Nat Hazards (2015) 76:651–666
DOI 10.1007/s11069-014-1509-5

ORIGINAL PAPER

The changing patterns of floods in Poyang Lake, China: characteristics and explanations

Xianghu Li · Qi Zhang · Chong-Yu Xu · Xuchun Ye

Received: 26 September 2013 / Accepted: 4 November 2014 / Published online: 9 November 2014

Abstract Poyang Lake, directly connected with the Yangtze River, is one of the most frequently flooded areas in China. The frequent large floods have caused huge damages to the environment and economy and threatened the life of approximately 10 million people. Understanding the changing characteristics of floods as well as the affecting factors is an important prerequisite of flood disaster prevention and mitigation. In this study, the characteristics of historical floods in Poyang Lake were identified and examined based on several widely used indices and Mann–Kendall test. The study also analyzed the related driving forces and discussed their relationships with Poyang Lake floods. The results show that the floods in Poyang Lake mainly occurred in mid- and late July. The inter-annual variation of highest flood stages and duration showed a long-term increasing linear trend. Also, a slightly increasing linear trend in the timing of highest stages indicated the floods have occurred later and later during the last 60 years. At the decadal scale, the flood situations were most severe in 1990s while gentle in 2000s in terms of the occurrence frequency and average duration. The climate change was the primary influence factor for

X. Li · Q. Zhang (✉)
Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, People's Republic of China
e-mail: qzhang@niglas.ac.cn

Q. Zhang
Key Laboratory of Poyang Lake Wetland and Watershed Research, Ministry of Education, Jiangxi Normal University, Nanchang 330022, People's Republic of China

C.-Y. Xu
Department of Hydrology and Water Resources, Wuhan University, Wuhan 430072, People's Republic of China

C.-Y. Xu
Department of Geosciences, University of Oslo, Oslo, Norway

X. Ye
School of Geographical Sciences, Southwest University, Chongqing 400715, People's Republic of China

changing of flood characteristics in Poyang Lake; i.e., the abnormally large rainfall during the flood season and subsequent large discharges of Yangtze River and runoff inflow from the basin were mainly responsible for the severe floods in 1990s. Also, the smallest storage capacity of Poyang Lake in 1990s due to the intensive human activities such as the great floodplain occupancy and levee construction further increased the severity of floods. While the rare floods in 2000s can be attributed to, on the one hand, the decrease in rainfall over the middle reaches of Yangtze River which caused the low streamflows of Yangtze River and runoff inflow from the Poyang Lake basin. On the other hand, the "return land to lake" policy, intensive sand mining in the lake and the flood control of Three Gorges Dam also played an important role in mitigation of flood frequency and severity.

Keywords Flood · Poyang Lake · Stages · Yangtze River · Runoff · Land reclamation

1 Introduction

Floods are one of the most common natural disasters worldwide, with severe economic losses (accounted for 40 % of global losses caused by natural disasters) and serious damage to towns and farms (Nakayama and Watanabe 2008; Garcia-Castellanos et al. 2009; Zhang and Li 2007; Nie et al. 2012). The global floods cost has reached a total of $470 billion since 1980 (HSBC 2011). About 196 million people in more than 90 countries were found to be exposed on average every year to catastrophic flooding (UNDP 2004). Europe alone suffered over 100 major damaging floods between 1998 and 2002, including the catastrophic floods along the Danube and Elbe rivers in 2002 (Barredo 2007, 2009), which have caused considerable casualties and economic losses (Kömüscü and Celik 2013). In China, floods are also the most frequently occurred natural disaster because of the strong influence of the East Asian monsoon (Renyi and Nan 2002; Yu et al. 2009). Two-third of Chinese territory area and over half of the total population are affected by a variety of flood events almost every year (Nakayama and Watanabe 2008; Wang et al. 2012). The National Climate Center of China reported an average annual economic loss of about $17 billion since 1990; especially, the severe floods in the Yangtze River and Nenjiang–Songhuajiang valleys during the summer of 1998 caused about $36 billion economic losses and more than 3,000 deaths (Nie et al. 2012). Accordingly, strengthening the available research regarding the spatial and temporal changes in flood events and their affecting factors, as well as scientific management of disaster risk, has a very important practical significance (Lecce and Pavlowsky 2004; Martinez and Le Toan 2007) and has caused a widespread concern (Nie et al. 2012).

Historically, the Yangtze River has been known for its frequent huge floods that have halted to a large degree the social advancement of the basin, especially in the middle and lower reaches (Zhao 2000; Cai et al. 2001). Poyang Lake, the largest freshwater lake in China, is located in the middle and lower reaches of the Yangtze River (Fig. 1) and directly exchanges water with the Yangtze River (Hu et al. 2007). The frequent large floods in Poyang Lake have caused huge damage to the environment and the agricultural economy and threatened the life of approximately 10 million people in the region. 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 msl) which can be considered to major flood events, and there were 6 years (1954, 1983, 1995, 1996, 1998 and 1999) during which the lake had severe floods (defined as the water level exceeding 21.0 m). Moreover, it has recently been shown that the frequency and severity of the floods in Poyang Lake have increased during 1990s

