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Variation of Floods Characteristics and Their Responses to Climate and Human Activities in Poyang Lake, China

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Abstract: The Poyang Lake is one of the most frequently flooded areas in China. Understanding the changing characteristics of floods as well as the affecting factors is an important prerequisite of flood disaster prevention and mitigation. The present study identified the characteristics variations of historical floods in the Poyang Lake and their tendencies based on the Mann-Kendall (M-K) test, and also investigated the related affecting factors, both from climate and human activities. The results revealed that the highest flood stages, duration as well as hazard coefficient of floods showed a long-term increasing linear trend during the last 60 years with the M-K statistic of 1.49, 1.60 and 1.50, respectively. And, a slightly increasing linear trend in the timing of the highest stages indicated the floods occurred later and later during the last six decades. The rainfall during the flood season and subsequent discharges of the Changjiang (Yangtze) River and runoff from the Poyang Lake Basin were mainly responsible for the severe flood situation in the Poyang Lake in the 1990s. In addition, the intensive human activities, including land reclamation and levee construction, also played a supplementary role in increasing severity of major floods. While, the fewer floods in the Poyang Lake after 2000 can be attributed to not only the less rainfall over the Poyang Lake Basin and low discharges of the Changjiang River during flood periods, but also the stronger influences of human activity which increased the floodwater storage of the Poyang Lake than before.

Keywords: flood characteristics; water level; land reclamation; Changjiang River; Poyang Lake

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1 Introduction

Among global losses caused by natural disasters, floods accounted for 40%, tropical cyclones accounted for 20%, droughts accounted for 15%, earthquakes accounted for 15%, and all other factors accounted for 10% (Zhang and Li, 2007; Nie *et al*., 2012). Floods are the most significant cause of loss from natural hazard events, moreover, in the last few decades, the frequency and consequences of extreme flood events have increased rapidly worldwide (Bouwer *et al*., 2007; Kron, 2009). Statistics indicate that about 1.96×10^8 persons in more than 90 countries were found to be exposed on average every year to catastrophic flooding (UNDP, 2004). Especially, 2011 was a record-breaking year with the occurrence of more than 100 disastrous floods worldwide, including Australia, Brazil, Colombia, the United States, Pakistan, Cambodia, Vietnam, Thailand, Philippines, and so on (Zevenbergen *et al*., 2013). The global floods cost has reached a total of 4.7×10^{11} dollars since 1980 (HSBC, 2011). In China, floods are also the most frequently occurred natural disaster, almost every year, China is affected by severe flooding, which causes considerable economic loss and serious damage

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to towns and farms (Nakayama and Watanabe, 2008; Yu *et al.*, 2009). The National Climate Center reported an average annual economic loss of about 1.70×10^{10} dollars since 1990, and especially the severe floods in the Changjiang (Yangtze) River and Nenjiang-Songhua Rivers valleys during the summer of 1998 caused about 3.60×10^{10} dollars of economic losses and more than 3000 deaths (Nie *et al.*, 2012).

The Poyang Lake, the largest freshwater lake in China, is one of the most frequently flooded areas in China (Qi *et al.*, 2009; Cai, 2010). Statistics indicate that from 1950 to 2010 there were 17 years during which the Poyang Lake stage exceeded the level of 20.0 m (above a.s.l.), which can be considered to major flood events, and there were six years during which the lake had severe floods. The frequent large floods in the Poyang Lake caused huge damage to the environment and the agricultural economy and threatened the life of approximately 1.0×10^7 persons in the region. For example, only a big flood event in 1998 resulted in economic losses of more than 5.0×10^9 dollars in the Poyang Lake region (Chen *et al.*, 2002). Moreover, it has recently been shown that the frequency and severity of the floods in the Poyang Lake have increased since 1990 (Guo *et al.*, 2008), owing to the southward shift of major warm season rain bands to the south of the Changjiang River Basin and increased fluctuation of warm season rainfall in the Poyang Lake Basin (Hu *et al.*, 2007).

Recognizing the changing characteristics of floods as well as the affecting factors is indispensable to real-time flood hazard prediction systems (Bates and Anderson, 1996; Hong *et al.*, 2010), and this has become an important prerequisite of flood disaster prevention and mitigation (Nie *et al.*, 2012). Usually, the severe floods in the Changjiang River Basin are resulted from abnormally high rainfall events (Nakayama and Shankman, 2013), i.e., during June–September 1998 and 1954 areal averaged precipitation totals were significantly above the usual level and the most excessive rainfall occurred during June–July, when areal averaged totals exceeded 300 mm and 220 mm of the normal value, respectively (Nakayama and Watanabe, 2008). Also in the Poyang Lake Basin, the highest rainfall amount was observed during June–July with the total rainfall of 1100 mm and 950 mm, respectively, in 1998 and 1954. On the other hand, landscape changes due to human activity were the main causes of an increasing severity of major floods (Yin and Li, 2001; Piao *et al.*, 2003; Zhao and Fang, 2004; Zhao *et al.*, 2005), such as land reclamation and levee construction around the Poyang Lake, lake sedimentation, sand-digging, and so on. In addition, higher Changjiang River stage is also an important factor, which will block outflow from the Poyang Lake and in some cases cause backflow from the Changjiang River to the Poyang Lake, increasing its water level and flood occurrence (Yin *et al.*, 2007; Wang *et al.*, 2008; Nakayama and Shankman, 2013). More important, the construction and operation of the Three Gorges Dam (TGD) in the upstream of the Changjiang River, which further modulates the water flow to and from the lake, have significantly increased the complexity (Hu *et al.*, 2007).

