EARTH Interactions

Hydroclimate Analysis of Severe Floods in China's Poyang Lake Region

David Shankman*

Department of Geography, University of Alabama, Tuscaloosa, Alabama

Barry D. Keim

Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana

Tadanobu Nakayama

Center for Global Environmental Research, Tsukuba, Japan

Rongfang Li

Jiangxi Institute of Water Sciences, Nanchang, China

Dunyin Wu

Jiangxi Normal University, Nanchang, China

W. Craig Remington

Cartographic Research Laboratory, University of Alabama, Tuscaloosa, Alabama

Received 3 April 2012; accepted 22 September 2012

* Corresponding author address: David Shankman, Department of Geography, University of Alabama, Tuscaloosa, AL 35487.
E-mail address: shankman@bama.ua.edu

DOI: 10.1175/2012EI000455.1

ABSTRACT: Poyang Lake in Jiangxi Province is the largest freshwater lake in China and is historically a region of significant floods. Maximum annual lake stage and the number of severe flood events have increased during the past few decades because of levee construction that reduced the area available for floodwater storage. The most severe floods since 1950 occurred during 1954, 1973, 1983, 1995, and 1998. Each of these floods followed El Niño events that influence the Asian monsoon and that are directly linked to rainfall in the Changjiang (Yangtze River) basin. The 1954 flood was the largest ever recorded until the 1990s. That year the peak Changjiang stage at Hukou was 21.6 m, which was 1.6 m above the previous record high. The last major flood on the Changjiang was during 1998, when the peak Changjiang stage reached 22.5 m, higher than during 1954, even though peak discharge was lower. The most severe floods, including those in 1954 and 1998, require both 1) high rainfall and tributary discharge into Poyang Lake and 2) high Changjiang discharge and stage at Hukou that backflows into the lake or slows Poyang Lake drainage. Since gauging stations were established on the Changjiang, these conditions always occurred following an El Niño.

KEYWORDS: ENSO; Floods; China; Poyang Lake; Yangtze River

1. Introduction

Poyang Lake in Jiangxi Province is the largest freshwater lake in China and is historically a region of severe floods. At its northern end, Poyang Lake drains into the Changjiang (Yangtze River), the longest river in China. The five major rivers in Jiangxi that flow into Poyang Lake have headwaters in the surrounding mountains (Figure 1). During the summer wet season, May–September, the lake covers an area of 3800 km^2, inundating the low-lying alluvial plains surrounding the lake and flooding the lower sections of large river flowing into it. A much larger area would be submerged during this time of year, but for centuries vast sections of the floodplains have been protected by levees. These levees, until the past few decades, were poorly constructed and often not well maintained and in some cases too small to protect against the most severe floods. As a result, there have been catastrophic levee failures during recent centuries that caused great hardship and have accounted for thousands, possibly tens of thousands, of deaths among farmers who grow rice on the rich soils in the surrounding plains.

A 500-yr Poyang Lake flood chronology (1500–2000) shows 35 severe floods, or about once every 14 years (Min 1992; Shankman et al. 2006). Severe floods occurred every century, but with a greater frequency since 1950. Flood stage dramatically increased during this period, which is attributed to construction of levees that reduced the area available for floodwater storage (Min 1999). All severe Poyang Lake floods since gauging stations were first established along the Changjiang are associated with El Niño events that result in above average precipitation throughout much of south-central China (Shankman et al. 2006). The purpose of this project is to examine the relationship of rainfall and stream discharge of both the Changjiang and tributaries flowing into Poyang Lake to the most severe floods since 1950. Specifically, we examine 1) the frequency and intensity of severe floods during the past few decades, 2) timing and strength of El Niño events during these floods, and 3) rainfall and river discharge during the 1954 and 1998 floods that set record highs.

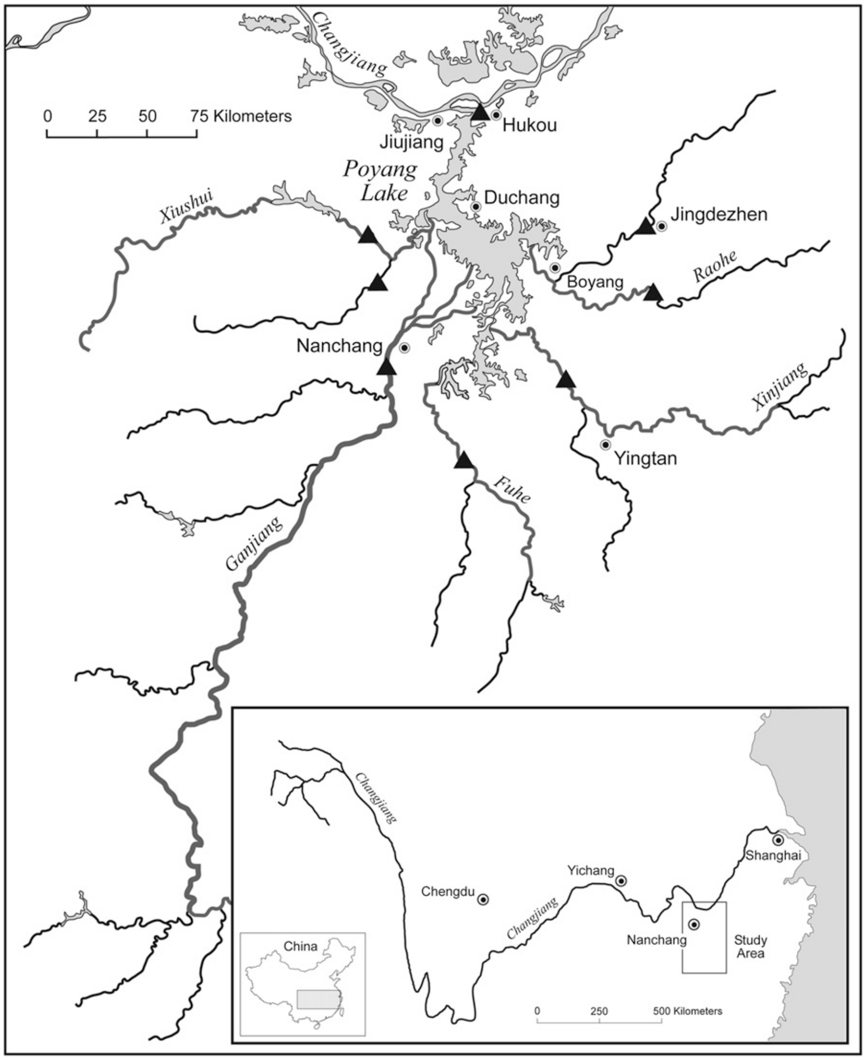

Figure 1. Map of the Poyang Lake region. Triangles show positions of gauging stations.