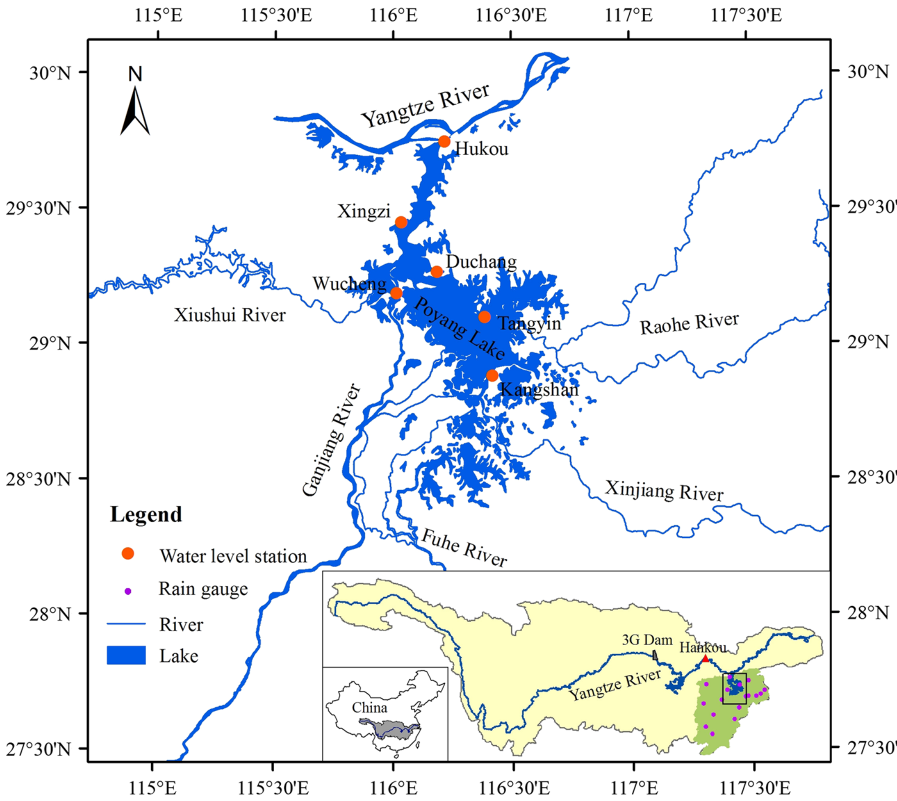

Fig. 1 Location of study area and the distribution of stations

(Guo et al. 2008). In the summer of 1995, the lake stage was slightly higher than that during the 1954 flood which was the largest ever recorded until the middle of 1990s and caused severe economic losses (Wang and Dong 2000; Jiang and Shi 2003). Three years later an even larger flood occurred in 1998, which was the largest flood ever recorded. The Poyang Lake stage reached 22.53 m (above msl), which exceeded the previously recorded highest water level by 0.74 m. For 23 consecutive days, the lake stage exceeded the highest level recorded in 1995 (Shankman et al. 2006). Catastrophic levee failures occurred along the lake boundaries and the lower sections of tributary rivers, resulted in an extensive agricultural losses, serious damage of several cities and many agricultural villages, and massive population relocation (Shankman and Liang 2003; Shankman et al. 2006), with the direct economic losses of more than $5 billion in Poyang Lake region (Chen et al. 2002).

The changing characteristic of floods is a basic issue and has raised extensive concern. Understanding the changing characteristics of Poyang Lake floods will benefit the sustainable economic development in the catchment (Wang et al. 2012). More importantly, 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). Therefore, the objectives of the study are designed to (1) identify and examine the characteristics of historical floods in Poyang Lake and investigate their tendencies, including the occurrence date, frequency, flood stage, and duration in the last six decades; and (2) analyze the related driving forces, both climate and human activities, and discuss their relationships with Poyang Lake floods in different periods.

The rest of this paper is organized as follows. In the next section, details of the study area, climate and used data are presented. In Sect. 3, the indexes and methods used in the study are briefly described with the help of cited references. Major results of this study are presented in Sect. 4. Section 5 mainly discusses the possible driving forces of floods from various aspects and the flood situations in Poyang Lake in the future, and Sect. 6 summarizes the conclusions.

2 Study area and data

Poyang Lake is located in the middle and lower reaches of the Yangtze River, China (28°22′–29°45′N and 115°47′–116°45′E), which connects with Yangtze River and receives water flows from the five rivers in Poyang Lake basin: Xiushui River, Ganjiang River, Fuhe River, Xinjiang River and Raohe River (Fig. 1). Poyang Lake has an average water depth of 8.4 m and a storage capacity of 27.6 billion m^3 when the water level at Hukou station is 21.71 m (Li et al. 2014). The length (south to north) of the lake is about 173 km and its maximum width (west to east) is 74 km. Generally, the lake water level is jointly influenced by the runoff inflow from the Poyang Lake basin and the blocking effect from Yangtze River. Under normal conditions, the water level in the south is higher than in the north, and Poyang Lake flows from the south and discharges (outflow) into the Yangtze River through a channel in its northern part. However, during the wet season, the elevated water level of the Yangtze River may impede the south–north water flow, and even sometimes (usually between July and September) results in a reversed north–south flow (Shankman et al. 2006).

