INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **26**: 1255–1266 (2006)

FLOOD FREQUENCY IN CHINA'S POYANG LAKE REGION: TRENDS AND TELECONNECTIONS

DAVID SHANKMAN,[a,]* BARRY D. KEIM[b] and JIE SONG[c]
[a] *Department of Geography, University of Alabama, Tuscaloosa, Alabama 35487-0322, and Adjunct Professor, Key Lab of Poyang Lake Ecological Environment and Resource Development, Jiangxi Normal University, China*
[b] *Louisiana Office of State Climatology, Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[c] *Department of Geography, Northern Illinios University, DeKalb, Illinios 60115, USA*

Received 14 April 2005
Revised 6 October 2005
Accepted 6 December 2005

ABSTRACT

Poyang Lake in Jiangxi Province is the largest freshwater lake in China and is historically a region of significant floods. Annual events of peak lake stage and of severe floods have increased dramatically during the past few decades. This trend is related primarily to levee construction at the periphery of the lake and along the middle of the Changjiang (Yangtze River), which protects a large rural population. These levees reduce the area formerly available for floodwater storage resulting in higher lake stages during the summer flood season and catastrophic levee failures. The most severe floods in the Poyang Lake since 1950, and ranked in descending order of severity, occurred in 1998, 1995, 1954, 1983, 1992, 1973, and 1977. All of these floods occurred during or immediately following El Niño events, which are directly linked to rainfall in central China. The 2-year recurrence interval for maximum annual lake stage during El Niño years is 1.2 m higher than during non-El Niño years. The 10-year recurrence interval is 1.4 m higher during El Niño years than during non-El Niño years. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: China; climate variability; flooding; El Niño-Southern Oscillation; Poyang Lake

1. INTRODUCTION

The Poyang Lake in Jiangxi Province is the largest lake in China, covering about 4000 km^2 during high water levels (Figure 1). The area immediately surrounding Poyang Lake consists of low-lying alluvial plains prone to floods. The mountains near the boundaries of Jiangxi surround this region and all the five major rivers in this province flow into the Poyang Lake. Poyang Lake drains through a narrow outlet into the Changjiang (Yangtze River), which is the longest river in China. Poyang Lake, and the lower sections of large rivers flowing into the lake, regularly flood during the summer wet season. Several of the floods since the early 1950s have been classified as severe events. The largest flood ever recorded was during 1998 when for several consecutive weeks the lake and river stages exceeded historic highs. Catastrophic levee failures occurred along the lake boundaries and the lower sections of tributary rivers, resulting in extensive agricultural losses, damage to several cities and many agricultural villages, and massive population relocation (Shankman and Liang, 2003).

From 1950 to 1998, there were seven years during which Poyang Lake had severe floods, defined as a stage when the water level exceeded 20.5 m (above msl). During 1954, Poyang Lake had the highest water level ever recorded till then. This record held until 1995 when the maximum stage was slightly higher. The great flood of 1998 occurred three years later. All of these flood events in the Poyang Lake region occurred

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* Correspondence to: David Shankman, University of Alabama, Geography, Tuscaloosa, Alabama, USA;
e-mail: Shankman@bama.ua.edu