2. Regional overview

Poyang Lake occupies an area of low elevation immediately south of the Changjiang alluvial valley. Lake level depends on both Changjiang stage and discharge from the Jiangxi basin. The rainy season in southern China typically begins in late spring and continues throughout the summer. Most years, discharge from the Jiangxi basin increases during early to midsummer, raising the level of Poyang Lake, which drains into the Changjiang at Hukou. This flow into the Changjiang is easily detectable when observing the relatively clear lake water entering the muddy, sediment-laden water of the Changjiang. From July to early September, Poyang Lake tributary discharge steadily decreases, while at the same time Changjiang discharge and stage increases (Figure 2). If Changjiang stage exceeds that of the lake, the previous flow of water from the lake into the

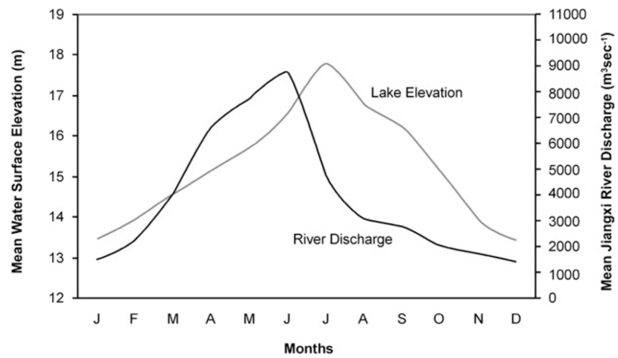

Figure 2. Poyang Lake hydrograph showing discharge of the five major rivers in Jiangxi flowing into the lake and lake stage.

Changjiang reverses and the muddy water from the Changjiang flows into the lake. The highest annual lake stage generally ranges from about 18 to 21 m above mean sea level (MSL) during the summer monsoon season in southern China but may be higher or lower during unusually wet or dry years (Shankman et al. 2006).

The Poyang Lake watershed area is 162 000 km^2. The headwaters of the Jiangxi basin are located in the surrounding mountains. This is an area of high local relief with peaks greater than 1500-m elevation. The five major rivers in Jiangxi flowing into Poyang Lake are the Xuishui, Ganjiang, Fuhe, Xinjiang, and Raohe. Stream gradient decreases as these rivers flow onto the relatively flat region surrounding Poyang Lake. The lower sections of Jiangxi rivers meander through broad alluvial valleys. Sediment deposition from Ganjiang, and to a lesser extent the Fuhe, has created a large delta plain on the southern and western shores of Poyang Lake that is dissected by their distributaries. The Ganjiang is the largest river in Jiangxi and contributes a larger discharge and sediment load than the flow and sediment contribution of the other rivers combined.

Jiangxi Province is in China's most important rice growing region. River deltas surrounding Poyang Lake, in addition to the broad alluvial valleys of tributary streams, support intensive cultivation. An extensive levee system designed to protect low-lying areas from floods has been in place for centuries. Historically, the largest levees were high enough to protect from normal yearly floods but inadequate during severe floods. Levee construction projects since the 1950s have increased levee height and the area of flood protection. These levees now protect millions of people living in the low-lying areas at the margins of Poyang Lake and in the alluvial valleys along the large rivers in this region. Flood control policies were modified during the past decade with a focus on permanent removal of some levees and the opening of others during severe floods to increase floodwater storage (Jiang 2006; Shankman et al. 2009).

3. Data and methods

Stage data used in this study to examine the severity and duration of floods are from the Hukou gauging station at the mouth of Poyang Lake (1950–2007). The annual maximum lake stage time series, from 1950 until 1998, shows a strong upward trend. To determine the relative severity of these floods, data were detrended using a 10-yr running mean. Analysis was performed on the deviations of annual maximum stage from the mean that was set to zero. This allowed for a relative comparison of specific flooding events from differing decades, minus the overall upward trend during the past few decades. Severe floods during this period were classified as those with a maximum stage at least 2 m above average in the time-series trend line.

An evaluation of the influence of El Niño events on rainfall was based on Niño-3.4 sea surface temperature anomalies, so that an El Niño event was defined as anytime the 5-month average departure was equal to or greater than 0.4°C as recommended by Trenberth (Trenberth 1997) for the fall, winter, or spring prior to the summer floods or during the summer in which the peak stage is reached. This definition for an El Niño event, which includes a broad time scale, was used because effects of warm sea surface temperatures on upper air circulation in South Asia lag several months after the event (Huang et al. 2004).

The 1954 and 1998 floods were the most severe ever recorded. Hydroclimate analysis for each flood included rainfall and discharge both into and out of Poyang Lake. Daily rainfall records were from Chengdu and Yichang, both upstream of Poyang Lake, and Nanchang, which is near the western shore of the lake (Figure 1). Daily discharge of tributaries into Poyang Lake was calculated during the 1954 and 1998 summer floods. These data were from gauging stations on the five major rivers flowing into Poyang Lake. Discharge data from the lake into the Changjiang are from the Hukou gauging station.

