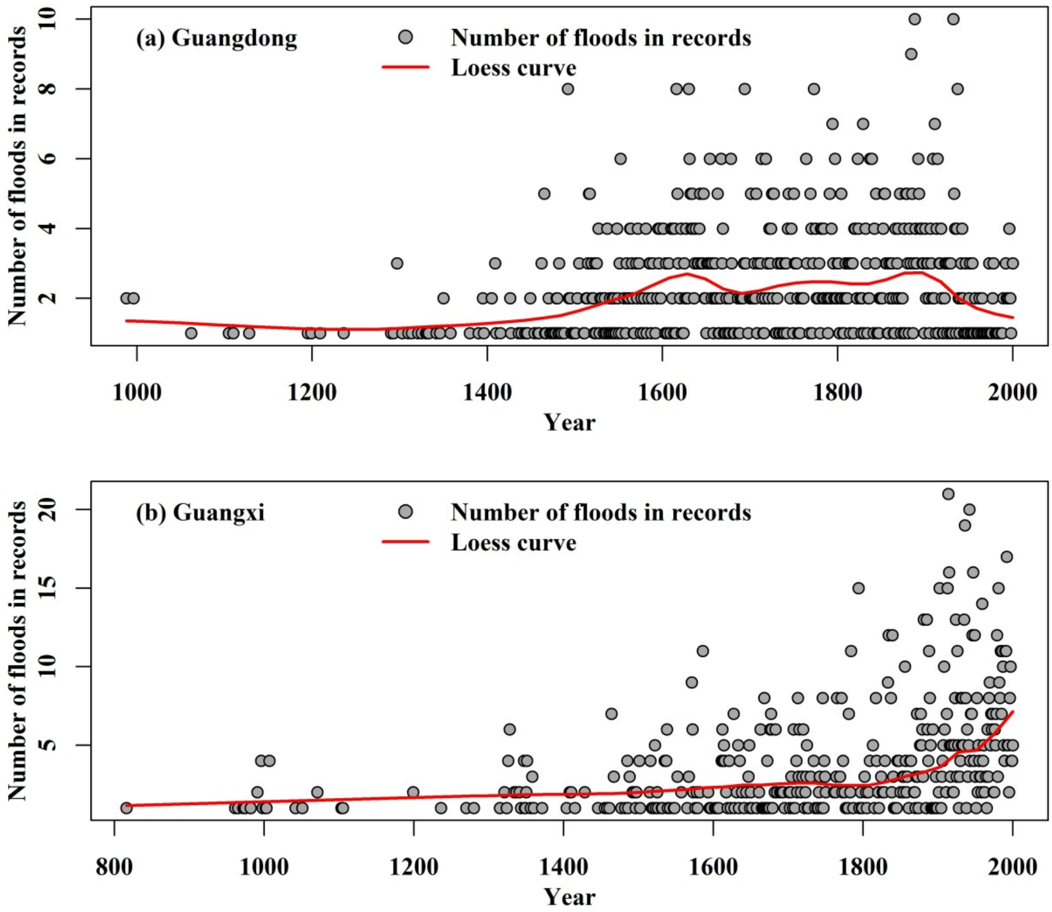

Fig. 9 Temporal changes in occurrence rates of flood hazards of past 1000 years in Guangdong (a) and Guangxi provinces (b).