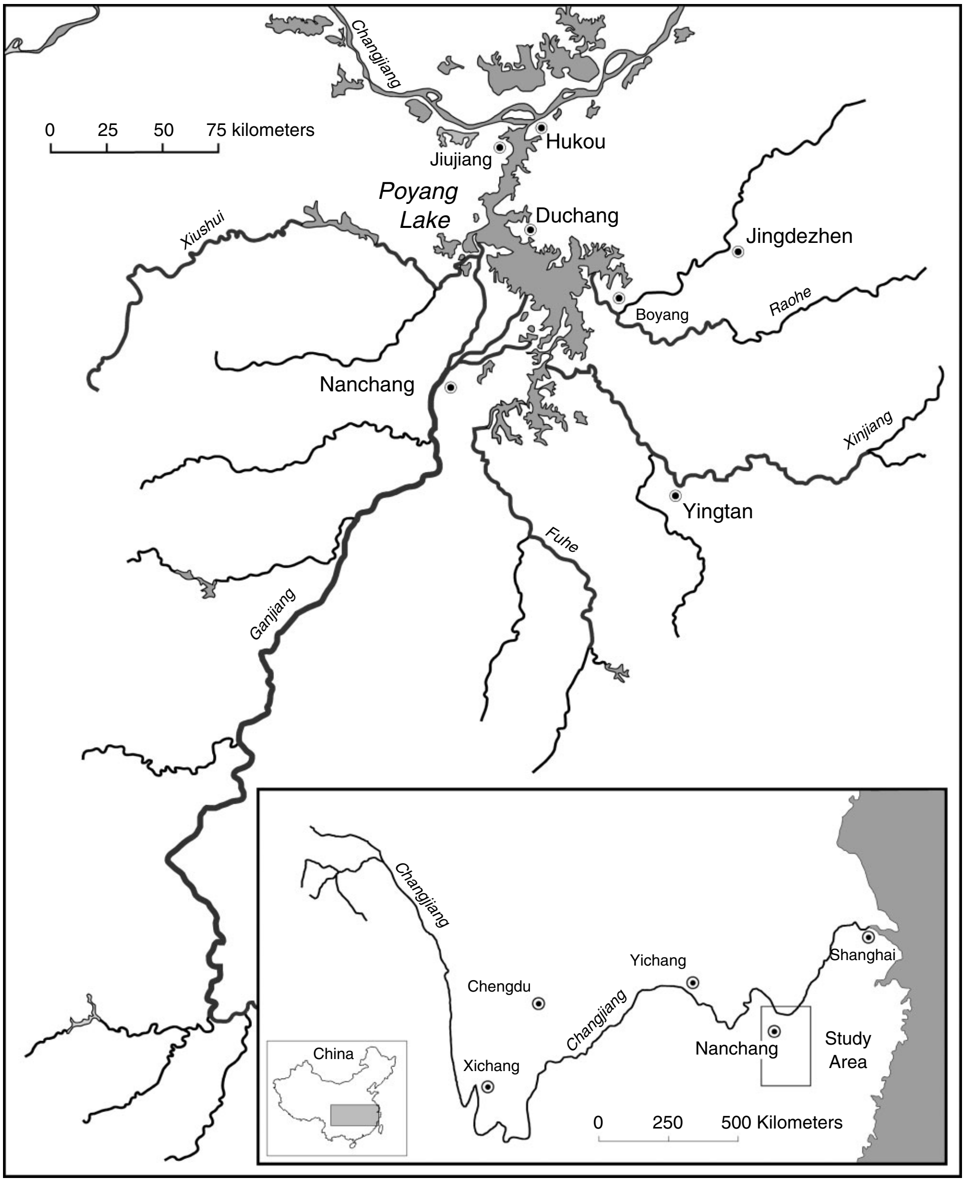

Figure 1. Map of the Poyang Lake drainage basin

during or immediately following El Niño events. This paper investigates the Poyang Lake stage data from 1950 to 1998 (the latest year lake stage data are available from the Jiangxi Provincial Government Bureau of Hydrology) to determine the impact of El Niño on floods in this region. Specifically, we (1) describe a time series of annual maximum lake stages, (2) develop flood recurrence intervals for El Niño and non-El Niño years, and (3) discuss the impact of recent changes in land use and flood control techniques that will likely affect the severity of future flood events.

2. REGIONAL OVERVIEW

The Poyang Lake watershed area is 162 000 km^2. The size of the Poyang Lake surface area fluctuates greatly throughout the year. During the summer wet season, the lake surface area can exceed 4000 km^2. During the relatively dry fall and winter, the lake surface elevation decreases and the lake area will typically shrink to less than 3000 km^2. Drainage for Poyang Lake, and therefore almost all of Jiangxi, is a narrow outlet into the Changjiang, which lies on the northern border of the province. Headwaters of the Jiangxi rivers are located in the surrounding mountains that are areas of high local relief. The five major rivers in Jiangxi flowing into the Poyang Lake are the Xuishui, Ganjiang, Fuhe, Xinjiang, and Raohe (Figure 1). Stream gradient decreases as these rivers flow onto the relatively flat region surrounding the Poyang Lake. The lower sections of the Jiangxi rivers meander through broad alluvial valleys. Sediment deposition from the Jiangxi rivers, most notably the Ganjiang and the Fuhe, has created a large delta plain on the southern and western shores of the Poyang Lake, which is dissected by its distributaries. The Ganjiang is the largest river in the region extending 750 km. It contributes 55% of the total discharge into the Poyang Lake and carries by far the greatest sediment load.

The Poyang Lake water level is determined primarily by the water surface elevation of the Changjiang, and to a lesser extent by the discharge from the Jiangxi rivers. The rainy season in Jiangxi usually begins in April. Typically, the Jiangxi rivers' discharge increases from April to June, raising the level of water in Poyang Lake, which drains into the Changjiang (Figure 2). From July to September, the Jiangxi rivers' discharge decreases. However, at the same time the Changjiang water level increases because of the summer concentration of rainfall and snowmelt in the mountainous headwaters region in western China. As a result, usually in mid July, the direction of water flow from the lake into the Changjiang reverses and water begins to flow from the Changjiang into the Poyang Lake. Maximum discharge from the Changjiang typically occurs during the mid to late summer months. The most severe floods in the Poyang Lake region occur when a high discharge from the Jiangxi rivers occurs later than normal in summer while the level of the Changjiang is also high.

The Jiangxi Province is in the center of China's rice growing region. The river deltas surrounding Poyang Lake and the broad alluvial valleys of tributary streams support intensive cultivation. Most counties surrounding Poyang Lake have a rural population density of 400–800 persons/km^2 (Su *et al.*, 1993). Because of the high population density in rural Jiangxi, the average amount of agricultural land per farmer ranges from only 1000 to 1500 m^2. An extensive levee system to protect low-lying areas from floods has been in place for centuries. Before 1950 the total length of levees in Jiangxi was about 3100 km. During that time, the largest levees were high enough to afford protection from the expected yearly floods but were inadequate during severe flood events. Since the 1950s, major levee construction projects have increased the levee heights and the area of flood protection. There are now about 6400 km of levees that afford protection to 10 000 km^2 of farmland and to a population of about 10 million people who live in the low-lying areas at the margins of Poyang Lake and in the alluvial valleys along the large rivers in this region (Peng, 1999).

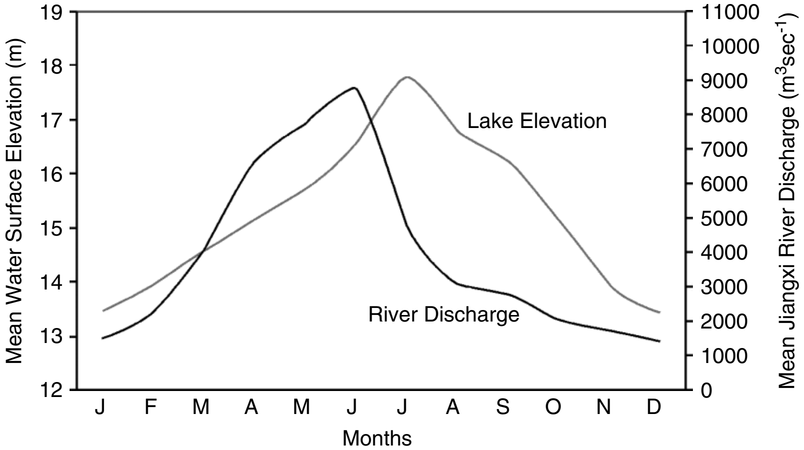

Figure 2. Mean monthly Poyang Lake stage and Jiangxi river discharge, 1954–2000

3. ENSO AND THE ASIAN MONSOON

The intensity of the Asian summer monsoon, which influences precipitation in both northern and southern China, is teleconnected with El Niño-Southern Oscillation (ENSO) events (Diaz and Fu, 1984; Guo, 1984; Whetton *et al*., 1990; Whetton and Rutherfurd, 1994). The Pacific subtropical high-pressure over the western North Pacific Ocean controls the progress and retreat of the summer monsoon over East Asia. The strength and location of the subtropical high plays a decisive role in determining the location of rain belts and quantity of precipitation in China during the summer wet season. Three key parameters are normally used to describe the characteristics of the subtropical high: (1) subtropical high-pressure area bounded by a specified geopotential height, normally at a value of 5880 geopotential meters on a 500-hPa map, (2) the longitude of its westward extruding edge, and (3) the latitude of the east–west oriented subtropical ridge line, which is defined as the highest pressure points connected within the subtropical high-pressure area. These parameters have a high correlation with precipitation in the Changjiang valley that includes the Poyang Lake watershed (Cai *et al*., 2003). Impacts on the location and intensity of the subtropical high, however, can lag by about 6 months or more from the ENSO event, thus, El Niño impacts can still take place months after the event (Huang *et al*., 2004).