Numerous researchers have so far investigated the changing characteristic of floods as well as the affecting factors in the middle reaches of the Changjiang River. For example, Huang *et al.* (1998) studied the features of the catastrophic flood in the Changjiang River Basin during the summer of 1998 and analyzed the main causes. Yu *et al.* (2009) also examined the characteristics of historical floods and associated monsoon precipitation in the Changjiang River Basin and found that the intensifying anthropogenic activity in the last century were the key causes for recently human-induced floods. Nakayama and Shankman (2013) investigated the effects of TGD and water transfer project on the Changjiang River floods, also the roles of flood storage ability of lakes in the Changjiang River Basin (Nakayama and Watanabe, 2008). Shankman *et al.* (2006) analyzed the flood frequency in the Poyang Lake region and found that the most severe floods occurred during or immediately following El Niño events. However, the occurrence of severe floods in the Poyang Lake region and the triggering caused in different periods are still unclear. Due to the importance of understanding the change of the flood characteristics in the basin, from the management perspective to make sound decisions and policies (Wang *et al.*, 2012), it is necessary to strengthen the available research regarding the temporal changes in flood events and their affecting factors (Nie *et al.*, 2012).

Therefore, the objectives of the study are designed to 1) identify and examine the characteristics of historical floods in the Poyang Lake and analyze their tendencies, including the occurrence date, frequency, flood stage, duration, hazard degree, *etc.*, in the last six decades; and

2) investigate the related driving forces, both climate and human activities, and discuss their relationships with the Poyang Lake floods in different periods.

2 Study Area and Data

The Poyang Lake is located in the middle and lower reaches of the Changjiang River, China (28°22'–29°45'N, 115°47'–116°45'E), which receives water flows primarily from the five rivers: Xiushui River, Ganjiang River, Fuhe River, Xinjiang River, and Raohe River and discharges into the Changjiang River through a channel in its northern part (Fig. 1). The Poyang Lake has an average water depth of 8.4 m and a storage capacity of 2.76×10^{10} m^3 when the water level at Hukou is 21.71 m (http://www.poyanglake.net/pyhgk.htm). The length (from south to north) of the lake is about 173 km and its maximum width (from west to east) is 74 km. The Poyang Lake region has a subtropical wet climate characterized with a mean annual precipitation of 1680 mm for the period of 1960–2007 and mean annual temperature of 17.5℃. Annual precipitation shows a wet season

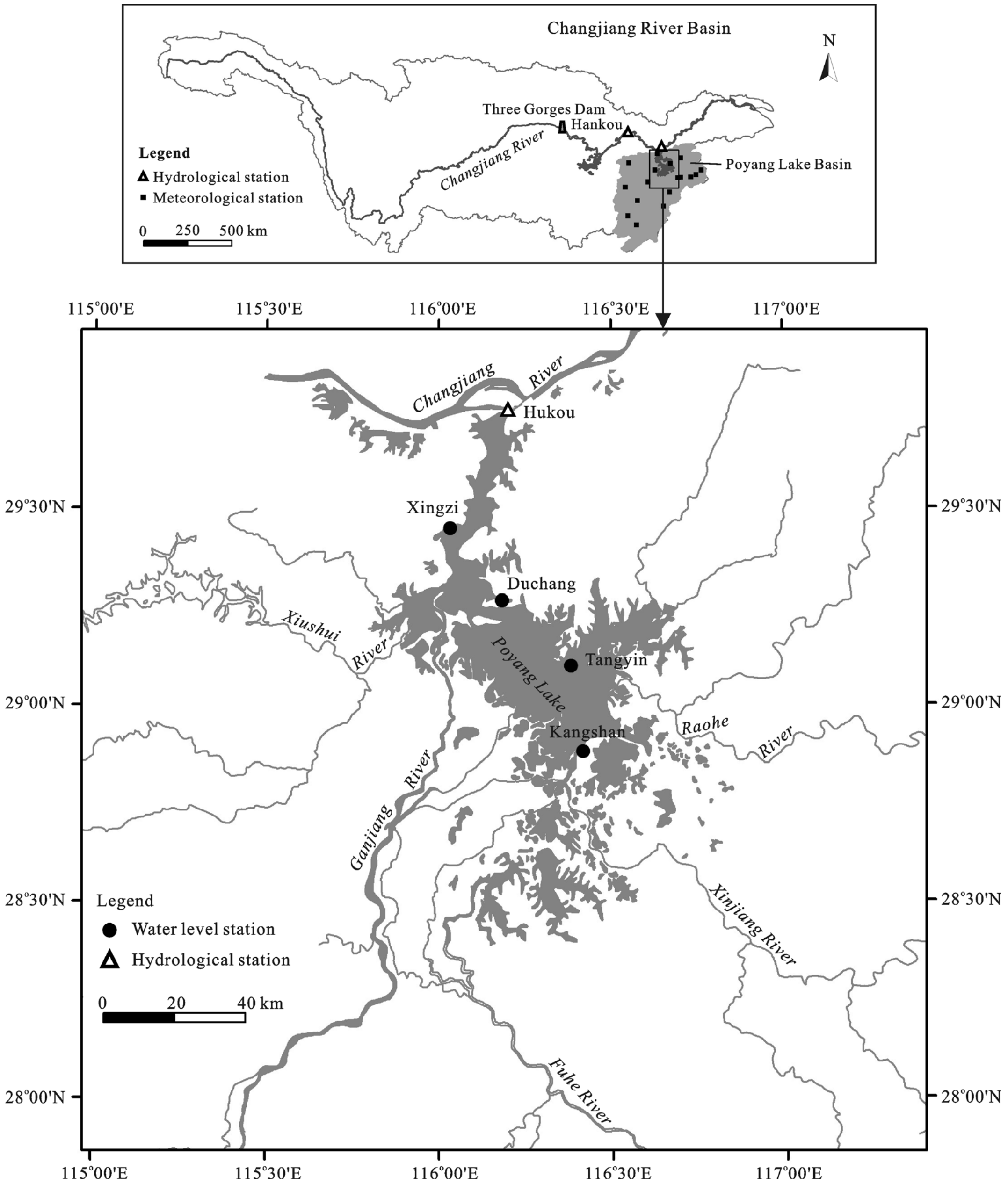

Fig. 1 Location of study area and distribution of stations

and a dry season and a short transition period in between. Precipitation increases quickly from January to June and decreases sharply in July, and after September, the dry season sets in and lasts through December (Li *et al.*, 2012).