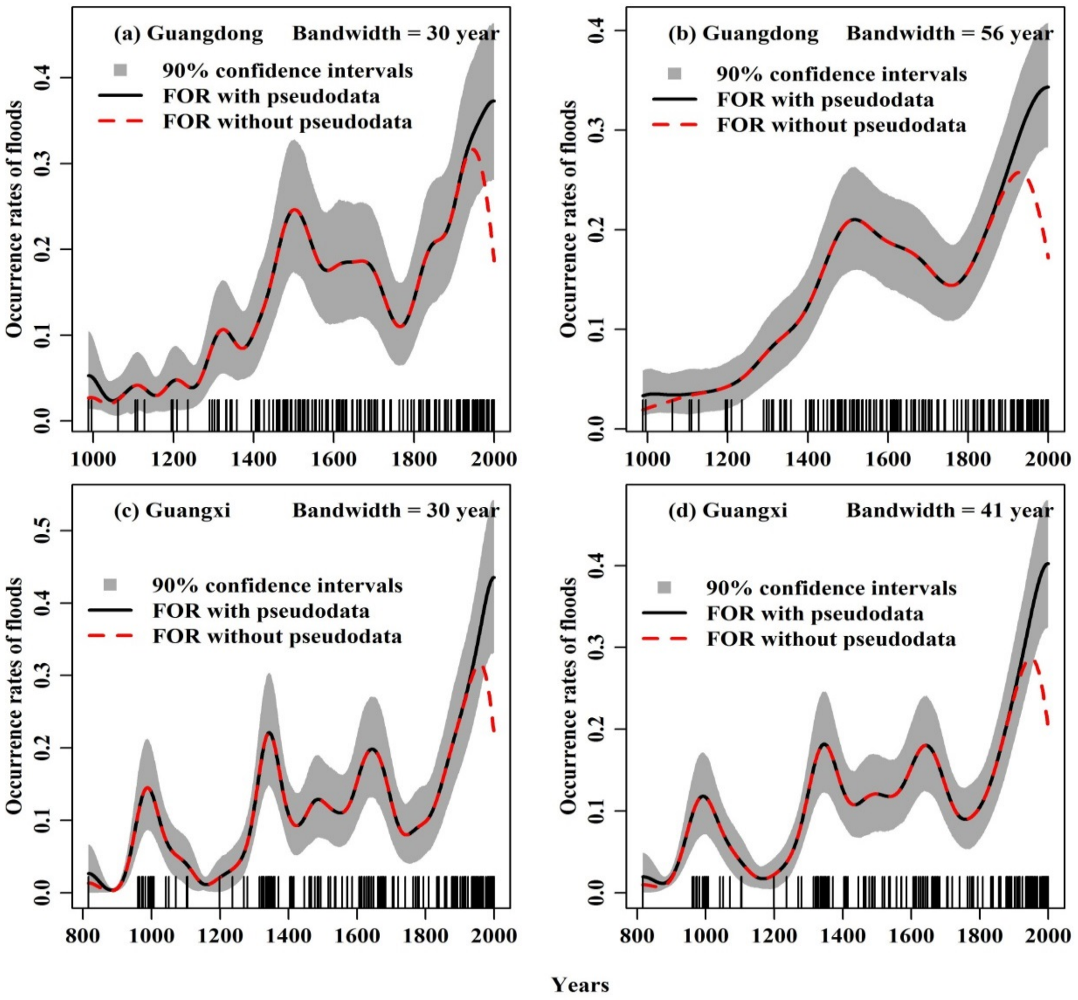

Fig. 10 Temporal variations of frequency of flood hazards during past 1000 years in Guangdong and Guangxi provinces.