During normal years, active Intertropical Convergence Zone development and the Hadley circulation lead to the formation of western Pacific subtropical high-pressure with an east–west ridge line at 500 hPa, migrating from south to north successively (Zhang and Jiang, 2001). The movement of anticyclonic circulation creates southeast and southwest monsoon winds that transport moisture into south and central China. In April and May of a normal or La Nina year, the subtropical high intensifies and migrates westward and northward, with a ridgeline of high-pressure anchored near 23 °N latitude. In June, the Changjiang valley is controlled by the western edge of the subtropical high, which frequently advects warm moist air from the southeast. When this warm and humid air mass encounters cold air from the arid north, the warmer southeasterly air flow is usually lifted along a stationary front causing abundant overrunning rainfall called 'plum rain' or 'meiyu' (Samel *et al*., 1995). During early or mid July in a normal year, the subtropical high migrates northward again with a ridge line of high-pressure settling at 30 °N. As a result the plum rain ceases, and hot and dry weather dominates this region because of the control of the subtropical high.

During El Niño events the Pacific trade winds weaken dramatically, leading to a reduction in intensity or reversal of the Walker circulation. The primary area of uplift within the Walker circulation then shifts from the western Pacific to the International Date Line. A composite of the 500-hPa pattern of the seven greatest flood years during or immediately following an El Niño shows the strengthening of the subtropical high in the western Pacific near the South China Sea and the location of its ridge line remaining persistently southward rather than migrating northward with time (Figure 3(A)). This persistent pattern of the subtropical high in the South China Sea can also be illustrated through examination of the difference in geopotential heights at 500 hPa between high flood years associated with El Niño and low flow years (Figure 3(B)). The positive departures in 500-hPa heights near the South China Sea is evidence of its persistence in the area, and the negative heights in the northwestern Pacific depicts the lack of northward migration during the great flood events on the Poyang Lake. As a result, the low level divergence at the western edge of the subtropical high, which is located in southeast Asia during El Niño years, favors warm and moist air moving northward (inland) to the Changjiang basin, promoting active and persistent plum rains. Thus, the southward location of the subtropical high is in a position to cause flooding in the Changjiang river valley, including Poyang Lake. Examining a reconstructed time series of the Southern Oscillation Index, a commonly used ENSO indicator, Song (1998) found a noticeable increase in the frequency of ENSO occurrence since the 1950s, flooding and drought events in China have increased correspondingly (Song, 2000).

With regard to the 1998 Poyang Lake flood, heavier than normal snowpack accumulated in the QingHai and Tibetan plateaus during the spring before the floods. These plateaus are in the headwater region of the Changjiang and the snowmelt there was a major contributor to the increased Changjiang discharge during the summer (Chen, 2001). Further, because of higher albedos over the extensive snow cover, a strong energy drop over the continent resulted in a forceful meridional circulation and winter monsoon. The stronger northwest monsoon wind delayed the onset of the summer monsoon circulation. This favored a persistently blocking

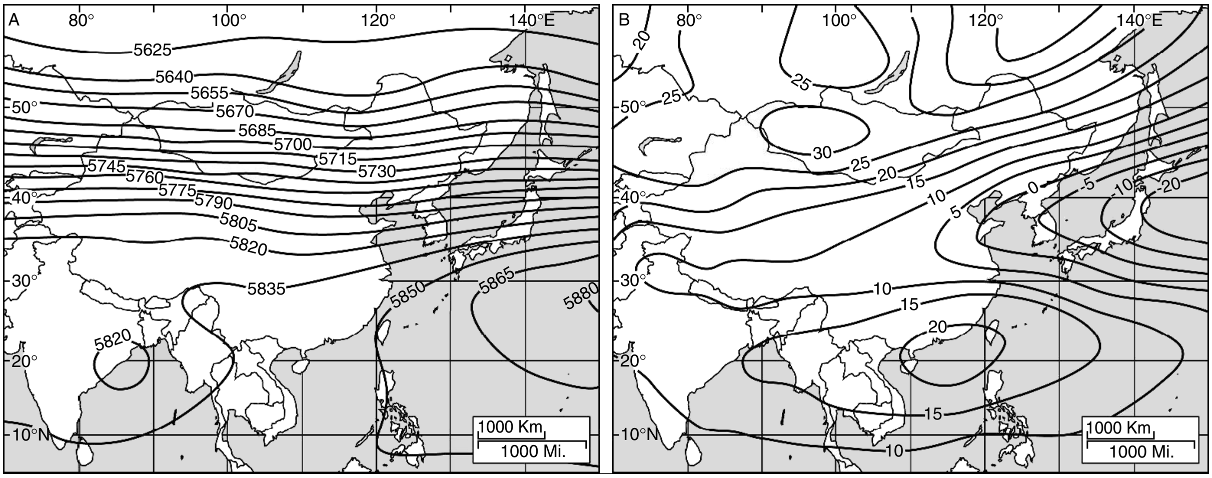

Figure 3. Composite upper air configuration at 500 hPa for (A) summers (JJA) during the seven severe flood years (1954, 1973, 1977, 1983, 1992, 1995, 1998), and (B) difference in summer 500-hPa elevations between the severe flood years and seven years with the lowest maximum annual lake stage. Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado from their website at <http://www.cdc.noaa.gov/>