Generally, the lake water level is jointly influenced by the runoff inflow from the Poyang Lake Basin and the discharges of the Changjiang River. In response to the annual cycle of precipitation, discharges from the Poyang Lake Basin have an annual course shown by the solid line in Fig. 2a, with large runoff inflow starting in February and climaxing from April to mid-July. From mid-July onward the runoff decreases quickly (Hu *et al.*, 2007). This hydrograph of the Poyang Lake Basin explains the primary features of the first half in the annual variation of the water level of the Poyang Lake, while the second half of the annual course of lake level is mainly controlled by the discharges of the Changjiang River. The Changjiang River effect dominates the lake level from June and peaks in July and persists through October (Hu *et al.*, 2007; Guo *et al.*, 2012). Additionally, the lake water surface has relatively large gradients in dry seasons, i.e., the water level at the south of lake is as much as 5–6 m higher than that at the north, while in wet seasons, the differences of water level at different stations are small and the lake surface almost is horizontal (Fig. 2b).

Daily water level of the Poyang Lake was measured at Hukou during 1950–2010, which were used to identify the characteristics of historical floods of the Poyang Lake, such as the flood stage, occurrence date, duration, *etc*. In addition to the daily rainfall data, which are obtained from National Meteorological Information Center of China for 14 stations in the Poyang Lake Basin during the period of 1953–2010, the observed daily stream flows from five rivers are also collected. These data have been widely used for different studies previously (Li *et al.*, 2012; 2013; 2014) and the qualities of the data are quite reliable, which were used in the study to measure the variation of precipitation in the basin and the inflows from basin to the Poyang Lake. Additionally, the water fluxes measured at Hankou station are collected to describe the flow variations of the Changjiang River and examine its effect on the water level of the Poyang Lake. Moreover, other data including the land reclamation around the Poyang Lake, lake volume, sand-digging in the lake, and sediment discharges into the lake are also collected from statistical bureau of local government or literatures (Shankman and Liang, 2003; Shankman *et al.*, 2006; Min *et al.*, 2011) to investigate the effects on severity of flood.

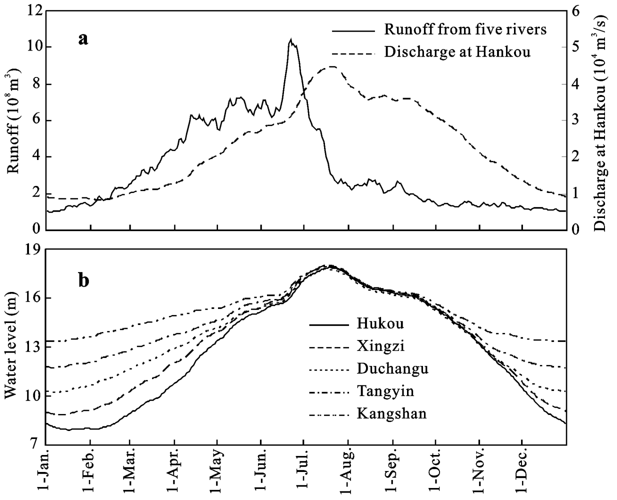

Fig. 2 Variation of average runoff from five rivers and Changjiang River discharge at Hankou (a) and water level at different stations in Poyang Lake (b) during 1960–2010

3 Methods

To conveniently describe and reflect the frequency and severity of floods, the flood event can be defined in the study as the Poyang Lake stage at Hukou station exceeding the level of 19.0 m, which is also the warning stage. Accordingly, the lake stages exceeding the level of 20.0 m is considered to a major flood event and 21.0 m is classified to a severe flood event. Several widely used indices, including the flood stage, frequency, occurrence date, duration, hazard degree as well as distribution curve of average annual exceedance days are calculated. In particular, the hazard degree is an integrated coefficient to describe the severity of flood in terms of flood stage and duration (Min, 1996). The values of hazard degree are calculated as the followings (Min, 1996; Guo *et al.*, 2011):

$$\delta = a\delta_H + b\delta_N \tag{1}$$

$$\delta_H = \frac{H_i - H_{\min}}{H_{\max} - H_{\min}} \tag{2}$$

$$\delta_N = \sum_{i=1}^{3} C_i \delta_{N_i} \tag{3}$$

$$\delta_{N_i} = \frac{N_i - N_{\min}}{N_{\max} - N_{\min}} \tag{4}$$

where δ is hazard degree of flood; δ_H and δ_N are hazards resulting from high flood stage and duration respectively, *a* and *b* are their weighting coefficients and set the values of 0.6 and 0.4 respectively according to the studies by Guo *et al*. (2011) and Min (1996); H_i is annual maximal water level; $H_{\max}$ and $H_{\min}$ are maximal and minimal flood stage, respectively; N_i are the *i*th duration corresponding to the lake stages exceeding the level of 19.0 m, 20.0 m, and 21.0 m (i = 1, 2, and 3), and $N_{\max}$ and $N_{\min}$ are maximal and minimal duration for different lake stages respectively; δ_{N_i} are hazards resulting from the *i*th duration when the lake stages exceed the level of 19.0 m, 20.0 m, and 21.0 m (i = 1, 2, and 3); C_i are their weighting coefficients and set the values of 0.15, 0.30, and 0.55, respectively.

In addition, the Mann-Kendall test (M-K test) (Mann, 1945; Kendall, 1975) was applied in this study to analyze the temporal variation of flood characteristics. The M-K test is a rank-based non-parametric method, due to its robustness against the influence of abnormal data and especially its reliability for biased variables, it has been widely used to detect the trend of hydro-climatic data (Xu *et al*., 2004; Chen *et al*., 2007; Novotny and Stefan, 2007; Zhao *et al*., 2010; Ye *et al*., 2013).