Changjiang discharge was examined during the 1954 and 1998 floods. Discharge was not recorded at Hukou during the 1954 flood. To compare discharge during these two floods we use discharge data from the Hankou gauging station during 1954, which is located 304 km upstream of Hukou. No major tributaries enter the Changjiang between Hankou and Hukou; therefore, discharge at these two stations is similar. A regression analysis of Changjiang discharge at Hankou and Juijiang, which is only 24 km upstream of Hukou (and using data during the 1954 flood) shows a strong relationship ($R^2 = 0.9876$) (Figure 3).

4. Frequency of severe floods

From 1950 to 2007, five floods were classified as severe (1954, 1973, 1983, 1995, and 1998), a frequency of about once every 10 years. All of these floods had a maximum stage greater than 21 m at Hukou at the lake's mouth except during 1973, which was only slightly lower at 20.9 m. Maximum annual lake stage progressively increased during the second half of the twentieth century. The 10-yr mean during the 1960s ranged from 18 to 18.6 m (Figure 4). This value rose each decade and during the late 1990s reached 21 m, an increase of greater than 2 m during this 40-yr period. The 1954 flood was 2.9 m above the time-series trend line, which was by far the most severe when measured using this relative perspective. The 1954 flood is often used as a reference when discussing later flood events. Although not the highest flood, it caused severe economic damage. Many levees at that time were not high enough or strong enough to protect low-lying areas at the margins of Poyang Lake. The 1998 flood was the most severe based on

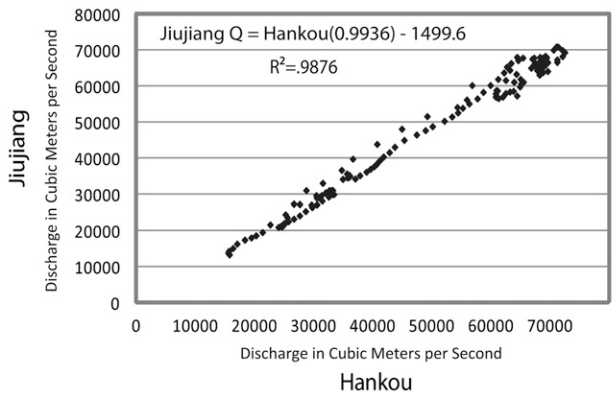

Figure 3. Regression analysis of Changjiang discharge during the 1954 flood at the Hankou and Juijiang gauging stations.

lake stage. This flood event, however, ranked second based on its 2.2-m departure from the trend line. This ranking is largely the result of the average maximum lake stage during the 1990s being much greater than during previous decades. No severe floods occurred since 1998 and since that time average maximum lake stage has decreased.

The increasing severity of floods during the second half of the twentieth century was largely attributable to levee construction and the loss of floodwater storage around Poyang Lake and along the Changjiang. Maximum Poyang Lake surface area from 1954 to 1998 decreased 25%, from 5160 to 3860 km^2 (Min 1999). Before extensive levee construction, floodwater spread out across the floodplain during the late spring and early summer months. Most major levees in Jiangxi are built on or very near riverbanks and protect low-lying areas at the margins of Poyang Lake, including the Ganjiang and Fuhe delta. These levees constrict floodwater resulting in a higher water surface elevation during floods of equal discharge. Increasing flood severity was also related to levee construction along the middle Changjiang that detached the main channel from the surrounding floodplain (Zong and Chen 2000; Wang and Plate 2002) in addition to levee improvements. Many of these levees failed during the 1954 flood, and the volume of floodwater diversion through these breaches was 1.023×10^{11} m^3 compared to only 1.0×10^{10} m^3 in 1998 (Li et al. 2003). Improvement in levee quality reduced flood risk in adjacent floodplains, but constraining water to the main channel forced the river to a higher stage.

Changjiang channel aggradation during previous decades (1950s–80s) has further increased flood risk. There is evidence that historic sedimentation of the Changjiang channel is related to deforestation and accelerated soil erosion in the upper and middle Changjiang watershed. This has not, however, been verified and the exact relationship between upper and middle watershed erosion and increased channel aggradation is not certain (Wang et al. 2007). Although average annual peak stage has increased during this period, discharge has been almost constant indicating a smaller channel cross section (Jun and Chen 2001; Chen and Lu 2003).

Average sedimentation rates of about 2.5 mm yr^{-1} suggest decreasing lake volume that could increase flood risk (Shankman et al. 2009). Sediment deposition