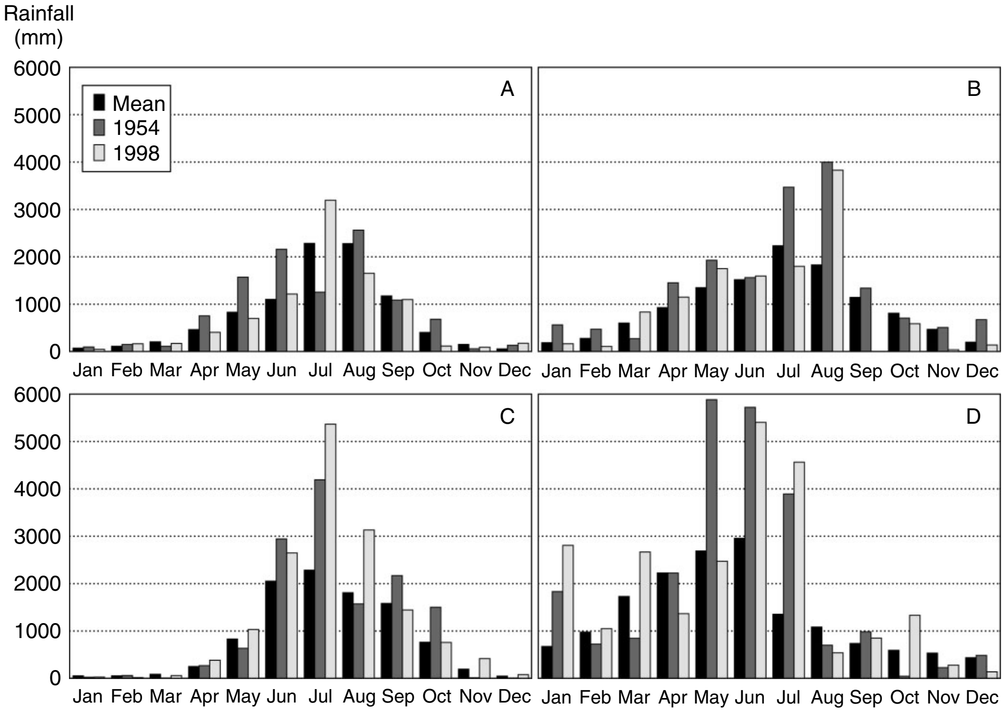

Figure 4. Monthly precipitation during 1954 and 1998, and average monthly precipitation (1951–2000) for recording station in the Changjiang river valley: (A) Xichang, (B) Chengdu, (C) Yichang, (D) Nanchang. Location of each station is shown in Figure 1. Source: Global Historical Climate Network, National Climatic Data Center

high-pressure pattern in the mid and high latitudes over Asia, and a weakened and southward withdrawn subtropical high-pressure system at the low latitudes (Samel and Liang, 2003). As the result, warm and moist air from the western edge of the southward subtropical high-pressure could not reach the midlatitudes, causing bitter drought in northern China but higher than normal rainfall in southern China. At the Nanchang recording station near Poyang Lake, the precipitation for June and July 1998 were 5400 mm (2500 mm above average) and 4500 mm (3300 mm above average), respectively (Figure 4). The precipitation upstream on the Changjiang showed a similar pattern. Summer precipitation during 1954 was also well above the average, although peak floods during that year occurred earlier in the summer compared to 1998.

4. ANNUAL MAXIMUM LAKE STAGES

The annual average maximum stage for Poyang Lake is 19.2 m (above msl), but is significantly higher or lower during unusually wet or dry years. The lowest annual peak stage during the period of record was 16 m during 1972 (Figure 5). Lake stage greater than 19.5 m at the Duchang recording station on the eastern shore of the lake is considered to be a major flood event. From 1950 to 1998 there were 16 years during which the lake stage exceeded the level of 19.5 m, or about once in every three years. The Lake stage exceeding 20.5 m is classified as a severe flood by Min (2000) and occurred seven times during the period of record (1954, 1973, 1977, 1983, 1992, 1995, 1998), or about once every six years. The 1954 flood was the largest ever recorded until the 1990s. During the 1950s the levees were not high enough to protect low-lying areas and the 1954 flood caused severe economic losses. In 1995, the lake stage was slightly higher than it was during the 1954 flood. Three years later occurred the great flood of 1998, which was the largest flood ever recorded. The Poyang Lake reached 22.4 m, which exceeded the previously recorded highest water level by 0.6 m. For 23 consecutive days the lake stage exceeded the high levels recorded in 1995. The downstream sections of the Jiangxi rivers were also at historic high levels.

The maximum annual stage and the number of severe floods in the Poyang Lake have increased rapidly during the past few decades. The linear regression line shown on Figure 5 indicates a statistically significant positive trend ($p = 0.002$). During the 1950s the average level of the annual maximum stage was 18.5 m. The lake stage exceeded 19 m only in two years during this decade. The increased average peak stage was strongly influenced by the 1954 maximum flood stage of 21.8 m, which until the 1990s was the greatest flood ever recorded in the region. In contrast, during the nine years of available data from 1990 to 1998, the average annual maximum lake stage was 20.4 m, which is 1.9 m higher than that during the 1950s. Also, during the 1990s the maximum lake stage was greater than 19 m in every year and exceeded 20 m in four years. The average annual summer rainfall in the Changjiang river basin has increased during the last four

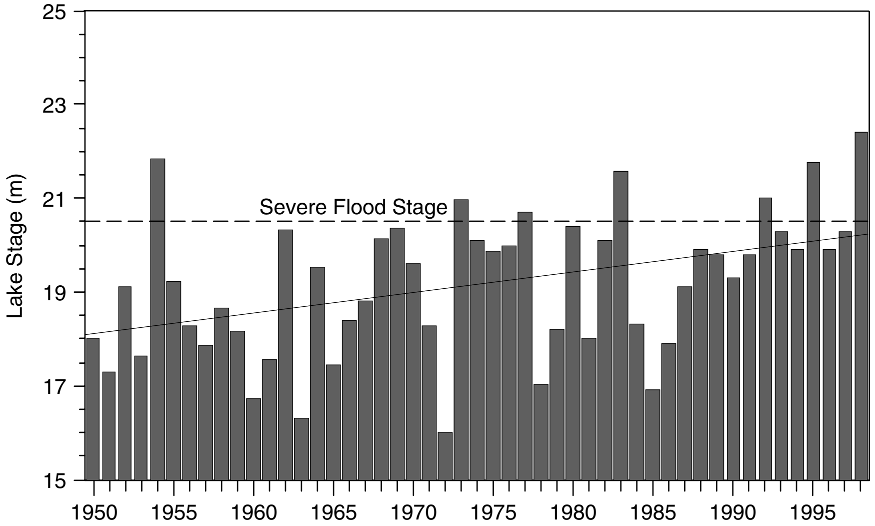

Figure 5. Annual maximum Poyang Lake stage with linear regression trend slope, 1950–1998. Flood stage from Min (1999)

decades (Ren *et al.*, 2004). However, this is a weak trend that is mostly defined by the data from 1992, 1995, and 1998, during which time severe Changjiang floods occurred.