To detect the existence of any step change points in the hydrological data $X_t = (x_1, x_2, x_3, \cdots, x_n)$, the accumulative number n_i of samples that $x_i > x_j$ $(1 \le j \le i)$ should be first calculated (Ye *et al*., 2013). The normally distributed statistic d_k can be calculated as follows:

$$d_k = \sum_{i=1}^{k} n_i \quad (2 \le k \le n) \tag{5}$$

Under the null hypothesis of no trend, d_k is asymptotically normal and independently from distribution with expected mean value $E(d_k)$ and the variance $Var(d_k)$ as follows:

$$E(d_k) = \frac{k(k-1)}{4} \tag{6}$$

$$Var(d_k) = \frac{k(k-1)(2k+5)}{72} \tag{7}$$

Under the above assumption, the normalized variable statistic $UF(d_k)$ is calculated as:

$$UF(d_k) = \frac{d_k - E(d_k)}{\sqrt{Var(d_k)}} \quad (k = 1,\ 2,\ 3, \cdots,\ n) \tag{8}$$

where $UF(d_k)$ is the forward sequence, and the backward sequence $UB(d_k)$ is calculated by using the same equation but with a reversed series of data. When the null hypothesis is rejected (i.e., if any of the points in the forward sequence are outside the confidence interval), the detection of an increasing ($UF(d_k) > 0$) or a decreasing ($UF(d_k) < 0$) trend is indicated. The sequential version of the test used here enables detection of the approximate time of occurrence of the trend by locating the intersection of the forward and backward curves of the test statistic. An intersection point within the confidence interval indicates the beginning of a step change point (Moraes *et al*., 1998; Zhang *et al*., 2011).

4 Results and Discussion

4.1 Variation of flood characteristics in Poyang Lake

The frequency distribution of annual highest water level at the Poyang Lake during 1950–2010 is shown in Fig. 3. It was found that the empirical frequency was fitted by the curve of Pearson type III distribution with an average of 18.97 m, a coefficient of variation (C_v) of 0.085 and skewness (C_s) of 0.153, and the lake stages are 22.90 m, 22.41 m, 21.69 m, 21.06 m, 20.31 m and 18.93 m for the floods with a probability of occurrence of 1.0%, 2.0%, 5.0%, 10.0%, 20.0%, and 50.0% (correspond to the return periods of 100 years, 50 years, 20 years, 10 years, 5 years, and 2 years), respectively. The highest recorded lake stage was 22.53 m in 1998, which is close to that of 100 years return period flood.

The variation of annual highest stages and the timing of highest stages series in the Poyang Lake and their corresponding M-K sequential test during 1950–2010 at Hukou station are shown in Figs. 4 and 5 respectively. As explained in the Methods Section, the UF curve shows the changing trend of annual highest stages and the timing of highest stages. The time series has a downward trend if UF < 0 and an increasing trend if UF > 0. If the UF values are higher than the critical values (the two dashed lines above and below zero), then this upward or downward trend is significant at 95% significance level (Xu *et al*., 2004; Chen *et al*., 2007; Ye *et al*., 2013). When the UF and UB curves intersect at a certain time, the intersection point denotes the change point (Zhang *et al*., 2005; Zhao *et al*., 2010). As shown in Fig. 4a, the highest stages show a long-term increasing trend with the M-K statistic of 1.49 (Table 1). The

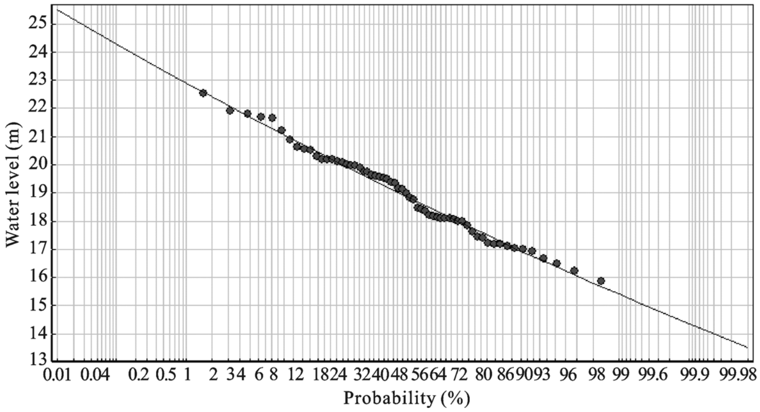

Fig. 3 Scatter plot of annual maximal water level at Hukou station against their empirical frequency during 1950–2010 and curve of Pearson Type III distribution

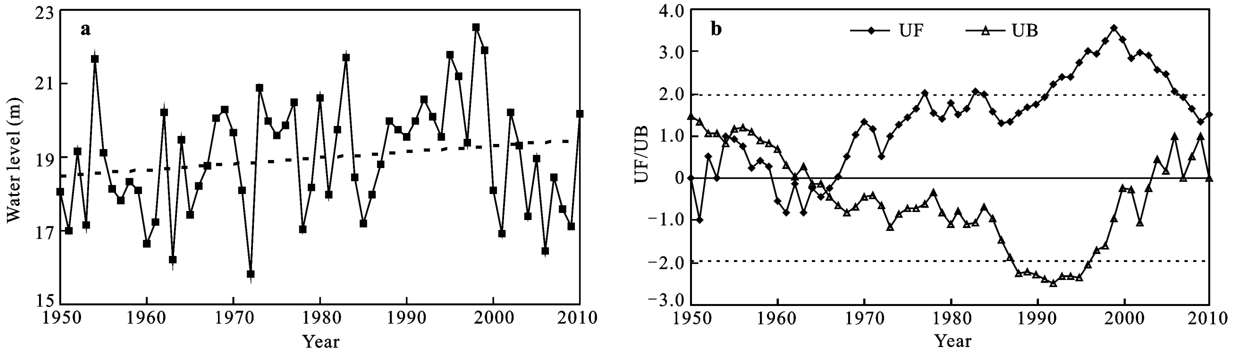

Fig. 4 Variation of flood stages (a) and corresponding M-K trend test (b). Long dashed line in left figure means linear trend for this period, and horizontal dashed lines in right figure represent critical value of 0.05 significance level

higher flood stages observed in 1995, 1998 and 1999 than that in 1954 indicated that the flood situations in 1990s were worse than before. Figure 4b shows that an abrupt change of the highest stages occurred in 1965, and after that the annual highest stages increased continuously. Especially, the increasing trend was significant in 1990s at the significance level (α = 0.05) as the values of UF are above the critical values.

The timing of highest stages is the day from the beginning of the year when lake flood reaches the maximal level. It is found from Fig. 5a that the timing of highest stages also show a long-term increase linear trend with the M-K statistic of 1.56 (Table 1), which indicates that the floods have occurred later and later in the study period. At the same time, a feeble increasing and decreasing trends were found in different periods with UF fluctuation between the two critical value lines as shown in Fig. 5b.