Poyang Lake area has a subtropical wet climate characterized with a mean annual precipitation of 1,630 mm for the period of 1960–2010 and annual mean temperature of 17.5 °C. Annual precipitation shows a wet season 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. 2014). In response to the annual cycle of precipitation, water flows from the Poyang Lake basin have an annual course, with large runoff inflow starting in February and climaxing from April to June (Hu et al. 2007). This hydrograph of the Poyang Lake basin, as already noted in previous researches (Hu et al. 2007), explains the primary features of the first half in the annual variation of the Poyang Lake water level. In July–September, following the northwestward march of the monsoon front and decrease in rainfall in the Poyang Lake basin, discharge to the lake diminishes. Meanwhile, the middle reach of the Yangtze River receives its annual peak precipitation and its discharge increases. The rising river flow and water level blocks the outflow from Poyang Lake and further elevates the lake level. This blocking effect from Yangtze River dominates the second half of the annual course of lake level (Guo et al. 2012). At the same time, the floodplains are inundated and thus form a big lake with its inundation area reaching >3,000 km^2 (Xu and Qin 1998) and volume of 320×10^8 m^3 in the wet season, but shrink to <1,000 km^2 to form a narrow meandering channel during the dry season (Xu et al. 2001) and exposes extensive floodplains and wetland areas. There are approximately 10 million people live at the marginal areas of the lake, and this region is one of the important rice-producing regions in China and has served as an important national food base (Liu et al. 2013).

Daily water level of Poyang Lake was measured at Hukou station from 1950 to 2010 and Xingzi, Duchang, Wucheng, Tangyin and Kangshan stations from 1955 to 2010. The locations of these stations are shown in Fig. 1. These water level data are used to identify the characteristics of historical Poyang Lake floods, such as the flood stage, occurrence date, duration. In addition to the daily rain gauge data, which are obtained from National Meteorological Information Center of China for 14 stations in the Poyang Lake basin during the period 1953–2010, the observed daily stream flows from the five rivers are also collected. These data are used in the study to measure the variation of precipitation in the basin and the inflows from the basin to Poyang Lake. Meanwhile, these data have been widely used in many other studies (Hu et al. 2007; Guo et al. 2008, 2012; Li et al. 2013, 2014; Ye et al. 2011, 2013), and they are proven to be good quality. Additionally, the water fluxes measured at Yichang station are collected to describe variations of the Yangtze River flow and examine its effect on the water level of Poyang Lake. Moreover, other data including the land reclamation around 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 to investigate the effects on severity of flood.

3 Methods

To conveniently describe and reflect the frequency and severity of floods, the flood event has been defined in the study as the Poyang Lake stages at Hukou station exceeded the level of 19.0 m, which is also the warning stage. Accordingly, the lake stages exceeded the level of 20.0 m is considered as a major flood event and 21.0 m is classified as a severe flood event. Moreover, several widely used indices, including the flood stage, frequency, occurrence date, duration, as well as distribution curve of average annual exceedance days are calculated by the authors in the study.

In addition, the Mann–Kendall test (hereafter we call it 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 nonparametric method due to its robustness against the influence of abnormal data and especially its reliability for biased variables, and it has been widely applied for trend detecting in hydro-climatic time series (e.g., Ye et al. 2013; Zhao et al. 2010; Novotny and Stefan 2007; Chen et al. 2007; Xu et al. 2004).

To detect the existence of any step change points in the hydrological data $X_t = (x_1, x_2, x_3, \ldots, x_n)$, 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:

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

Under the null hypothesis of no trend, d_k is asymptotically normally distributed with expected mean value $E(d_k)$ and variance $\mathrm{Var}(d_k)$ as follows:

$$E(d_k) = \frac{k(k-1)}{4} \tag{2}$$

$$\mathrm{Var}(d_k) = \frac{k(k-1)(2k+5)}{72} \tag{3}$$

Under the above assumption, the normalized variable statistic $U_{\mathrm{f}}(d_k)$ is calculated as:

$$U_{\mathrm{f}}(d_k) = \frac{d_k - E(d_k)}{\sqrt{\mathrm{Var}(d_k)}} \quad (k = 1, 2, 3, \ldots, n) \tag{4}$$

where $U_{\mathrm{f}}(d_k)$ is the forward sequence, and the backward sequence $U_{\mathrm{b}}(d_k)$ is calculated 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 [$U_{\mathrm{f}}(d_k) > 0$] or a decreasing [$U_{\mathrm{f}}(d_k) < 0$] 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

4.1 Intra-annual distribution of high stages in Poyang Lake

Due to the floods of Poyang Lake mainly occurred during June–September, the daily lake water levels measured at the six stations (namely Hukou, Xingzi, Duchang, Tangyin, Kangshan and Wucheng) (see Fig. 1) during this period were selected for statistical analysis of intra-annual distribution. In descriptive statistics, a box plot is a convenient way of graphically depicting groups of numerical data through their quartiles. So, in this study, the box plots were used to present the distribution characteristics of daily observed lake water level during June–September, i.e., the mean, upper and lower quartiles, maximum and minimum, at different stations, and the results were shown in Fig. 2. It is seen that in historical flood years, the water level at Hukou station was usually in the range of 12.02–21.76 m in June with a mean of 16.34 m, while 13.56–22.53 m with a mean of 18.86 m for July. Although a nearly equal water level range was presented in August, the mean water level, as well as upper and lower quartiles, was lower than that in July. A similar distribution characteristic of lake water level was also observed at other stations (Fig. 2). It is also noticeable from Fig. 2 that the maximal water levels in different stations were nearly equal due to the Poyang Lake will become a horizontal plane in flood period, but in other periods, the water level at southern of lake (upstream) is higher than that at the northern (downstream).