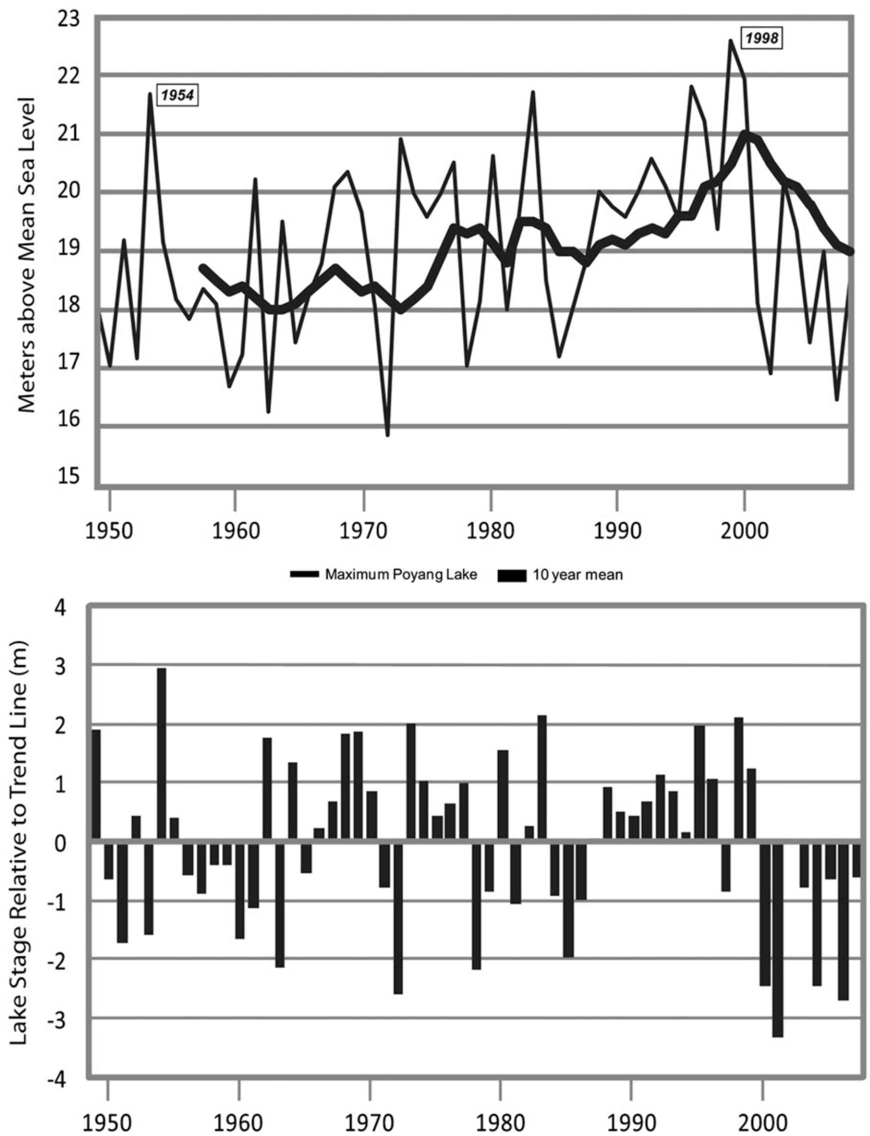

Figure 4. (top) Maximum annual Poyang Lake stage at Hukou, 1949–2007, and 10-yr running mean. (bottom) Detrended time series with the mean value for each year set to zero; maximum annual flood stage and analysis is performed on the deviations from the running mean.

increased significantly from the 1950s to the 1980s, and several studies noted that this change reflected increasing soil erosion in the Poyang Lake drainage basin caused by deforestation in headwater areas (see review of the Poyang Lake sediment budget by de Leeuw et al. 2010). Sediment deposition, however, had little impact on lake volume and flood risk, because the filling of the lake is being offset by tectonic subsidence and, more recently, extensive sand mining (Wang et al. 2005; Wu et al. 2007).

Average annual summer rainfall in the middle and lower Changjiang basin, including the Poyang Lake region, has increased during the past few decades (Su et al. 2006). Ren et al. (Ren et al. 2004), however, described this as a weak trend that was not a major cause of higher maximum annual lake stage.

5. El Niño events

All severe Poyang Lake floods, which occur during the summer monsoon, follow winter El Niño events. The Pacific subtropical high pressure over the western North Pacific Ocean controls the progress and retreat of the summer monsoon in eastern Asia. This pressure system during summer moves warm moist air inland from the southeast. When colliding with cold air from the arid north, this airflow is lifted, causing abundant rainfall (Samel et al. 1995). During a normal or La Niña year, this frontal boundary is generally pushed northward, and hot and dry summer weather dominates much of the middle and lower Changjiang basin. During El Niño, the front is blocked from moving far north, which results in heavy precipitation that can result in severe Changjiang floods. Although all severe floods follow an El Niño, not all of these events resulted in severe floods. A notable exception occurred during 1978. Although classified as an El Niño year, summer lake stage during that year was far below average (Shankman et al. 2006).

The five floods classified as severe occurred following winter and spring El Niño events (Figure 5). During all 5 years, the preceding winter El Niño weakened toward the late spring and approached a neutral summertime position (1983, 1995, and 1998) or moved into La Niña (1954 and 1973). Rainfall at Nanchang near the southwestern shore of Poyang Lake during the winter and spring was generally near or slightly above average during winter and spring preceding these floods. Rainfall during most summer months was far above average. Highest above average summer rainfall occurred during the 1973 flood when June rainfall was 450 mm above average; 1954, 1995, and 1998 had at least one summer month with rainfall greater than 300 mm above average; and 1983 had two summer months with rainfall greater than 150 mm above the monthly average.

El Niño is strongly linked to rainfall throughout the Changjiang basin, not only in the Poyang Lake region. Rainfall in the upper and middle Changjiang basin that determines downstream discharge is much higher during El Niño events (Samel et al. 1995; Samel and Liang 2003; Shankman et al. 2006). High Changjiang stage slows lake drainage but, as noted by Hu et al. (Hu et al. 2007), severe floods are unlikely without high lake basin rainfall and tributary discharge, regardless of Changjiang discharge. This is because at low stage, Poyang Lake provides a vast area for floodwater storage. Severe floods occur only when tributary discharge increases lake volume so that it surpasses floodwater storage. Changjiang backflow in the absence of high tributary discharge is unlikely to raise the lake to that level (Nakayama and Watanabe 2008).

Although El Niño events greatly increase the probability of above average rainfall, rainfall intensity is not directly related to the strength of El Niño. The 1953/54 El Niño was the weakest among the five severe floods, but this was the only flood year with rainfall at least 250 mm above average for three consecutive months. The strongest El Niño among these five events preceded the 1983 and 1998 floods, but rainfall, while still far above average, was less than during the 1954 flood.