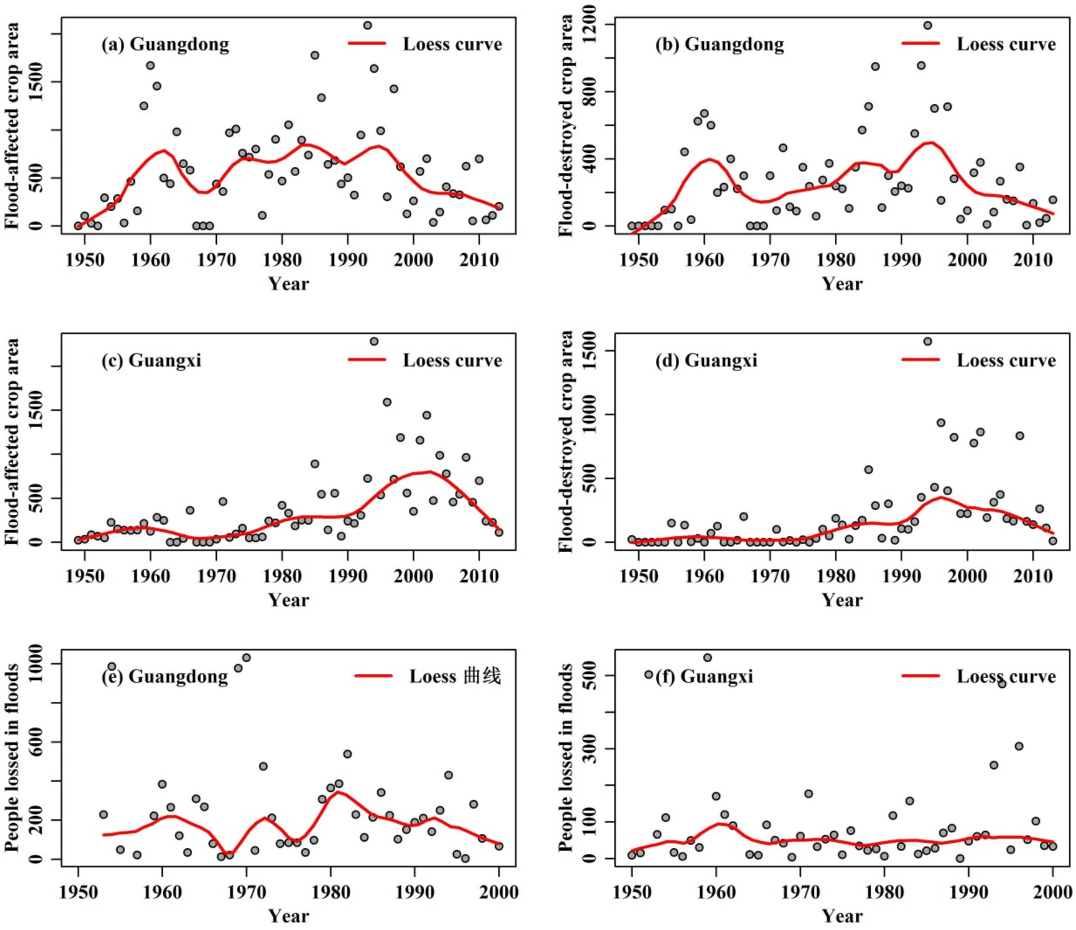

Fig. 11 Temporal changes of flood hazard-induced agricultural losses and mortality in Guangdong and Guangxi provinces.

Table 1 The detail information of hydrological stations in this study.

No.	Station name	Longitude (°E)	Latitude (°N)	Basin area (km^2)	Region	Starting year	Ending year	Record length
1	Qilinzui2	113.85	23.35	2866	III	1954	2014	61
2	Pingshi2	113.05	25.28	3567	II	1964	2014	51
3	Wenjiang	113.93	24.30	2000	II	1955	2014	60
4	Chixi4	113.13	25.38	396	II	1967	2014	48
5	Lishi2	113.53	24.85	6976	II	1955	2014	60
6	Xiaogulu	114.20	25.07	1881	II	1958	2014	57
7	Renhua3	113.75	25.10	1476	II	1964	2014	51
8	Jielongwan	114.18	24.90	281	II	1958	2014	57
9	Sanshui2	112.83	23.17	46646	II	1951	2014	64
10	Makou	112.80	23.12	353100	II	1951	2014	64
11	Shuangqiao	112.57	22.97	938	I	1958	2014	57
12	Dulin	109.90	20.83	47	IV	1975	2014	40
13	Hedishuiku	110.30	21.72	1495	IV	1965	2014	50
14	Gangwajiao3	110.07	21.50	3086	IV	1970	2014	45
15	Ruipo	110.03	21.77	208	IV	1967	2014	48
16	Gaozhou4	110.83	21.92	2905	IV	1975	2014	40
17	Xinhe	111.12	21.72	649	IV	1958	2014	57
18	Shigushuiku1	111.04	22.07	509	IV	1965	2014	50
19	Dabai	111.15	22.05	394	IV	1967	2014	48
20	Huazhoucheng	110.65	21.65	6151	IV	1956	2014	59
21	Liangdeshuiku	110.98	22.15	494	IV	1965	2014	50
22	Gaoyao	112.47	23.05	351535	I	1951	2014	64
23	Gulan	111.68	23.57	8273	I	1954	2007	54
24	Xiaoluo	111.67	23.25	76.2	I	1977	2014	38
25	Lingxia	114.57	23.25	20557	III	1953	2014	62
26	Boluo2	114.30	23.17	25325	III	1953	2014	62
27	Jianshan	115.63	23.67	1578	III	1958	2014	57
28	Shuikou2	115.90	23.98	6480	III	1953	2014	62
29	Tangjin	116.22	23.98	267	III	1959	2014	56
30	Hengshan2	116.35	24.47	12954	III	1954	2014	61
31	Xikou	116.65	24.53	9228	III	1959	2014	56
32	Baokeng	116.42	24.68	437	III	1958	2014	57
33	Lantang2	114.93	23.43	1080	III	1958	2014	57
34	Shuntian	114.77	24.12	1357	III	1966	2014	49
35	Heyuan	114.70	23.73	15750	III	1951	2014	64
36	Longchuan	115.25	24.12	7699	III	1952	2014	63
37	Lianping2	114.47	24.37	388	III	1971	2014	44
38	Xingfeng2	115.04	24.40	290	III	1972	2014	43
39	Jinshan	111.53	22.03	950	IV	1959	2014	56
40	Shigushuiku2	111.02	22.05	509	IV	1965	2013	49
41	Pomian_qudao	112.00	22.40	768	IV	1958	2014	57