Subsequently, the frequency of different lake stages occurred during June–September was defined as the number of total counts when the lake level exceeded the different lake level thresholds on the same date in different years of the 56-year period (1955–2010). The frequency distribution for lake level thresholds of 19.0, 20.0 and 21.0 m at the six stations was shown in Fig. 3. It is found that the frequency of mild floods (lake water level > 19.0 m) at Hukou station increased very fast from late June and reached its peak in mid- and late July, and then, the frequency decreased sharply in early August and lasted through September. Moreover, although the frequency of major floods (lake water level > 20.0 m) and severe floods (lake water level > 21.0 m) was smaller than that of the mild floods in whole flood periods, the most frequent floods still occurred in mid-July, regardless of the lake level thresholds. It is also noticeable from Fig. 3 that the frequency of lake level >20.0 m during late August to early September was relatively high, and the major floods occurring in this period were innegligible. The similar results can also be

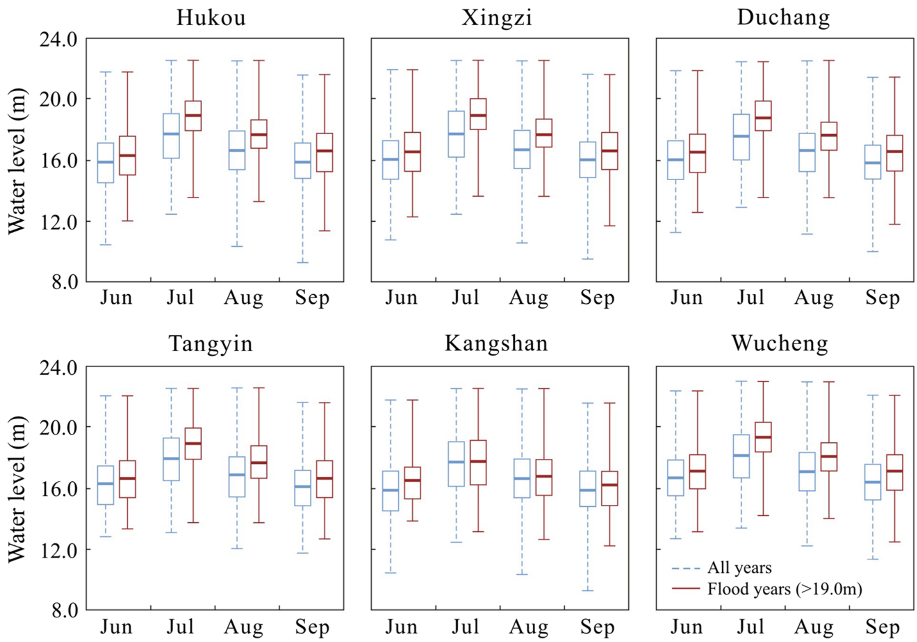

Fig. 2 Box plot of lake water level at different station during June–September

derived from other stations, and the only difference was that the peak frequency lasted a longer period at Wucheng than at other stations.

4.2 Inter-annual variation characteristics of floods in Poyang Lake

The variation of annual highest stages and the timing of highest stages series in Poyang Lake during 1950–2010 at Hukou station were shown in Fig. 4, and Table 1 shows the results of the corresponding M–K sequential test. It is seen from Fig. 4a that the highest stages showed a long-term increasing trend in the whole study period with the M–K statistic of 1.49 (Table 1), especially the increasing trend was significant during 1985–1999, while the flood stages also presented a distinct decrease since 1999. In addition, the timing of highest stages was investigated by Julian day number, which is the continuous count of days since the beginning of the year. We conducted a summary trend analysis of Julian day numbers when the lake flood reached the maximal level to evaluate the changes of flood date, i.e., to answer the question—have the Poyang Lake floods occurred earlier or later in different periods. As depicted in Fig. 4b, the Julian day numbers also showed a long-term increasing linear trend with the M–K statistic of 1.56 (Table 1), which means the floods have occurred later and later in the study period. However, the relative small Julian day numbers in the middle of 1950s, early and middle of 1970s, and 1990s indicated the floods occurred earlier during these periods than in other periods.

In addition to the highest flood stages, the flood duration is another very important factor in flood control. Generally, if the flood lasts longer, then the downstream flood control situation becomes more severe. Hence, it is also vital to analyze the flood duration series in addition to flood stages. Figure 5 shows the duration of different severity flood