Table 1 Results of M-K test for four variables of flood characteristics

	Max flood stages	Timing of max flood stages	Duration (> 19.0 m)	Hazard coefficient
M-K statistic	1.49	1.56	1.60	1.50

The duration is another critical component of floods to depict the flood hazards. Generally, the longer duration means the more severe flood damages. Figure 6 shows the duration of different severity flood events in the Poyang Lake during the last 60 years. It is found that the flood duration have increasing trend from 1950 regardless of above 19.0 m or above 20.0 m (the M-K statistic was 1.60 for above 19.0 m). The severe floods (lake water level > 21.0 m) were mainly observed during the late of 1990s, i.e., in the large flood of 1998, and there were 23 consecutive days that the lake stage exceeded the highest level recorded in 1995, and the duration of 21.0 m also was longer than that during 1954 flood.

Subsequently, the variation analysis of hazard coefficient of the Poyang Lake flood had also been performed, which can fully depict the characteristic of flood including the peak stages and duration. Figure 7 shows the

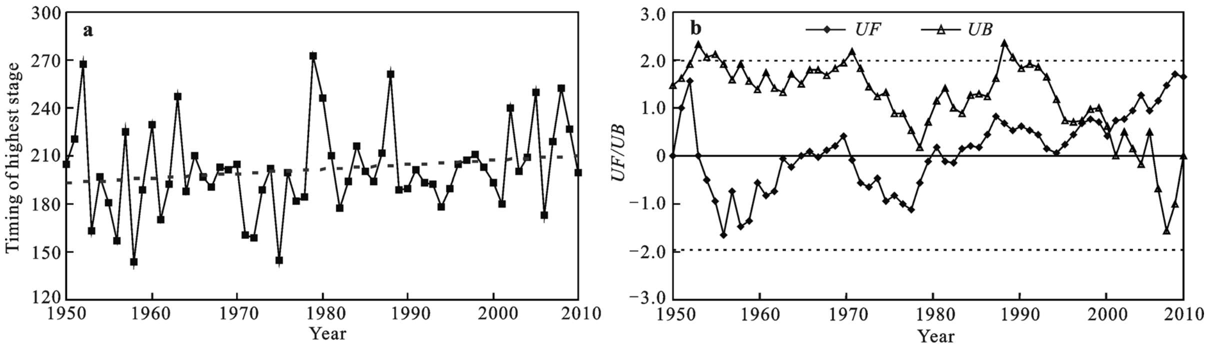

Fig. 5 Variation of timing of highest stages (a) and corresponding M-K trend test (b). Long dashed line in left figure means linear trend for this period, and horizontal dashed lines in right figure represent critical value of 0.05 significance level

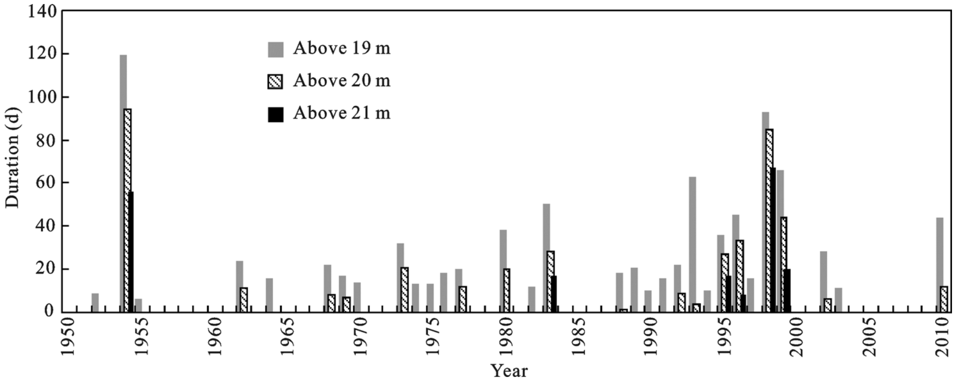

Fig. 6 Duration of different severity floods in Poyang Lake during last 60 years

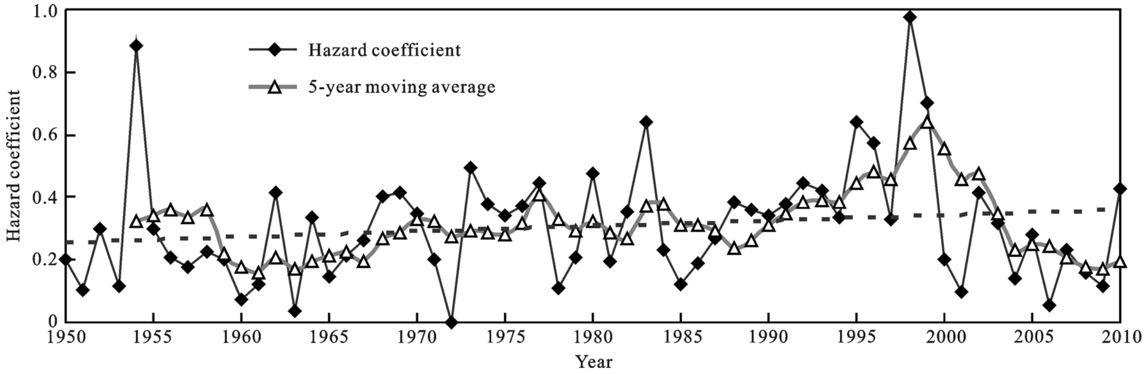

Fig. 7 Variation of hazard coefficient and 5-year moving average during 1950–2010. Long dashed line means linear trend of hazard coefficient for this period

variation of annual hazard coefficient and the 5-year moving average during the last 60 years. It is found that the hazard coefficients have an increasing trend in the whole period with the M-K statistic of 1.50 (Table 1), although the peak value occurred in 1998 and after that a decreasing trend was presented. The 5-year moving average, which was calculated for the hazard coefficient to depict its changing trend after smoothing noise, displayed a clear increasing trend before 1999 while a decreasing trend after 2000 due to the remarkable decline of peak stages and flood duration after 2000.