42	Pomian3	111.83	22.38	768	IV	1954	2014	61
43	Shuangjie	111.80	21.95	4345	IV	1952	2014	63
44	Huangjingtang	112.42	24.58	595	II	1958	2014	57
45	Gaodao	113.17	24.17	7007	II	1954	2014	61
46	Shijiao	112.95	23.57	38363	II	1954	2014	61
47	Mawu2	113.16	23.85	34.7	II	1972	2014	43
48	Damiaoxia	113.50	23.83	472	II	1960	2014	55
49	Gaolang2	113.30	23.86	216	II	1972	2014	43
50	Chaoan	116.65	23.67	29077	III	1951	2014	64
51	Chikan	116.25	23.68	641	III	1967	2014	48
52	Fukou	115.77	23.40	355	III	1959	2014	56
53	Cijiao	116.02	23.05	820	III	1955	2014	60
54	Dongqiaoyuan	116.13	23.48	2016	III	1953	2014	62
55	Guanliang	111.67	22.83	3164	I	1958	2014	57
56	Yaogu	112.28	22.87	1776	I	1958	2014	57
57	Hejiang2	110.57	21.90	3000	IV	1958	2014	57
58	Daxiang2	112.15	23.97	671	II	1959	2005	47
59	Denghuangshan	112.38	24.83	1084	II	1959	2005	47
60	Machi	113.20	23.90	300	II	1959	2005	47
61	Zhuzhou	112.35	23.73	553	II	1959	2005	47
62	Qianjiang	108.97	23.63	128938	I	1951	2010	60
63	Dahuangjiangkou	110.20	23.57	288544	I	1951	2010	60
64	Wuzhou	111.30	23.48	327006	I	1951	2010	60
65	Jiangbian	103.62	24.00	25116	I	1951	2010	60
66	Panjiangqiao	105.38	25.88	14492	I	1951	2010	60
67	Zhexiang	106.20	24.92	82480	I	1951	2009	59
68	Yongwei	109.28	25.70	13045	I	1951	2010	60
69	Sancha	108.95	24.47	16280	I	1951	2010	60
70	Liuzhou	109.40	24.32	45413	I	1951	2010	60
71	Pingle	110.67	24.60	12159	I	1951	2010	60
72	Baise	106.63	23.90	21720	I	1951	2010	60
73	Xinhe	107.20	22.45	5791	I	1951	2010	60
74	Nanning	108.23	22.83	72656	I	1951	2010	60
75	Guigang	109.62	23.08	86333	I	1951	2010	60
76	Jinji	110.83	23.22	9103	I	1951	2010	60
77	Changba	113.68	24.87	6794	II	1951	2010	60
78	Changle	109.42	21.83	6645	I	1951	2010	60