Shankman and Liang (2003) identified land reclamation and levee construction as the major factors responsible for the increase in the frequency of severe floods. The area and volume of Poyang Lake has decreased significantly because of land reclamation. Use of levees to protect the reclaimed land began centuries ago. However, in recent decades, land reclamation has become more common. In most cases, the shallow areas at the lake margins protected by levees have not been filled and therefore are likely to be submerged if nearby levees fail. The total land reclaimed from 1954 to 1998 was 1300 km^2, which resulted in a decrease in the surface lake area from 5160 km^2 to 3860 km^2 – a 25% decrease during the 44-year period. The surface area of the lake during the peak of the 1998 flood was much greater than in the previous years because of levee failures that allowed the water to spread beyond the normal high water boundaries. Reclamation occurred along the shallow margins of the lake and did not affect the deeper areas. Therefore, the reduction in lake volume because of the reclamation during the same period was not as significant. Lake volume during this 41-year period decreased 22%, from 37 to 28.9 billion m^3 (Figure 6).

There are two other factors that are likely responsible for the increased severity of the Poyang Lake floods; lake sedimentation and higher Changjiang stage. The impact of both is probably much less than that of levee construction. Although the buildup of sediment has not reduced the lake volume to the same extent as land reclamation, its effects are significant. From 1956 to 1985, average annual sediment deposition was 13.15 million tons, causing an average lakebed accumulation of 0.2 cm per year, or about 10 cm every 50 years (Zhu *et al.*, 1987). Min (1999) estimated that sediment deposition reduced the total volume of Poyang Lake by 4.8% during 1954–1997. The levee system in the delta of Ganjiang and Fuhe has increased the sediment deposition in the lake. The levees prevent floodwater from spreading out across the extensive floodplain surfaces. Normally, the water slows down as it moves out of the channel and across the floodplain and deposits the sediments that would build up into progressively higher surfaces on the alluvial plains. However, the levees restrict the water to the channels, which continue to carry most of the sediment into the lake.

The frequency of occurrence of the high water level on the Changjiang has increased throughout the twentieth century. From 1904 to 1940, the Changjiang near Hukou reached the 20 m level seven times or on average once every 5 years; from 1941 to 1983, 16 times or once every 2.5 years; and from 1970 to 1998, 14 times or once every 2 years (Hu and Zhu, 1998). As already noted, the higher Changjiang stage usually occurs during July and August, which is later than the early summer flooding of Poyang Lake. The Poyang Lake water level depends mostly on the Changjiang. However, an increased Jiangxi river discharge later than normal during summer and therefore concurrent with the high Changjiang discharge will increase the probability of floods. High river discharge into the Poyang Lake already at flood stage will cause the rivers to backup and the upstream sections will reach a higher water level than would occur otherwise.

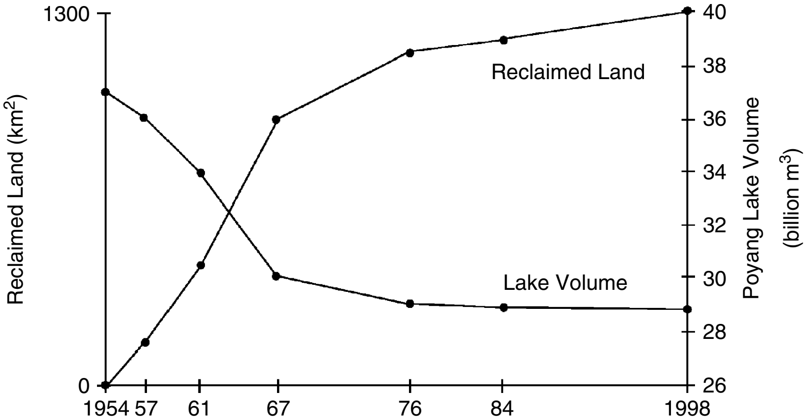

Figure 6. Total amount of reclaimed agricultural land and decrease in Poyang Lake volume (based on water surface elevation of 22 m), 1954–1998. (Source: Min, 1999)

5. FLOOD HISTORY AND ENSO

5.1. Detrended annual maximum lake stage time series

The annual maximum series shown in Figure 5 was detrended using a linear least-squares regression fit to the data. The detrended time series set the slope of the data to zero, and the analysis is performed on the deviations from the slope. This allows for a relative comparison of specific flooding events from different decades, minus the overall upward trend during the 49-year period (Figure 7). The 1998 flood was the most severe on the basis of the lake stage. However, this flood event ranked second on the basis of 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 for any previous decade on record. The 1973 and 1983 floods were 1.8 m and 2.0 m, respectively, above the trend-line, and the 1954 flood was 3.6 m above the 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 the later flood events. Although not the highest flood, it caused severe economic damage. Most levees at that time were neither high enough nor strong enough to protect low-lying areas at the margins of Poyang Lake. From this point of view, the 1954 flood was the most severe ever recorded.

5.2. Flood recurrence intervals and effects of El Niño

The entire peak annual flood stage time series was analyzed for their association with the ENSO. Twenty annual maximum flood stages were classified as El Niño events (on the basis of the flood stages in these years occurring during or immediately following an El Niño), while the remaining 29 were classified into the non-El Niño events (Figure 7). These frequencies are in general agreement with the results of Trenberth (1997). All seven of the severe floods (lake stage >20.5 m) and 14 of the 16 major floods (lake stage >19.5 m) on the Poyang Lake occurred during or immediately following El Niño events. An interesting exception occurred during 1978. The flood stages of this year are classified as an El Niño event, yet the Poyang Lake stage that summer was far below average.