4.2 Effects of hydro-climate changes on characteristics of flood

As already noted in previous researches (Guo *et al*., 2008), the water level of the Poyang Lake was dominated mostly by the discharges of the Changjiang River during flood periods. The discharges anomaly of the Changjiang River at Hankou station during July–September was selected and calculated (Fig. 8). It is found that the average discharges during flood periods varied greatly and displayed a slight increasing trend with alternate positive and negative discharge anomaly before

1999, and after that the anomaly was mainly negative. As shown in Fig. 8, the 5-year moving average displayed more clearly that the years of major floods occurred, i.e., 1968, 1969, 1983, 1995, 1996, 1998, 1999, were also the periods with large positive anomaly of discharges. Accordingly, the relatively high values of R^2 (from 0.75 to 0.90) (Fig. 9) demonstrated that the large discharges of the Changjiang River in flood season may increase the lake water level and then block outflow from the Poyang Lake. The high discharges was usually ascribed to abnormally high rainfall events, i.e., during June–September 1998 areal averaged rainfall totals were significantly above the usual level and the most excessive rainfall occurred during June–July, when areal averaged totals exceed 300 mm of the normal value (Nakayama and Watanabe, 2008), and the large discharges resulted in the water level reached as high as 22.53 m at Hukou station. At the same time, the serious channel aggradation and reduction in channel capacity of the Changjiang River in the 1990s, which have been validated for the channel reach near the Poyang Lake (Yang *et al*., 2006; Shankman *et al*., 2009), further raised the water level of the Poyang Lake and increased the severity of floods.

On the other hand, the water level of the Poyang Lake also depended on the runoff inflow from the basin in flood season. Usually, the Poyang Lake Basin has its peak precipitation season in April–June and a sharp decrease in precipitation during the period of July–September, so the runoff increased quickly from April and reached its peak in June and then decreased sharply in July. However, when a large runoff from the basin generated later than normal in summer while the level of the Changjiang River was also high, a severe flood in the Poyang Lake may occur (Shankman *et al*., 2006). Figure 10 shows the variation of average rainfall and runoff anomaly of the Poyang Lake Basin during flood season (June–September). It is found that the average runoff varied greatly and the positive anomaly was mainly observed during 1970–1976 and the 1990s, while negative anomaly dominates in other periods. These inter-annual variations of the runoff were mainly attributed to the climate variability (Fig. 10a). For example, the flood occurred in 1999, when the rainfall amount

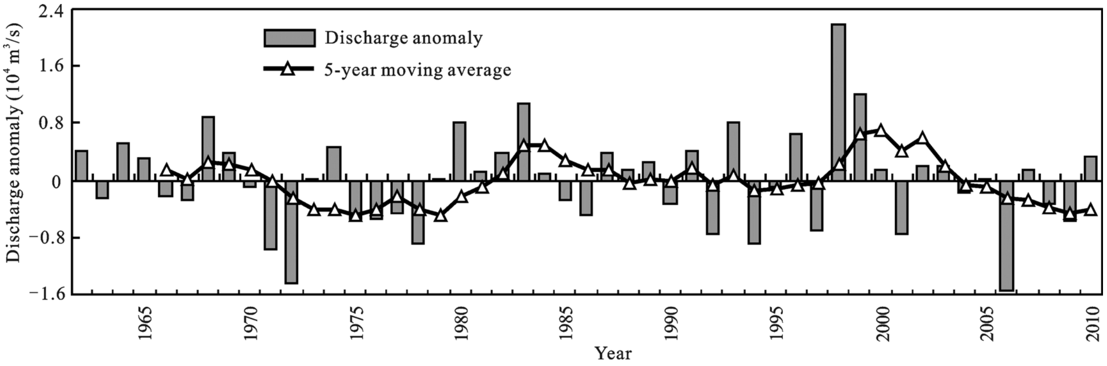

Fig. 8 Variation of discharges anomaly of Changjiang River at Hankou station in July–September during last 50 years

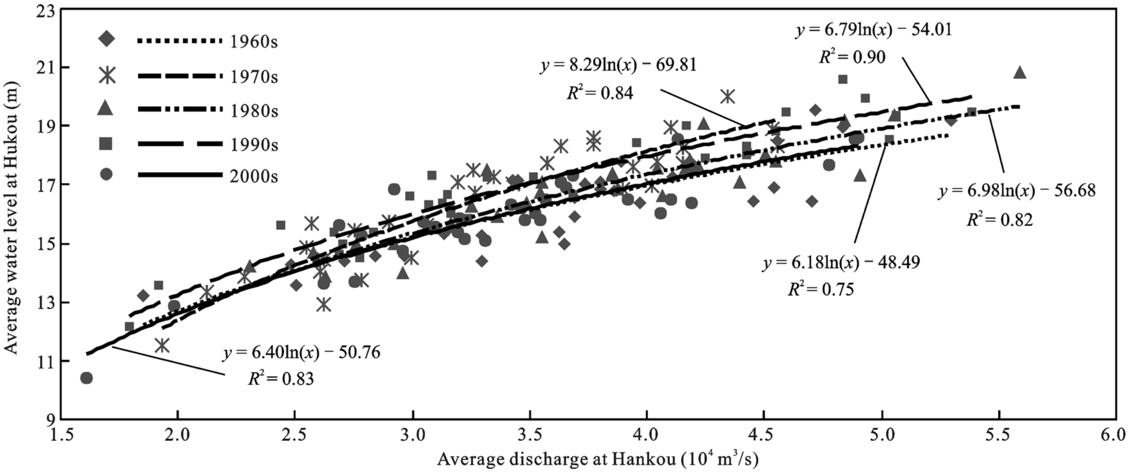

Fig. 9 Relationship of discharges at Hankou and water level at Hukou during July–September in different decades

and the average discharges into the lake during July–August were observed as much as 650 mm and 7200 m^3/s, which far more than the normal level in the period. Therefore, the large discharges of the Changjiang River with the high water level encountered the larger runoff inflow from the basin than normal during flood periods was a significant reason for triggering the severe floods in the Poyang Lake, i.e., 1954, 1973, 1980, 1983, 1995, 1998 and 1999.