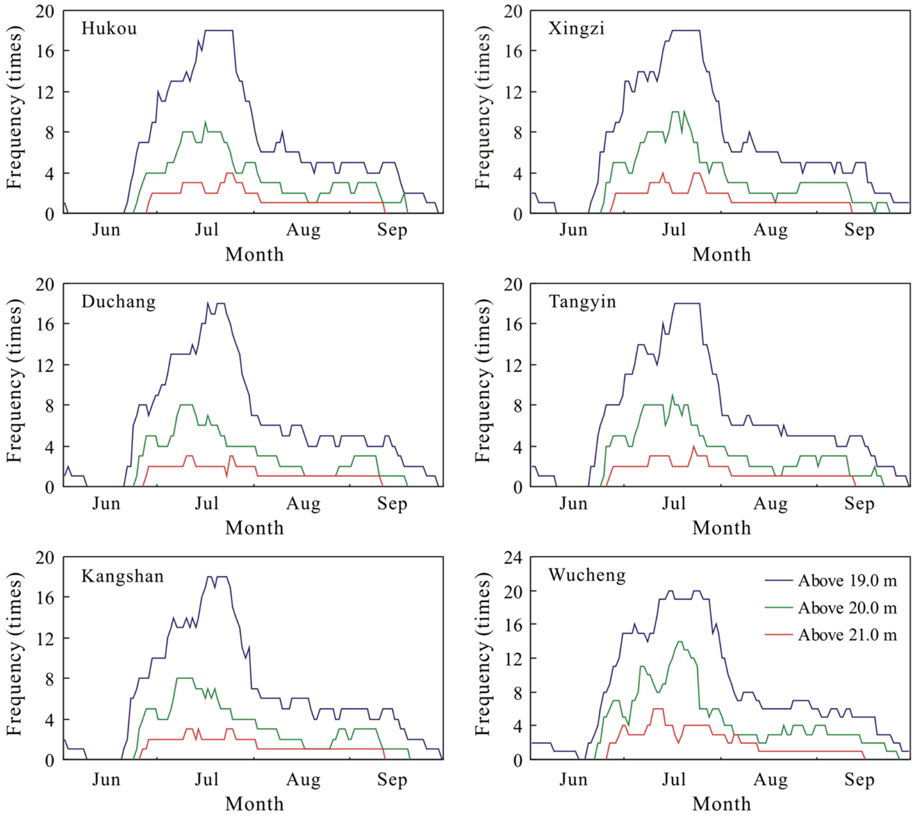

Fig. 3 Frequency distribution for different lake level thresholds during June–September

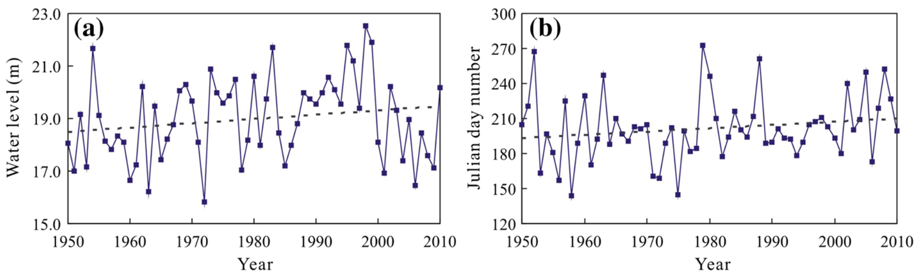

Fig. 4 Inter-annual variation of flood stages (**a**) and the timing of highest stages (**b**) (The *long dashed line* means linear trend for this period)

Table 1 Results of M–K test for three variables of flood characteristics

	Max flood stages	Timing of max flood stages	Duration (>19.0 m)
M–K statistic	1.49	1.56	1.60

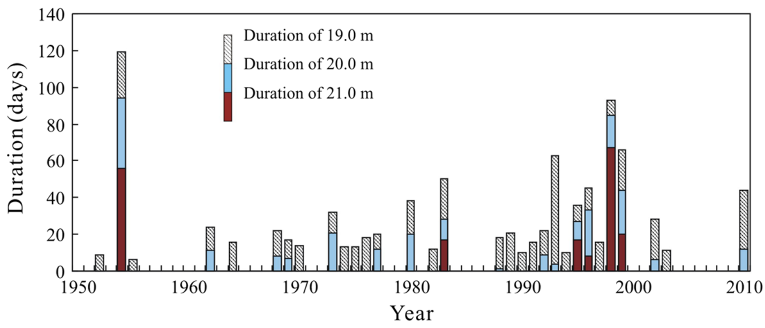

Fig. 5 Duration of different severity floods in Poyang Lake during the last 60 years

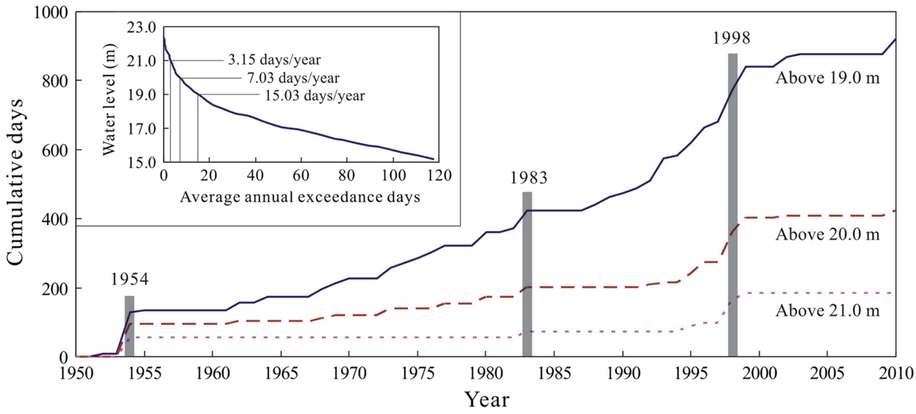

Fig. 6 Cumulative sum of flood duration above different threshold lake stages

events in Poyang Lake during the last 60 years. It is obvious that the flood duration has an increasing trend from 1950 regardless of mild flood or major flood (the M–K statistic was 1.60 for mild flood). The cumulative sum of flood duration above different lake stages threshold (Fig. 6) also showed the characteristics of increasing gradients of different severity flood events. Generally, the higher gradient indicates the longer flood duration, i.e., 1954, 1983 and during 1990s.