The detrended time series was split into two mutually exclusive series: one an annual series following an El Niño event, and the other including the combination of all neutral and La Nina conditions. El Niño events were determined using the El Niño 3.4 sea-surface temperature (SST) anomalies. Thus, an El Niño event was defined as occurring anytime the 5-month average departure was equal to or greater than 0.4 °C as

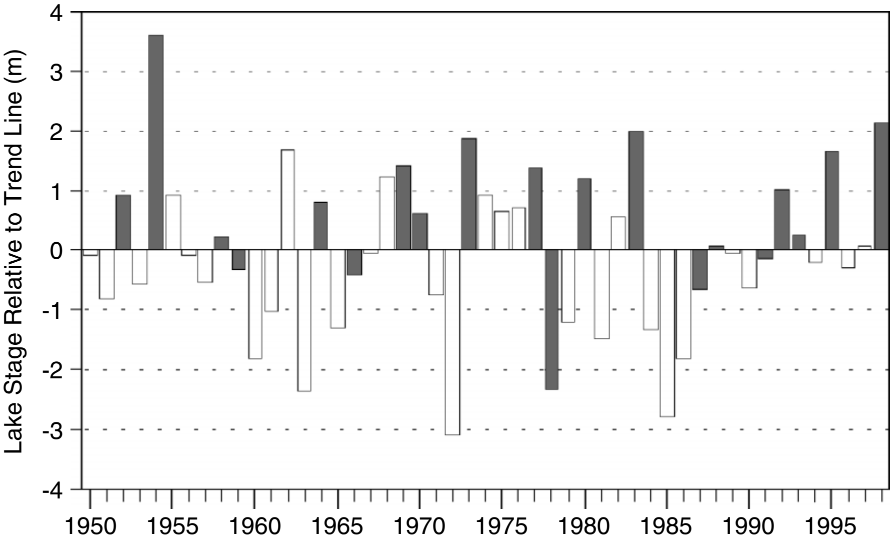

Figure 7. Detrended annual maximum series Poyang Lake stage represented as a deviation (in meters) from the trend slope shown in Figure 4. Shaded bars indicate years during or immediately following El Niño events

recommended by Trenberth (1997) for the fall (SON), winter (DJF), or spring (MAM) prior to the summer (JJA) peak lake stage, or during the summer in which the peak stage is reached. This definition for an El Niño event, which includes a broad timescale, was used because the effects of warm SST's on upper air circulation in south Asia lag several months after the event, a point already discussed.

El Niño conditions are clearly associated with the more severe floods on Poyang Lake. The recurrence intervals are adjusted to the average annual maximum stage during the late 1990s to reflect the most current hydrologic conditions for which data are available. For extreme value analysis, Gumbel (1958) distribution was selected because (1) of its common usage (Hershfield, 1961; Keim and Faiers, 1996, among others) and (2) it produces lower values at the 50- and 100-year intervals compared to other distributions (Wilks, 1993; Keim and Faiers, 2000), which is appropriate for these data as levees are overtopped. Quantile estimates for maximum lake stage indicate that a flood with a 2-year recurrence interval during El Niño years (20.8 m) is 1.2 m higher than during non-El Niño years (19.6 m) (Figure 8). The 5-year recurrence interval is about 1.4 m higher during El Niño years. During an El Niño event the level of the 5-year flood event is 21.9 m, which exceeds the Min (2000) classification of a severe flood event (>21.5 m) by 0.4 m. As noted earlier, during the 1998 flood, the Poyang Lake stage reached 22.4 m. This was an El Niño year and this flood was classified as an 8-year event using detrended data.

As you move toward the rarer end of the distribution, there is a clear trend showing an increasing difference between El Niño and non-El Niño years when comparing recurrence intervals. For example, the recurrence interval differences between these two series for 50- and 100-year events are 1.5 m and 1.6 m, respectively. However, we are reluctant to draw strong conclusions about this trend. There are several factors that must be taken into account when evaluating future flood risk, including new flood control projects, lake sedimentation

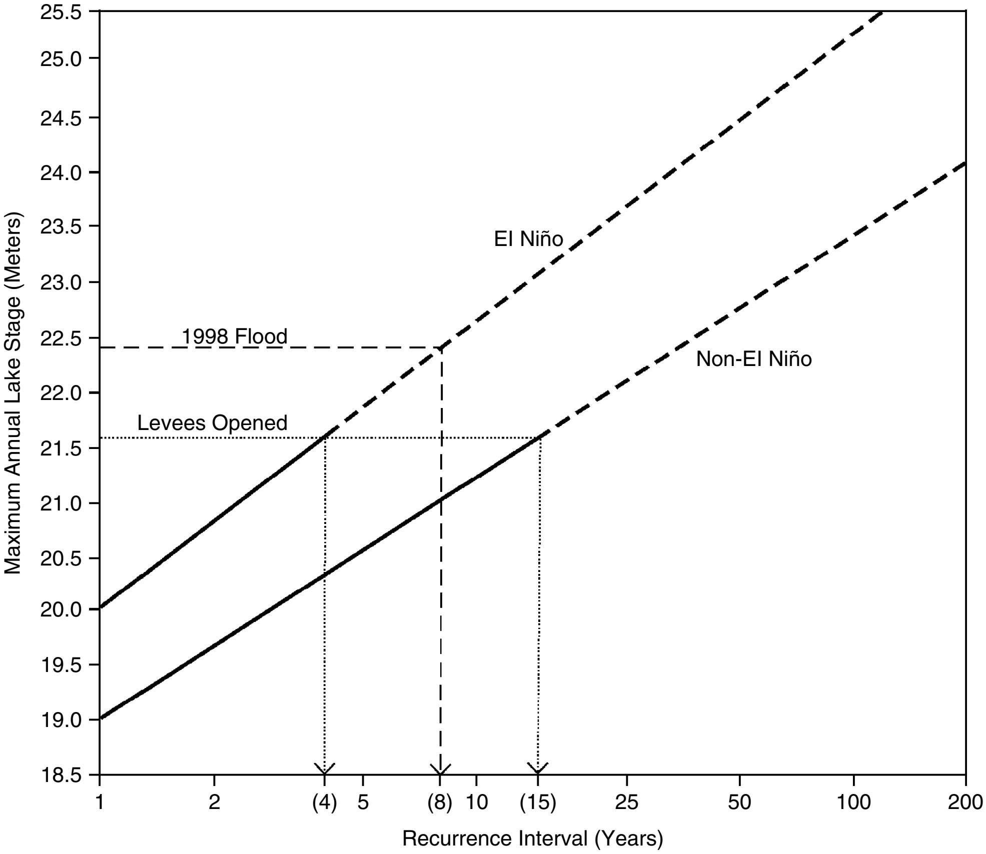

Figure 8. Recurrence intervals for Poyang Lake maximum annuals stages during El Niño and non-El Niño events

that reduces lake volume, and the completion of the Three-Gorges Dam on the Changjiang upstream of Poyang Lake, which may affect lake drainage during flood events. Each of these factors are discussed in the concluding section that addresses future flood risk.