While in the 2000s, it is found that the rainfall over the middle reaches of the Changjiang River (also including the Poyang Lake Basin) decreased markedly since 2000 (Fig. 10). The negative anomalies of summer rainfall resulted in lower river flow of the Changjiang River and runoff from the basin (Fig. 8 and Fig. 10). Therefore, a weakened blocking effect of the Changjiang River further promoted the outflows from the lake to the river (Hu *et al*., 2007; Liu *et al*., 2013), which was a principal cause for the fewer floods in the Poyang Lake after 2000.

4.3 Effects of human activities on characteristics of flood

The effects of landscape changes due to human activity on development of floods in the Poyang Lake were also inneglectable, which were the main causes of an increasing severity of major floods (Yin and Li, 2001; Piao *et al*., 2003; Zhao and Fang, 2004; Zhao *et al*., 2005). Statistics indicated that the Poyang Lake shrank significantly in the area from 5160 km^2 in the 1950s to 3860 km^2 in the late 1990s with a 25.2% decrease during 44 years and decreased in volume from 3.70×10^{10} m^3 to 2.89×10^{10} m^3 with a 21.9% decrease during the same period (Shankman *et al*., 2006) as shown in Fig. 11a. Shankman and Liang (2003) identified land reclamation and levee construction as the major factors responsible for the decrease in the area and volume of the Poyang Lake. As shown in Fig. 11a, the land reclamation in the Poyang Lake was moderate in the 1950s (no more than 2800 km^2), but become more ubiquitous since the 1960s in order to increase the food supplies and reached its peak in the late 1990s, with as much as 3900 km^2.

Moreover, large amount of sediment discharges from the five rivers to the lake during the 1960s–1980s as well as the 1990s (Fig. 11b) due to the deforestation to farm and other human activities in the basin, distinctly enhanced the sediment deposition in the Poyang Lake. Min (1999) estimated that the sediment deposition reduced the total volume of the Poyang Lake by 4.8% during 1954–1997. Therefore, the land reclamation, levee construction and sediment deposition jointly reduced

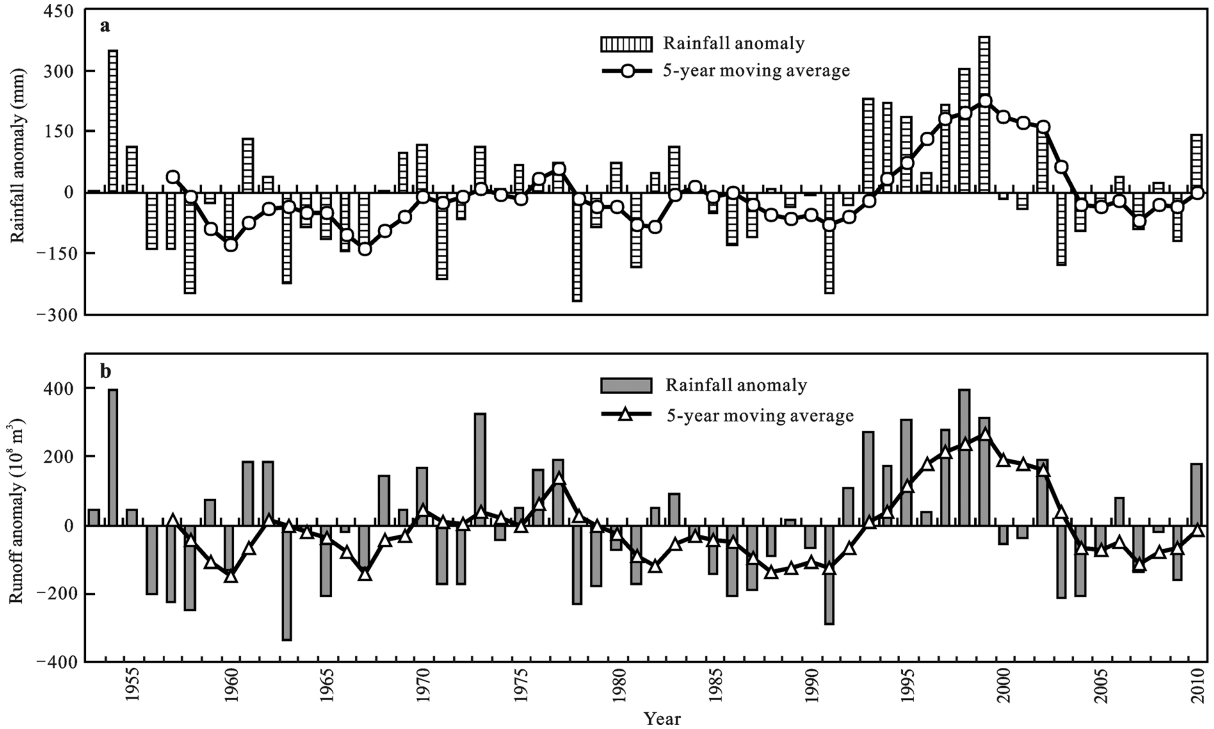

Fig. 10 Anomalies of rainfall over Poyang Lake Basin (a) and runoff from five rivers (b) during June–September

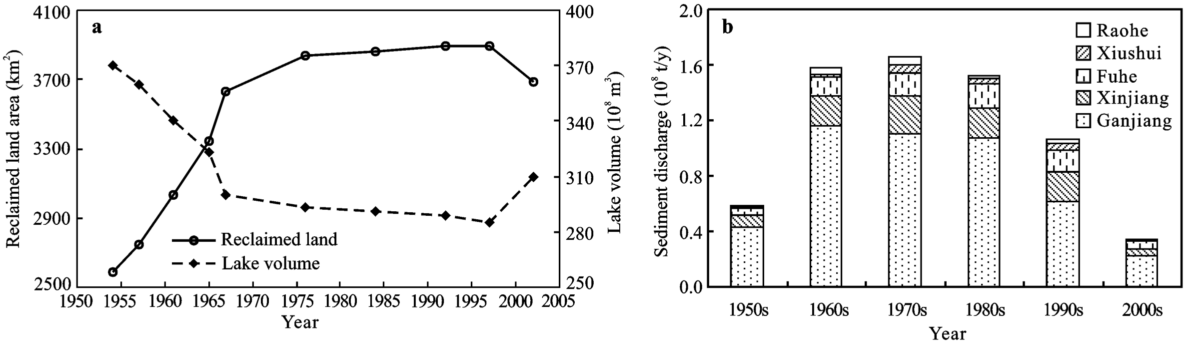

Fig. 11 Variation of reclamation land area and lake volume in Poyang Lake (a) (supplement based on Shankman *et al*., 2006) and sediment discharges from five rivers (b)