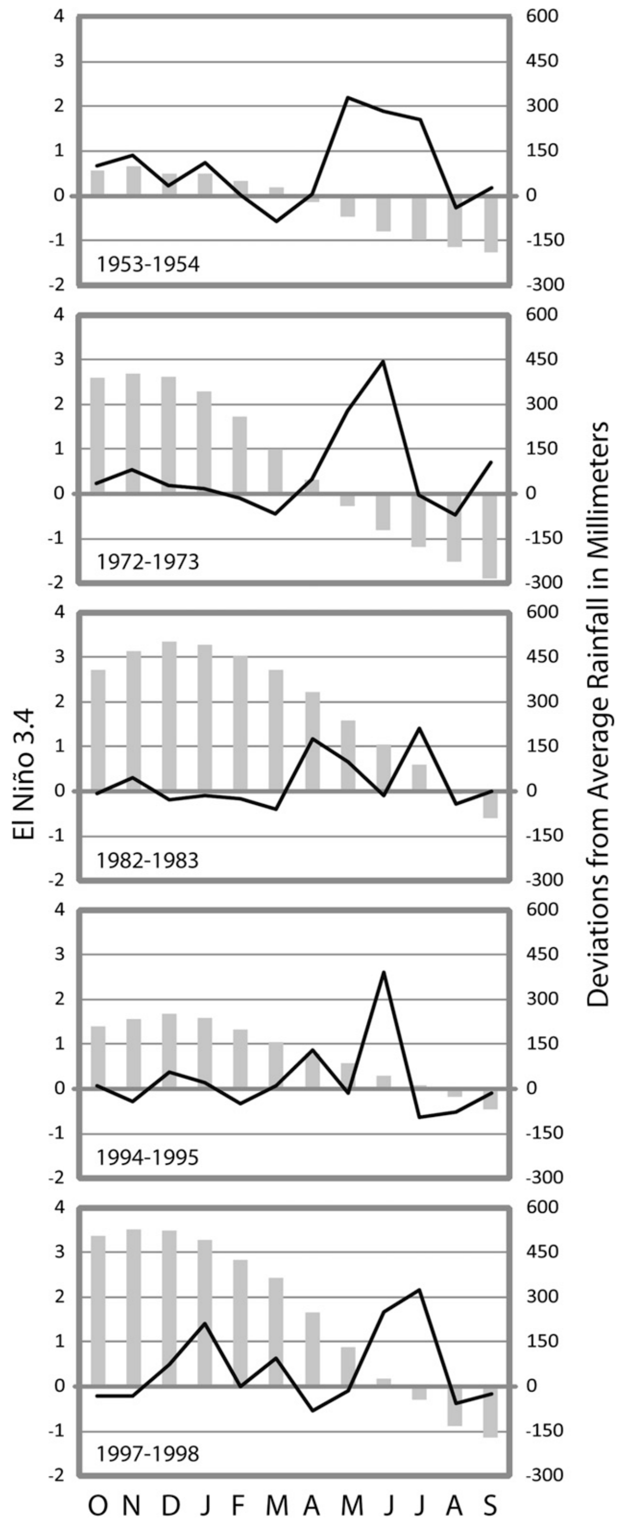

Figure 5. Niño-3.4 and Nanchang, Jiangxi, rainfall deviations from average (preceding and during severe floods that occurred during 1950–2007).

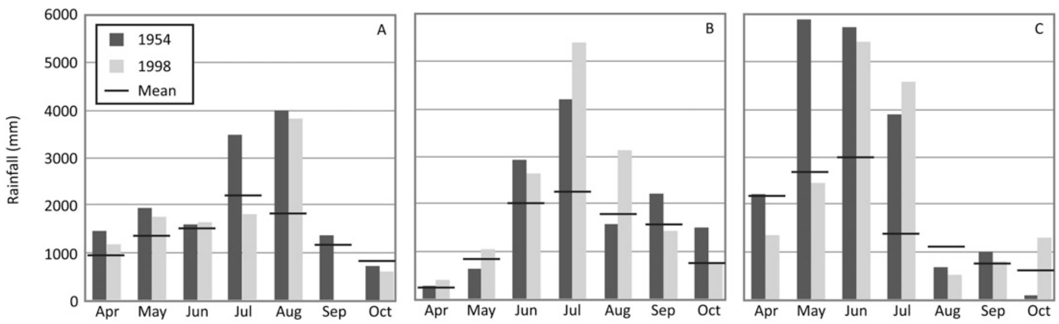

Figure 6. Rainfall at (a) Chengdu, (b) Yichang, and (c) Nanchang during 1954 and 1998.

6. 1954 flood analysis

The 1954 flood had the highest water level ever recorded in Poyang Lake until that time (21.6 m) and was well above the previous record high during 1931 (20 m). As already noted, this was the most severe flood during the past few decades based on the time series shown in Figure 4. Rainfall during March and April, immediately preceding the summer monsoon, was near or slightly below average, and tributary discharge at this time averaged less than 10 000 cm s^{-1}. At Nanchang, near the western shore of the lake, rainfall during May, June, and July was 3100 (210%), 2700 (193%), and 2500 mm (300%) above average, respectively (Figure 6). As a result of heavy rainfall within the Poyang Lake region, tributary discharge was exceptionally high. The five major rivers flowing into Poyang Lake reached maximum total discharge of about 33 000 cm s^{-1} on 19 June, which was 4 times greater than the preflood discharge (Figure 7). Discharge fell to less than 14 000 cm s^{-1} on 25 June but then increased until reaching a second peak of 31 000 cm s^{-1} on 1 July.

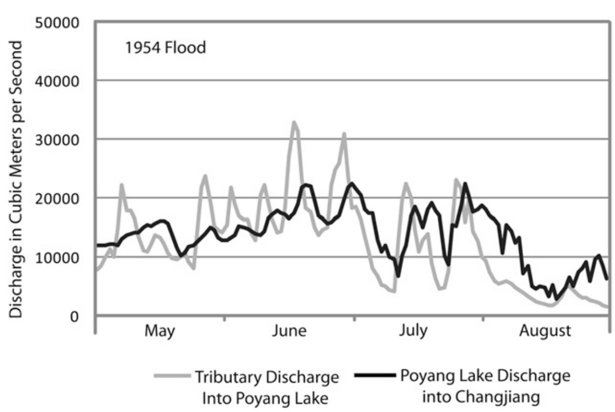

Figure 7. Tributary discharge into Poyang Lake and Poyang Lake discharge into the Changjiang during the 1954 flood.