6. FUTURE FLOOD RISK

ENSO is a major determinant of precipitation patterns in the Changjiang drainage. All of the severe floods in the Poyang Lake region occurred during or in the months following El Niño events. Clearly, understanding the relationship of ENSO to the Asian monsoon is necessary for flood prediction. However, this relationship is not entirely understood. Poyang Lake did not reach flood stage during or immediately following all the El Niño events. Other factors influencing the Asian monsoon that are not entirely clear include the Pacific Decadal Oscillation that may dampen the effects of El Niño. During neutral or La Nina years, the Poyang Lake occasionally reached the flood stage (19.5 m), but at these times the region never had a severe flood, defined as a lake stage exceeding 21.5 m.

The historic lake stage data used in this investigation show an increasing average maximum lake stage and flood severity from the 1950s until the late 1990s. A continuation of this trend would suggest an ominous future for the Poyang Lake. However, increasing flood severity in recent decades should not be viewed as a certain indication of increasing flood risk in the coming decades. Predicting future floods in this region is complicated by a variety of human activities. These include the implementation of new flood control techniques that are based mostly on the abandonment of some levees and opening of others during extreme floods to increase the area of floodwater storage. Large-scale land reclamation and levee building projects have stopped and, following the 1998 flood, the Jiangxi provincial government developed an aggressive plan to increase the floodwater storage area by the full or partial abandonment of reclaimed farmland protected by levees (Zhao, 1999). Levees protecting a total land area of 170 km^2 at the margins of Poyang Lake will not be maintained. This area will not have adequate flood protection and everyone living in these areas will be relocated. Levees protecting an additional 660 km^2 area will be maintained, some at a height of 20.5 m and others at 21.6 m, which is higher than the other major levees surrounding the lake. During extreme floods when additional water storage is necessary, as occurred during 1998, levees will be opened or overtopped, and those living in this region will be temporarily relocated. This flood control plan will increase Poyang Lake's volume by 11%, assuming a water level of 22 m.

The flood control plan to increase lake area may be partially offset by river and lake sediment deposition that is reducing lake volume. Lake sedimentation during recent decades probably averaged no less than 0.2 cm/year, although this figure could be significantly higher (Zhang, 1988; Xiang *et al.*, 2002). We should not assume that this rate will continue into the future. There is strong evidence that sediment delivery into the Poyang Lake has increased significantly during the past few decades. The increase in areas of severe soil erosion in Jiangxi is likely responsible for significant aggradation of the largest Poyang Lake tributaries (Ouyang and Chen, 2000; Zuo, 1999) and strongly suggests a higher rate of sediment delivery into the lake. Sedimentation will have only a minor effect on the lake volume in the near future, but the cumulative impact will be significant during the next few decades.

The Three-Gorges Dam being built on the Changjiang, upstream of Poyang Lake, could also influence flood risk in the Poyang Lake region. As mentioned earlier, severe flooding on the Changjiang usually occurs during July and August. To increase the floodwater storage capacity of the reservoir and to protect against late summer flooding, the reservoir will be lowered during late spring and early summer months. Release of water from the dam during this period will increase the discharge and water level of the Changjiang downstream. The problem facing the Poyang Lake region is that the higher water level of the Changjiang during early summer months will occur at the same time as that of the Jiangxi rivers' discharge when the Poyang Lake water levels are usually greatest. The higher water level of the Changjiang during early summer will slow the Poyang Lake discharge into the Changjiang and in some cases cause the Changjiang to flow into Poyang Lake, increasing its water level and flood period (Hu and Zhu, 1998; Liu and Wu, 1999). Therefore, the Three-Gorges Dam will not significantly reduce severe floods during early summer, as had occurred during the 1954 flood.

Accurate prediction of future floods in this region is difficult. As already mentioned, the frequency of El Niño events has increased during the past few decades. If this trend continues, we can expect more severe floods in the Poyang Lake region. However, we should remember that (1) there is no certainty that this trend will continue and (2) the relationship between ENSO and rainfall in southern China is not perfect. Future flood prediction is also difficult considering the extensive landscape changes during recent decades. Restrictions on new levee construction and recently implemented flood control methods give a certain degree of optimism that the flood risk has been lessened since the occurrence of the 1998 flood. However, the extensive levee system in this region that significantly reduces the area for floodwater storage is a major problem that has not been addressed. Considering the large rural population in this region that must be protected from floods, widespread levee removal is not a practical alternative and there is no easy solution that will continue to provide widespread flood protection and at the same time increase floodwater storage.

We should continue to use the 1954 flood as a reference when considering the possibility of future catastrophic floods. Although not reaching the same stage as the 1998 flood, this event was the reference before the extensive levee building period that occurred after the 1950s and, therefore, when the floodwater storage area was much greater than what currently exists. To understand the future risks in the Poyang Lake region, we cannot look exclusively at the Jiangxi landscape. Extensive levee systems built in recent decades that we previously described in Jiangxi have also been built along the middle of much of the Changjiang and at the margins of many other large lakes that drain into the Changjiang and which provide floodwater storage. Therefore, the current area available for floodwater storage is much less than during the 1950s. The reduction of floodwater storage throughout the middle Changjiang has contributed to higher river stages than would otherwise have occurred. This is significant since the water level in the Poyang Lake is largely determined by the Changjiang, and a higher river stage will slow the Poyang Lake drainage. If rainfall patterns in the Changjiang river valley again match those that occurred during 1954, the Three-Gorges Dam reservoir will be inadequate to protect the regions downstream (Hu and Zhu, 1998; Liu and Wu, 1999), and considering the greatly limited area for floodwater storage both in the Poyang Lake and along the Changjiang into which the Poyang Lake drains, we should expect a severe flood that will probably be the most destructive ever recorded.

REFERENCES

Cai X, Zhen-zhi W, Bin W. 2003. Relationship between West Pacific subtropical high and ENSO and its influence on rainfall distribution of rainy season in Fujian. *Journal of Tropical Meteorology* **19**: 36–42.