the storage capacity of the Poyang Lake to its lowest volume in the 1990s. Due to the runoff from basin dominated the variation of lake level during the first half of year (Hu *et al*., 2007; Guo *et al*., 2012), the relationship of total runoff inflow from five rivers against lake water level at Xingzi during January–April in different decades was analyzed. It is found that the water level was higher in the 1990s than in other periods with the same runoff inflow (Fig. 12).

After 1998, the governments adopted a new flood management policy namely 'return land to lake' to increase the floodwater storage of the Poyang Lake (Min, 2004; Peng *et al*., 2005; Nakayama and Shankman, 2013). Through efforts of several years, both the lake area and volume increased larger than that during the late 1990s (Dai *et al*., 2005; Shankman *et al*., 2009) as shown in Fig. 10a. Also, Fig. 11b indicated that the sediment loads into the lake were observed the lowest in the 2000s due to the tree planting and reservoirs blocking in the middle and upstream of the five rivers. At the same time, an intensive sand mining has been displaced to the Poyang Lake from the Changjiang River when a sand mining ban was imposed in the Changjiang River in 2000 (Wu *et al*., 2007), which further increased the volume of the Poyang Lake. According to the estimation of Leeuw *et al*. (2010), sand mining resulted in a weight sand of 4.5 × 10^8 t/yr exported from the Poyang Lake since 2000, which is equivalent to a lake volume increase of 2.4 × 10^8 m^3, and has changed the lake from a net sediment accumulating system into a sediment exporting system. These human activities after 2000 jointly resulted in a higher floodwater storage of the Poyang Lake than before (Fig. 12). More importantly, the construction of the TGD in the middle reaches of the Changjiang River commenced in 1997 and testing operations began in 2003 has also played an important role in flood protection of the Poyang Lake (Nakayama and Shankman, 2013), i.e., the TGD decreased the discharges of the Changjiang River from about 7 × 10^4 m^3/s to 4 × 10^4 m^3/s with a 40% decrease during the flood periods of 2010 and mitigated the pressure of flood control in the Poyang Lake (http://www.cjw.

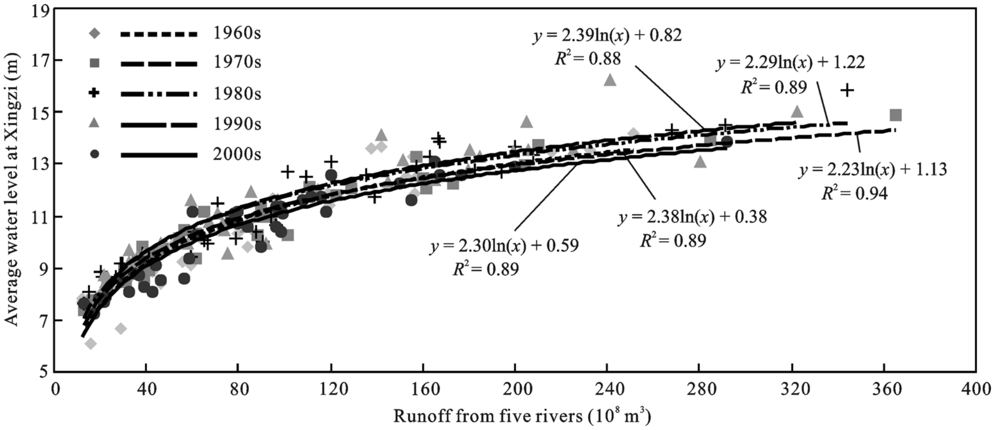

Fig. 12 Relationship of total runoff inflow from five rivers and average water level at Xingzi during January–April in different decades

com.cn/). Therefore, the intensive human activities after 2000 were another important reason for fewer floods in the Poyang Lake in the 2000s.

5 Summary and Conclusions

This study identified and examined the characteristics of historical floods of the Poyang Lake and analyzed their tendencies, including the max flood stage, timing of peak flood stages, duration, frequency and hazard degree in the last six decades. The study also investigated the related driving forces, both climate and human activities, and discussed their relationships with the floods of the Poyang Lake in different periods. The results show that the highest flood stages, duration as well as hazard coefficient of floods show the long-term increasing linear trend during the last 60 years. And the slightly increasing linear trend in the timing of the highest stages indicates that the Poyang Lake floods occurred later and later during the last six decades. The large discharges of the Changjiang River, the serious channel aggradation and the large runoff from the basin in summer jointly result in the severe floods in the Poyang Lake in the 1990s. At the same time, the effects of land reclamation and levee construction as well as sediment deposition in the Poyang Lake are also inneglectable, which reduces the storage capacity of the Poyang Lake to the lowest in the 1990s and further increases the severity of floods in the period. While, the fewer floods in the Poyang Lake after 2000 attributes to not only the low streamflows and water level of the Changjiang River, the less rainfall over the Poyang Lake basin during flood periods, but also the stronger influences of human activity increasing the floodwater storage of the Poyang Lake than before.

In addition, it should be pointed out that the influences of climate change and human activities on the occurrence, development and severity of floods in the Poyang Lake were analyzed and discussed based on the qualitative analysis method in this study. However, the Poyang Lake is a dynamic system with huge water level and area changes, and the qualitative analysis is insufficient to understand their relationships with the runoff and water level in the Poyang Lake. The quantitative analysis has its inherent advantages in depicting the processes and mechanism of influences than the qualitative analysis, therefore, it is necessary in the next studies to adopt the quantitative analysis methods to determine accurately the relative contribution of climate change and human activities to the floods of the Poyang Lake.

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