4.3 Decadal variation characteristics of floods in Poyang Lake

The variation characteristics of floods in Poyang Lake were also analyzed at decadal scale to provide insight into the decadal variability of flood events. Figure 7 shows the changing processes of lake stage averaged per 10 years during June–September in different decades. It is seen that the peak stages in different decades occurred in mid- or late July as expected. At the same time, the highest peak stages in 1990s indicated that the flood events are most severe in 1990s than in other decades. Similar situations were observed further in Fig. 8 which shows the comparison of average annual exceedance days per 10 years. It is found that the curve of 1990s lay higher than others at the high threshold stages. The average annual exceedance days for threshold stages of 19.0, 20.0 and 21.0 m were about 37, 20

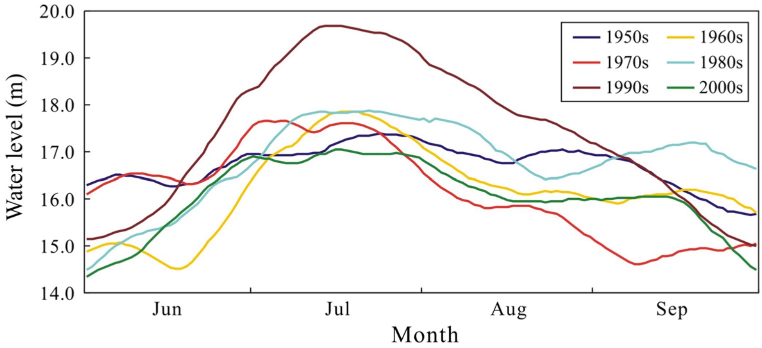

Fig. 7 Changing processes of lake stage averaged per 10 years during June–September

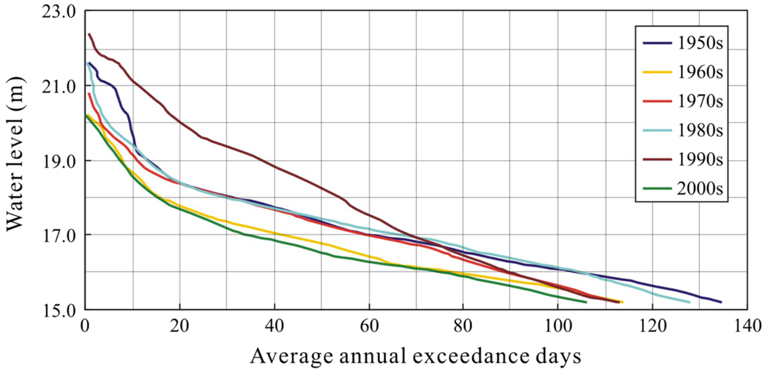

Fig. 8 Comparison of average annual exceedance days per 10 years

and 11 days, respectively. While for the curve of 2000s, it was no more than 8 and 2 days, respectively, for stages threshold of 19.0 and 20.0 m. Figure 8, together with Fig. 7, demonstrated that the flood control situation in Poyang Lake was most severe in 1990s and had turned to the best in 2000s.

Figure 9 shows the inter-decadal variation of flood frequency and average duration. It is seen that the average duration of mild floods per 10 years increased from 10–13 days in 1950s and 1960s to nearly 40 days in 1990s. The figure demonstrated that the increasing trend is notable in the average duration and also the frequency of floods. For example, the number of mild floods per 10 years increased from three times in 1950s to ten times in 1990s. Similarly, the times and average duration of major floods also increased from 1950s and 1960s and reached their peaks in 1990s. It is also noticeable from Fig. 9 that the numbers and average duration of mild and major floods in 2000s were the lowest during the last 60 years, and the severe floods never happened during the period.

5 Discussion

The previous section presented the variation characteristics of floods in Poyang Lake during the last 60 years at different scales, which showed that the severity, frequency, as

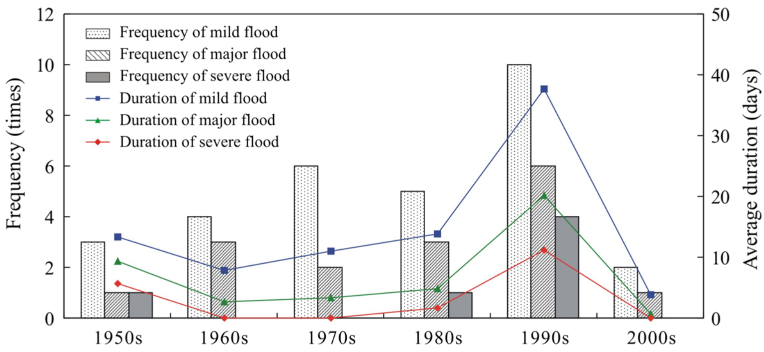

Fig. 9 Inter-decadal variation of flood frequency and average duration

well as duration of floods keep changing in different periods. Possible influence factors of these changes can be identified as the discharges of the Yangtze River, runoff from basin into the lake, as well as the human activities in the Poyang Lake.