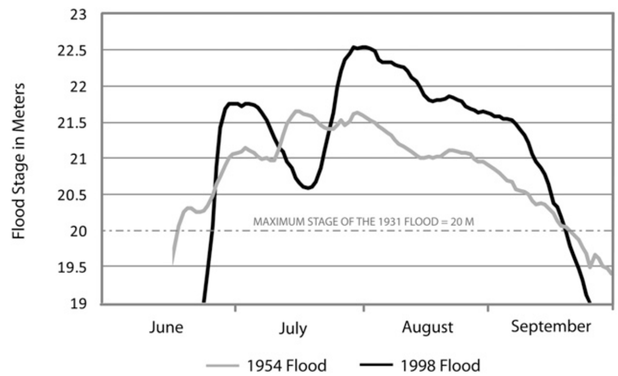

Figure 8. Maximum lake stage during the 1954 and 1998 floods.

The rapid increase in lake stage during early summer is related to tributary discharge into the lake consistently greater than lake discharge into the Changjiang. Tributary discharge during June exceeded lake discharge by an average of 5000 cm s^{-1}, which dramatically increased lake volume. On 21 June, lake stage exceeded the previous record high during the 1931 flood (20 m) and remained above this level until 23 August, a total of 93 days (Figure 8). For 36 consecutive days in this period lake stage was no less than 21 m. Tributary discharge into the lake varied widely throughout the summer (Figure 7). Lake stage, however, remained persistently high, indicating that during major floods water level is highly dependent on the Changjiang that slows lake drainage, as opposed to short-term fluctuations in tributary discharge. Poyang lake volume at peak stage reached a record high of about 31×10^9 m^3. Lake discharge into the Changjiang peaked at greater than 22 000 cm s^{-1} 2–3 days after maximum tributary flow. Changjiang discharge at the mouth of Poyang Lake ranged from about 53 000 to 61 000 cm s^{-1} for most of July; increased to 70 000 cm s^{-1} on 11 August; and peaked at 75 900 cm s^{-1} on 16 August, which set and still remains a record high. Maximum Poyang Lake drainage increased Changjiang discharge by greater than 30%.

A total of 61 major levees located directly along the Changjiang were breached and large areas of the adjacent alluvial valleys were inundated, resulting in about 33 000 deaths (Dong 1999). Several of the major levees on the southern and western shore of Poyang Lake were overtopped and thousands of square kilometers in the Ganjiang and Fuhe River deltas, which is a densely populated, intense rice-growing region, were submerged (Peng 1999; Dong 1999). Levee failures along the main channel of the Changjiang and around Poyang Lake and other large lakes in this region significantly increased floodwater storage. If most levees had withstood the flood, Changjiang discharge at the mouth of Poyang Lake certainly would have been much higher and resulted in an even high peak lake stage. After the 1954 flood, China undertook an aggressive flood prevention policy that included improvement of existing levees (Zong and Chen 2000). As a result, few levee failures occurred during later floods. Changjiang flow during these events was largely held within the levees. Regardless, discharge along the middle Changjiang, including at the mouth of Poyang Lake during later floods, never exceeded the record high set in 1954.

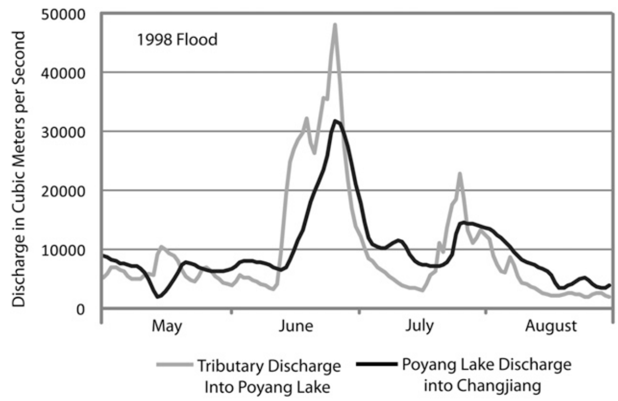

Figure 9. Tributary discharge into Poyang Lake and Poyang Lake discharge into the Changjiang during the 1998 flood.

7. 1998 flood analysis

Forty-four years after the 1954 flood was the great 1998 flood, which was the highest in recorded history (22.5 m), 0.9 m higher than during 1954. May rainfall was slightly below average, and during this time tributary discharge into the lake averaged less than 7000 cm s^{-1}. Above average rainfall at Poyang Lake during summer 1998 began in June, which was about one month later than initial heavy rainfall preceding the 1954 flood. The heaviest rainfall occurred during June and July, which was 2400 (180%) and 3100 mm (320%) above average, respectively (Figure 6). During a 14-day period (13–27 June), tributary discharge increased from about 7000 cm s^{-1} to a peak of 48 000 cm s^{-1}, which greatly exceeded the 1954 peak and was 7 times greater than the average preflood flow. Lake discharge at about the same time increased from a preflood average of 7000 cm s^{-1} to a peak of 32 000 cm s^{-1} (Figure 9).

Poyang Lake stage during late May and early June ranged from 14.4 to 15.9 m. Stage increased rapidly beginning on 15 June and, as during 1954, was related to a dramatic increase in tributary discharge. For the next 15 days, tributary discharge exceeded lake discharge by an average of 12 000 cm s^{-1}. Lake stage on 15 June was 15.1 m, and on June 27 it was 21.4 m, which was a 6.3-m rise in less than 2 weeks. Lake stage remained above 21 m for 16 consecutive days. After falling about 1 m in mid-July, lake stage rose to a second peak greater than 22 m on 27 July and reached maximum stage of 22.5 m on 30 July. Lake stage remained above 22 m, which was 0.4 m above the 1954 maximum stage, for 19 consecutive days. The dramatic increase in lake stage during late June and record high stage in late July correspond to periods when tributary discharge into the lake greatly exceeded lake discharge into the Changjiang.

After the 1954 flood, many new levees were built along the Changjiang and at the margins of Poyang Lake (Min 1999). New levees were constructed directly on riverbanks and along lakeshores, which as mentioned earlier, substantially reduced floodwater storage. Lake volume at peak stage was about 27 × 10^9 m^3. Even though peak lake stage during 1998 was higher than during the 1954 flood, lake volume was about 10% lower. During the 1998 flood, only one major levee on the Changjiang and another on the southern shore of Poyang lake failed, reflecting dramatic improvement in levee construction since 1954. Many smaller, less important levees at the margins of Poyang Lake and along its tributaries were breached. Millions of people were evacuated to higher ground, but few deaths occurred compared to 1954 (Dong 1999; Zong and Chen 2000).