Chen L. 2001. The role of anomalous snow cover over the Qinghai-Xizong Plateau and ENSO in the great floods of 1998 in the Changjiang River valley. *Chinese Journal of Atmospheric Sciences* **25**: 184–192.

Diaz HF, Fu C. 1984. Regional precipitation and temperature variability and its relationship to the Southern oscillation. In *The Climate of China and Global Climate*, Ye D, Fu C, Chao J, Yoshino M (eds). China Ocean Press: Beijing; 213–223, in Chinese.

Guo Q. 1984. The East Asia summer monsoon and the Southern oscillation, 1871–1980. In *The Climate of China and Global Climate*, Ye D, Fu C, Chao J, Yoshino M (eds). China Ocean Press: Beijing; 249–255, in Chinese.

Gumbel EJ. 1958. *Statistics of Extremes*. Columbia University Press: New York.

Hershfield DM. 1961. Rainfall frequency atlas of the United States. Technical Paper No. 40. Department of Commerce: Washington, DC.

Hu X, Zhu H. 1998. Three-Gorges project and flood protection of important cities in the Poyang Lake region. *Journal of Jiangxi Normal University* **22**(4): 365–370, in Chinese.

Huang R, Chen W, Bangliang Y, Renhe Z. 2004. Recent advances in studies of the interaction between the East Asian winter and summer monsoons and ENSO cycle. *Advances in Atmospheric Sciences* **21**: 407–424.

Keim BD, Faiers GE. 1996. Heavy rainfall distributions by season in Louisiana: Synoptic interpretations and quantile estimates. *Water Resources Bulletin* **32**(1): 117–124.

Keim BD, Faiers GE. 2000. A comparison of techniques to produce quantile estimates of heavy rainfall in Arid and mountainous environments: A test case in Western Texas. *Journal of Arid Environments* **44**(3): 267–276.

Liu X, Wu D. 1999. Brief analysis of the effect of the Poyang Lake water level in flood period by the Three-Gorges project. *Jiangxi Hydraulic Science and Technology* **25**(2): 71–75, in Chinese.

Min Q. 1999. Evaluation of the effects of Poyang Lake reclamation on floods. *Yangtze River* **30**(7): in Chinese.

Min Q. 2000. Study of the relationship between shape, water regime and innings of Poyang Lake. *Advances in Water Science* **11**: 76–81, in Chinese.

Ouyang Q, Chen J. 2000. Water and soil losses and hydrologic situation on Fuhe Watershed in Jiangxi. *Research of Soil and Water Conservation* **7**(3): 161–163, in Chinese.

Peng Z (ed.). 1999. *Jiangxi Province Levee Atlas*. Jiangxi Provincial Government Levee Department Publication: Nanchang, China, in Chinese.

Ren G, Chen Z, Yang H. 2004. Variation of precipitation and runoff in the Yangtze river catchments since 1960. In *Climate Change and Yangtze Floods*, Jiang R, King L, Gemmer M, Kundzewicz ZW (eds). Science Press: Beijing; 224–234.

Samel AN, Liang XZ. 2003. Understanding relationships between the 1998 Yangtze River flood and northeast Eurasian blocking. *Climate Research* **23**(2): 149–158.

Samel AN, Wang SW, Wang WC. 1995. A comparison between observed and GCM-simulated summer monsoon characteristics over China. *Journal of Climate* **8**(6): 1690–1696.

Shankman D, Liang Q. 2003. Landscape changes and increasing flood frequency in China's Poyang Lake region. *Professional Geographer* **55**(4): 434–446.

Song J. 1998. Reconstruction of the Southern oscillation from Dryness/Wetness in China for the last 500 years. *International Journal of Climatology* **18**: 1345–1355.

Song J. 2000. Changes in Dryness/wetness in China during the last 529 years. *International Journal of Climatology* **20**: 1003–1015.

Su S, Weigong Z, Huirn T (eds). 1993. *Poyang Lake Atlas*. Jiangxi Provincial Science Academy, China Science Academy (Nanjing Geography and Lake Research Institute), Jiangxi Provincial Mountain, River and Lake Development Committee. Scientific Press: Beijing, China, in Chinese.

Trenberth KE. 1997. The definition of El Niño. *Bulletin of the American Meteorological Society* **78**(12): 2771–2777.

Whetton P, Rutherfurd I. 1994. Historical ENSO teleconnections in the Eastern Hemisphere. *Climatic Change* **28**: 221–253.

Whetton P, Adamson D, Williams MAJ. 1990. Rainfall and river flow variability in Africa, Australia and East Asia linked to El Niño-Southern oscillation events. *Geological Society of Australia Symposium Proceedings* **1**: 21–26.

Wilks DS. 1993. Comparison of three-parameter probability distributions for representing annual and partial duration precipitation series. *Water Resources Research* **29**: 3543–3549.

Xiang L, Lu XX, Higgitt DL, Wang SM. 2002. Recent lake sedimentation in the middle and lower Yangtze basin inferred from ^{1}37Cs and ^{2}10Pb measurements. *Journal of Asian Earth Sciences* **21**: 77–86.

Zhang R. 1988. Sediment characteristic of Poyang Lake and the environmental effects. *Jiangxi Hydraulic Science and Technology* **17**: 227–231, in Chinese.

Zhang S, Jiang S. 2001. Possible influences of ITCZ in Asian monsoon regions on rainy season anomaly of North China. *Advances in Atmospheric Sciences* **18**(5): 1018–1028.

Zhao X. 1999. *Jiangxi Province Landuse General Plan: 1997–2010* (Preliminary Draft). Jiangxi Provincial Government Publication: Nanchang, China, in Chinese.

Zhu H, Guorong S, Yunfei W, Yuansheng Y, Li Z. 1987. Prediction of impacts of the three Gorges Dam project on the ecological function and environment of Poyang Lake. In *Collection of Papers On the Effects of the Three Gorges Dam On the Ecosystem and Environment and How to Deal With These Problems*. Scientific Press. Beijing; 319–332, in Chinese.

Zuo C. 1999. The present situation and future plan for water and soil conservation in Jiangxi. *Jiangxi Hydraulic Science and Technology* **25**(4): 199–203, in Chinese.