As already noted, the water level of Poyang Lake was dominated mostly by both the discharges of Yangtze River during flood periods and the runoff inflow from the basin. The large discharges of Yangtze River could block outflow from Poyang Lake and even cause backflow from the Yangtze River to Poyang Lake and then increase the lake water level (Yin et al. 2007; Wang et al. 2008; Nakayama and Shankman 2013). A great amount of runoff from the Poyang Lake basin generated later than normal (the peak runoff inflow usually appeared between April and June) in summer, when the level of the Yangtze River was also high, may easily trigger the floods in Poyang Lake. Figure 10 shows the anomaly variation of discharges of Yangtze River at Hankou station in July and runoff inflow to the lake during June–September. It is intriguing 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 and runoff inflow. From these coincidences, we believed that the severe floods easily occurred when a large discharge of Yangtze River in flood season encountered a larger runoff inflow from the basin than normal during flood periods. For example, the severe flood in 1998 was mainly resulted from the abnormally heavy precipitation events over the middle and upper reaches of the Yangtze River and subsequent large discharges of Yangtze River as well as the large runoff inflow from the Poyang Lake basin. As such, with the distinct decrease in precipitation over the middle reaches of Yangtze River (also including the Poyang Lake basin) since 2000 (Wang et al. 2009), the negative anomalies of summer rainfall resulted in lower river flow of Yangtze River and runoff inflow from the Poyang Lake basin (Fig. 10). A weakened blocking effect of the Yangtze River further promoted the outflows from the lake to the river (Liu et al. 2013; Hu et al. 2007), which was a principal cause for the fewer floods in Poyang Lake after 2000. Therefore, the climate change was a significant reason for changing of flood characteristics in Poyang Lake; i.e., the abnormally large rainfall during the flood season and subsequent large discharges of Yangtze River and runoff inflow from the Poyang Lake basin were mainly responsible for the severe flood situation in 1990s, and also the infrequent floods in 2000s in Poyang Lake were mostly ascribed to the decrease in rainfall over the middle reaches of Yangtze River.

In addition, landscape changes due to human activity also played a supplementary role in increasing severity of major floods (Yin and Li 2001; Piao et al. 2003; Zhao and Fang

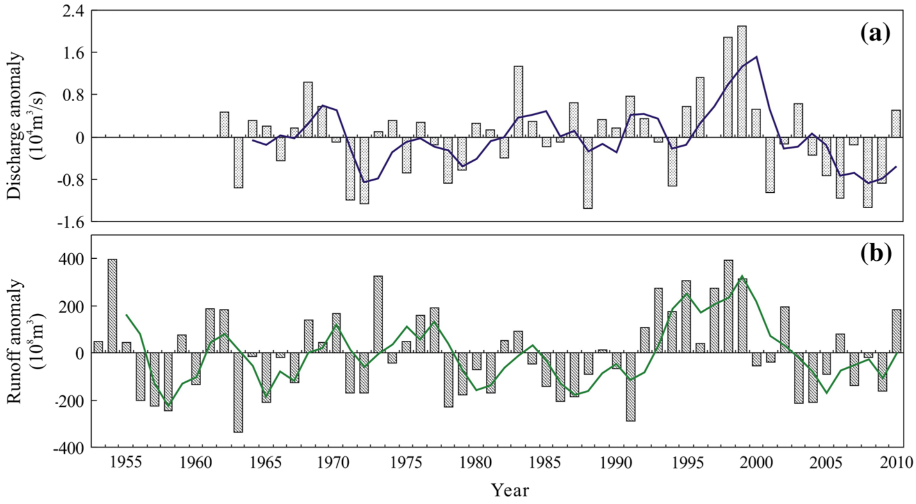

Fig. 10 Anomaly variation of discharges of Yangtze River at Hankou station in July (**a**) and runoff inflow from the basin during June–September (**b**) (the *long curve* means the 3-year moving average)

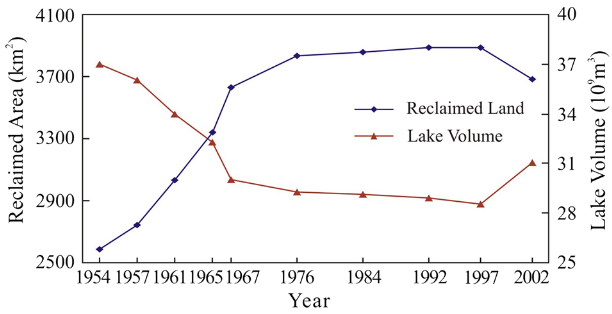

Fig. 11 Variation of reclamation area in Poyang Lake and lake volume (supplement based on Shankman et al. 2006)

2004; Zhao et al. 2005). Statistics indicated that the Poyang Lake shrank significantly in area from 5,160 km^2 in 1950s to 3,860 km^2 in late 1990s during the 44-year period and decreased in volume from 37 billion m^3 to 28.9 billion m^3 during the same period (Fig. 11). The land reclamation and levee construction in lake regions have been regarded as the major factors responsible for the decrease in lake storage capacity (Shankman and Liang 2003). Moreover, large amount of sediment discharges from the five rivers to the Poyang Lake during the 1960s–1980s as well as 1990s, due to the deforestation to farm and other human activities in the basin, also distinctly enhanced the sediment deposition in lake. Min (1999) estimated that the sediment deposition reduced the total volume of Poyang Lake by 4.8 % during 1954–1997. These human activities jointly reduced the storage capacity of Poyang Lake to its smallest volume in 1990s (Fig. 11), which increased, to some extent, the damages of floods.