8. Discussion

Severe floods occur when unusually high tributary discharge into Poyang Lake is concurrent with high Changjiang stage that slows lake drainage. Most years during the summer monsoon the Changjiang, when reaching a high stage, back flows into Poyang Lake. Lake stage increases during these events, but high Changjiang discharge is unlikely to cause severe floods on Poyang Lake in the absence of high precipitation and tributary discharge because of the large area available for floodwater storage (Min and Wang 1992; Nakayama and Watanabe 2008). Conversely, high precipitation and tributary discharge into the lake, but with only average Changjiang discharge, is unlikely to result in severe floods because the lake easily drains into the Changjiang.

Poyang Lake stage is dependent on a variety of conditions described in a complex hydrologic model developed by Nakayama and Watanabe (Nakayama and Watanabe 2008). However, during floods, when the lake expands from the eastern shore to Ganjiang levees to the west, so that seasonal wet–dry areas are submerged, the major factors determining lake stage can be described in simpler terms as follows:

$$\text{Stage} = Q\downarrow + Q\uparrow(d),$$

where $Q\downarrow$ refers to tributary discharge into Poyang Lake and $Q\uparrow(d)$ is lake discharge into the Changjiang (which can take on negative values) that is a function of d, hydraulic potential (determined by the slope of the water surface based on the difference between lake and river stage and Changjiang velocity).

Changjiang discharge at Hukou during the 1954 flood set a record high that has not been exceeded. Maximum discharge during the 1998 flood was only slightly lower. During both floods, a dramatic rise in $Q\downarrow$ during the early and midsummer increased d and therefore $Q\uparrow$. Lake discharge during the 1954 and 1998 floods was much higher than most years, even though the Changjiang also was at a very high stage. According to Hu et al. (Hu et al. 2007), the Changjiang during the 1998 flood should not be viewed as having a strong blocking effect on lake drainage. This assessment was based on large lake discharge when at a high stage. If, however, the Changjiang was at a lower stage, the lake would drain even more rapidly and would have reached a lower maximum level than otherwise occurred. We therefore recognize high Changjiang discharge as a significant contributor to major floods. The most severe floods, such as those in 1954 and 1998, require both 1) high rainfall and tributary discharge into Poyang Lake and 2) high Changjiang discharge and stage at Hukou that blocks Poyang Lake drainage. Since gauging stations were established on the Changjiang, these conditions always occurred following an El Niño.

A primary justification for building the Three Gorges Dam, which is on the Changjiang upstream of Poyang Lake, was flood control (for a review of this topic, see Edmonds 1992). However, there is strong evidence that, contrary to flood control objectives, these changes will not reduce peak discharge during the most severe floods in the Poyang Lake region. The Three Gorges Dam can be used to hold back floodwater during the summer for common annual floods, but the reservoir's storage capacity is too small to significantly reduce downstream discharge during the most severe floods. Two studies estimated potential peak discharge and stage, respectively, at Hukou after dam construction for hydrologic conditions similar to those occurring during the 1954 flood. Hu and Zhu (Hu and Zhu 1998) calculated that Changjiang discharge during the late summer months for a flood event of this magnitude would be unchanged after dam construction. Similarly, Liu and Wu (Liu and Wu 1999) calculated river stage would be unaffected. These findings are consistent with other studies reporting the dam's inability to have a substantial effect on Changjiang discharge during the most severe floods (Hartmann et al. 2004; Li et al. 2004).

Postdam construction, channel incision along the middle Changjiang, will increase channel capacity in the zone nearest the dam, resulting in lower river stage (Xu and Milliman 2009). Increasing floodwater storage has been planned along this section of Changjiang, which is far upstream of Poyang Lake (Li et al. 2004). Channel incision along the middle Changjiang will increase channel capacity and lower river stage so that during major floods the Changjiang will be below the level needed for floodwater to access these areas. An undiminished discharge will move downstream because the river is unable to spread into planned retention areas and the Three Gorges reservoir is too small to hold back water during the most severe floods. Further, according to the Changjiang Science Academy and China Academy of Science, the Three Gorges Dam will result in long-term channel aggradation along the middle Changjiang, including at the mouth of Poyang Lake, that will reduce channel capacity and force the river to a higher stage than would otherwise occur (Li et al. 2004). Not all studies are consistent with these findings. Wang et al. (Wang et al. 2007) provided evidence for channel bed stability or incision during the coming decades as opposed to aggradation.

Poyang Lake provides a large area of floodwater storage that must be considered when evaluating the causes of severe floods. Nakayama and Watanabe (Nakayama and Watanabe 2008) examined the influence of floodwater storage of large lakes on the middle Changjiang. They noted that Poyang Lake has an important flood storage function and calculated that an increase in floodwater storage so that the lake had a volume equal to that in 1954 would substantially moderate peak stage. Since the 1998 flood, the Jiangxi Provincial government has set a goal of increasing floodwater storage to be equivalent of that during the 1954 flood and that this would be accomplished by removing levees built in recent decades. The period of widespread levee construction ended during the 1990s, and since then many levees have been removed, forcing the relocation of hundreds of thousands of farmers from counties surrounding the lake (Jiang 2006). Regardless of the extent of levee removal, flood storage capacity is certainly much less now than during 1954 (Shankman et al. 2009). That year many of the large levees were overtopped, resulting in vast areas of the Ganjiang and Fuhe delta going underwater. Poyang Lake levees are higher and better able to withstand severe floods, so less area is available for floodwater storage compared to the 1950s. As such, Poyang Lake is still susceptible to severe floods. Considering the smaller area available for floodwater storage and the Three Gorges Dam limited ability to affect discharge during severe floods, if rainfall patterns and tributary discharge in addition to high Changjiang discharge match those that occurred during 1954, lake stage will almost certainly exceed the 1998 record.