While, it was worth mentioning that the effects of human activity since 2000, regardless of intensity or extent, have become stronger than before. After the great flood of 1998, a new policy namely "return land to lake" was adopted by the local governments to increase the floodwater storage of Poyang Lake (Nakayama and Shankman 2013), which included the removal of some levees and requiring an evacuation from the reclaimed land (Shankman and Liang 2003; Peng et al. 2005). Through several years of efforts, both the lake area and volume have become much larger than those during the late 1990s (Dai et al. 2005; Shankman et al. 2009) (Fig. 11). At the same time, an intensive sand mining, due to the sand demand in rapidly expanding cities in middle and lower reaches of Yangtze River, has been displaced to Poyang Lake from Yangtze River when a ban of sand mining was imposed in Yangtze River in 2000 (Wu et al. 2007), which has changed the Poyang Lake from a net sediment accumulating system into a sediment exporting system. According to the estimation of Leeuw et al. (2010), sand mining resulted in a weight of 4.5×10^8 ton sand exported from Poyang Lake per year since 2000, which is equivalent to a lake volume increase of 2.4×10^8 m^3. Especially in the northern parts of Poyang Lake, the lake bottoms declined as much as 10 m from those in 1990s. Therefore, sand mining distinctly increased the storage capacity of Poyang Lake and could mitigate the frequency and severity of floods. More importantly, the construction of the Three Gorges Dam (TGD) in the middle reaches of Yangtze River commenced in 1997 and testing operations began in 2003 have played an important role in flood protection of Poyang Lake (Nakayama and Shankman 2013). So, the intensive human activities above mentioned after 2000 were another important reason for rare floods in Poyang Lake in 2000s. In a word, the water level of Poyang Lake is a result of joint effects of the runoff inflow from the catchment, the hydraulic connection between the lake and Yangtze River, and the operation of the TGD.

Similarly, the second largest freshwater lake in China—Dongting Lake, which lies in the middle reaches of the Yangtze River—is about 300 km downstream of the TGD and 500 km upstream of Poyang Lake, also faced severe floods. Xiang and Li (2001) indicated that the Dongting Lake region suffered 296 floods of different intensities and ranges in history; especially, the great floods occurred quite often in the last decade of the twentieth century (Wang et al. 2011). Similar to Poyang Lake, the heavy precipitation events were mainly responsible for the floods in Dongting Lake region, since the two lake drainage areas were both under the influence of subtropical monsoon with significant seasonality in precipitation. In addition, the human activities, including land reclamation, levee construction, sediment deposition due to the deforestation, and sand mining, also played an important role in the development of floods in Dongting Lake (Jiang et al. 2007). Moreover, due to the shorter flow route from the TGD as well as the closer and more complex hydraulic connection with the Yangtze River, the modulated river flows by the TGD exerted a stronger influence on Dongting Lake than on Poyang Lake (Gao et al. 2013). For more detailed studies on the floods in Dongting Lake, please refer to the researches of Dai et al. (2005), Hayashi et al. (2008) and Lai et al. (2013). In summary, Poyang Lake and its neighboring Dongting Lake have similar physical settings on the same river system, and both suffered from severe floods. The results of the study may also be useful in understanding the characteristics of floods and driving forces in Dongting Lake, as well as in other similar lakes.

6 Conclusions

This paper identified and examined the characteristics of historical Poyang Lake floods and analyzed their tendencies, including the maximal flood stage, timing of peak flood stages, duration and frequency, in the last six decades. The results reveal that the floods in Poyang Lake mainly occurred in mid- and late July during the last 60 years. The inter-annual variation of highest flood stages and duration showed a long-term increasing linear trend with the M–K statistic of 1.49 and 1.60, respectively. Also, a slightly increasing linear trend in the timing of highest stages indicated that the Poyang Lake floods have occurred later and later during the last 60 years. At the decadal scale, the frequency and the average duration of mild floods per 10 years have increased from three times and 10–13 days in 1950s to ten times and nearly 40 days, respectively, in 1990s, while in 2000s, the number of floods and average duration were lowest.

The changing of floods can mainly be attributed to the effects of climate change and different human activities in Poyang Lake regions. For climate reason, the abnormally large rainfall during the flood season and subsequent large discharges of Yangtze River combined with the fact that a great amount of runoff from the lake basin generated later than normal in summer resulted in the severe floods in Poyang Lake in 1990s. At the same time, intensified human activities have weakened the storage capacity of Poyang Lake considerably with the great floodplain occupancy and levee construction, which further increased the frequency and damages of floods. Similarly, the rare floods in Poyang Lake after 2000 were attributed to both the climate reason and the change of human activities. During the 2000s, the rainfall over the middle reaches of Yangtze River has decreased, which caused the low streamflows of Yangtze River and runoff inflow from the Poyang Lake basin; meanwhile, the government's policy of "returning land to lake", intensive sand mining in the lake and the flood control of TGD have increased the total usable storage capacity of Poyang Lake.

Acknowledgments This work is jointly funded by the National Basic Research Program of China (973 Program) (2012CB417003), the Collaborative Innovation Center for Major Ecological Security Issues of Jiangxi Province and Monitoring Implementation (JXS-EW-00), the National Natural Science Foundation of China (41101024) and the Science Foundation of Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS2012135001). The authors are grateful to the anonymous reviewers and the editor who helped us improving the quality of original manuscript.

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