References

Chen, Y. C., and H. J. Lu, 2003: An analysis of the variation of maximum flood stage of the Lower Yangtze River. *J. Hydraul. Res.,* **41,** 235–238.

de Leeuw, J., D. Shankman, G. Wu, W. F. de Boer, J. Burnham, Q. He, H. Yesouand, and J. Xiao, 2010: Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China. *Reg. Environ. Change,* **10,** 95–102.

Dong, Z. Y., 1999: On '98 extraordinary flood in Chang Jiang River valley of China. *Proc. 28th Int. Association of Hydraulic Engineering and Research Congress,* Graz, Austria, IAHR.

Edmonds, R. L., 1992: The Sanxia (Three Gorges) project: The environmental argument surrounding China's super dam. *Global Ecol. Lett.,* **2,** 105–125.

Hartmann, K., S. Becker, and L. King, 2004: The Three-Gorge project: Its influence on the flood risk along the middle reaches of the Yangtze River and on the economy of the region surrounding the reservoir. *Climate Change and Yangtze Floods,* T. Jiang et al., Eds., Science Press, 396–404.

Hu, Q., S. Feng, H. Guo, G. Y. Chen, and T. Jiang, 2007: Interactions of the Yangtze River flow and hydrologic processes of the Poyang Lake, China. *J. Hydrol.,* **347,** 90–100.

Hu, X. Y., and H. F. Zhu, 1998: Three-Gorges project and flood protection of important cities in the Poyang Lake region (in Chinese). *J. Jiangxi Norm. Univ.,* **22,** 365–370.

Huang, R. H., W. Chen, B. L. Yan, and R. H. Zhang, 2004: Recent advances in studies of the interaction between the East Asian winter and summer monsoons and ENSO cycle. *Adv. Atmos. Sci.,* **21,** 407–424.

Jiang, L. G., 2006: Flood risk and land use change in the wetland restoration area around Poyang Lake, China (in Chinese). Ph.D. thesis, Chinese Academy of Science, 112 pp.

Jun, X., and Y. D. Chen, 2001: Water problems and opportunities in the hydrological sciences in China. *Hydrol. Sci.,* **46,** 907–921.

Li, G. X., Y. X. Jie, and Q. Y. Li, 2003: Yangtze Dyke and its strengthening. *Lowland Technol. Int.,* **5,** 39–46.

Li, R. Z., D. K. Xiong, and Y. Liu, 2004: Future change in the Poyang Lake wetland ecosystem (in Chinese). *Poyang Lake Wetland Ecosystem Evaluation,* X. H. Wang, Ed., Science Press, 151–173.

Liu, X. D., and D. Y. Wu, 1999: Brief analysis of the effect of the Poyang Lake water level in flood period by the Three-Gorges project (in Chinese). *Jiangxi Hydraul. Sci. Technol.,* **25,** 71–75.

Min, Q., 1992: Preliminary analysis of Poyang Lake relatively big flood occurrence characteristics during the past 500 years (in Chinese). *Jiangxi Hydraul. Sci. Technol.,* **18,** 76–83.

——, 1999: Impact evaluation of Poyang Lake reclamation on floods (in Chinese). *Yangtze River,* **7,** 30–32.

——, and Z. P. Wang, 1992: The varying tendency of the water level of the Poyang Lake in recent 40 years (in Chinese). *Jiangxi Hydraul. Sci. Technol.,* **18,** 360–364.

Nakayama, T., and M. Watanabe, 2008: Role of flood storage ability of lakes in the Changjiang River catchment. *Global Planet. Change,* **63,** 9–22.

Peng, Z., Ed., 1999: *Jiangxi Province Levee Atlas* (in Chinese). Jiangxi Provincial Government Levee Department, 120 pp.

Ren, G., Z. Chen, and H. Yang, 2004: Variation of precipitation and runoff in the Yangtze River catchments since 1960. *Climate Change and Yangtze Floods,* R. Jiang et al., Eds., Science Press, 224–234.

Samel, A. N., and X. Z. Liang, 2003: Understanding relationships between the 1998 Yangtze River flood and northeast Eurasian blocking. *Climate Res.,* **23,** 149–158.

——, S. W. Wang, and W. C. Wang, 1995: A comparison between observed and GCM-simulated summer monsoon characteristics over China. *J. Climate,* **8,** 1690–1696.

Shankman, D., B. D. Keim, and J. Song, 2006: Flood frequency in China's Poyang Lake region: Trends and teleconnections. *Int. J. Climatol.,* **26,** 1255–1266.

——, L. Davis, and J. de Leeuw, 2009: River management, landuse change, and future flood risk in China's Poyang Lake region. *Int. J. River Basin Manage.,* **7,** 423–431.

Su, B. D., T. Jiang, and W. B. Jin, 2006: Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China. *Theor. Appl. Climatol.,* **83,** 139–151.

Trenberth, K. E., 1997: The definition of El Nino. *Bull. Amer. Meteor. Soc.,* **78,** 2771–2777.

Wang, S. J., Z. Y. Chen, and D. G. Smith, 2005: Anastomosing river system along the subsiding middle Yangtze River basin, southern China. *Catena,* **60,** 147–163.

Wang, Z.-Y., and E. J. Plate, 2002: Recent flood disasters in China. *Water Marit. Eng.,* **154,** 177–188.

——, Y. Li, and Y. He, 2007: Sediment budget of the Yangtze River. *Water Resour. Res.,* **43,** W04401, doi:10.1029/2006WR005012.

Wu, G. F., J. de Leeuw, A. K. Skidmore, H. H. T. Prins, and Y. L. Liu, 2007: Concurrent monitoring of vessels and water turbidity enhances the strength of evidence in remotely sensed dredging impact assessment. *Water Res.,* **41,** 3271–3280.

Xu, K. H., and J. Milliman, 2009: Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. *Geomorphology,* **104,** 276–283.

Zong, Y. Q., and X. Q. Chen, 2000: The 1998 flood on the Yangtze, China. *Nat. Hazards,* **22,** 165–184.