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Analysis of historical floods on the Yangtze River, China: Characteristics and explanations

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ABSTRACT

This paper examines the characteristics of historical floods and associated monsoon precipitation in the Yangtze Catchment, with specific attention given to the middle and lower Yangtze basin. Based on in situ field observations and historical discharge, flood duration, and land-use information, etc, we propose a number of flood characteristics of the basin: 1) floods have occurred more frequently after 1950s, however, changes in discharge can only partially explain the occurrence of the floods; 2) spectral analysis on the annual mean water discharge during 1860–1985 in Hankou hydrological gauging station of the middle Yangtze River reveals 16.4-year and 2.5-year flood recurrences, which become shortened from what has been recorded in the Chinese historical literature on millennial time scale; 3) floods after 1950s tend to have higher water levels (both mean and peak) and longer duration than before, but with remarkably limited inundation area; and 4) a series of flood waves generated by monsoon precipitation in 1998, initiated from the middle Yangtze, highlights the basin-wide climate hazards with a recurrence of around 60 years. Intensifying anthropogenic activity in the last century, including deforestation, dyking, and lake–coast reclamation etc. that results directly in riverbeds aggradation and shrinkage of lake water area in the middle Yangtze basin, are the key causes for recently human-induced floods in the basin. Threatened land property in the basin reminds us to harmonize with the river and provide more space for flooding.

1. Introduction

The Yangtze River is about 6300 km long and has a drainage basin area of 1.80 million km^2 (Fig. 1A). It is the longest river in China and the third in the world in terms of length and discharge. The river flows across three major morphological steps from the western plateau to the eastern coast, a 6000-m elevational difference (Chen et al., 2001a,b; Fig. 1B). The river debouches the East China Sea by Shanghai on the coast.

The Yangtze River basin lies at the subtropical monsoon region (Chen et al., 2007). The mean annual precipitation in the basin ranges between 270 and 500 mm in the western region and 1600–1900 mm in the southeastern region (Gemmer et al., 2008). Annually, this area experiences a cold-dry winter and a warm-wet summer, and 70–80% of its annual rainfall occurs in the summer season. During years of El Nino, the enhanced subtropical high at the western North Pacific strengthens the summer East Asian monsoon, and brings larger amounts of precipitation to the Yangtze River catchment than the normal years. Under the monsoonal climate, floods occur annually in the summer, especially during June and July, when slowly drifting cold fronts meet the moist and stable subtropical air-mass and generate excess rainfall in the Yangtze catchment (Xiang and Bao, 1981; Zhang et al., 2008). The magnitude of floods may become larger during the years of El Nino, when the summer East Asian monsoon is enhanced.

A variety of geomorphological patterns occur from the upper to the lower part of the Yangtze River (Chen et al., 2001a). The upper reach of the Yangtze, from its source area to Yichang, runs primarily across mountainous terrain, especially in the Jinshajiang tributary and the Three Gorges valley (Fig. 1). The middle reach, from Yichang to Hukou, basically wanders through the Jianghan and Dongting basins on the flattened meandering fluvial plain. From Hukou to the estuary is the lower Yangtze reach, including the huge delta plain, where elevation is only 2–5 m above the mean sea level (m.s.l.) and is sensitive to sea storms during the summer season (Zhang et al., 2005).

Historically, the Yangtze River catchment 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 (e.g. Sutcliffe, 1987; Zhao, 2000; Cai et al., 2001). After a thousand years of embankment, the current levee reaches 10–15 m higher than the surrounding areas along the river channel bank (Chen et al., 2001b; Chen and Zhao, 2001; Yin et al., 2004). This embankment has largely aggraded the river channel, called the ‘suspending river’ (Yin and Li, 2001; Yin et al., 2004). Numerous lakes occur in the middle and

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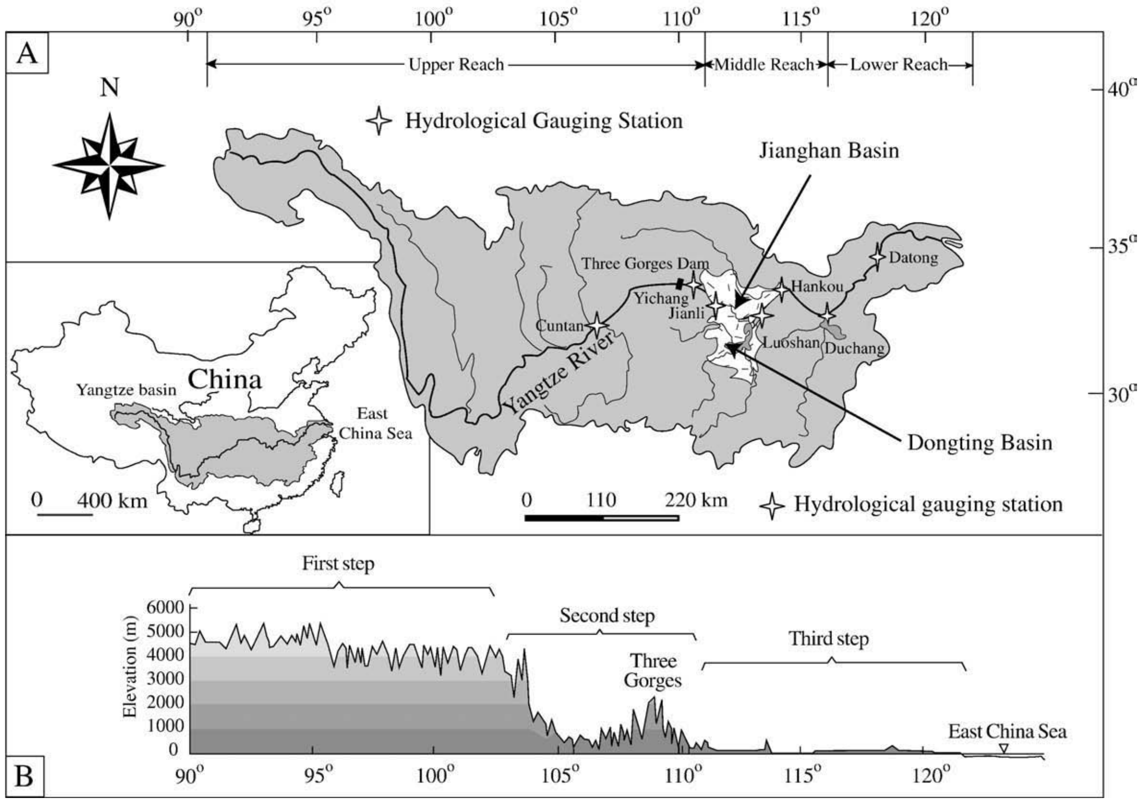

Fig. 1. Yangtze drainage basin. A) Indicated are tributary system, positions of hydrological gauging station and the site of Three Gorges Dam. Also denoted are the Jianghan and Dongting basins; B) Topography of the Yangtze catchment: three morphological steps.

lower Yangtze basin, including the lakes of Dongting and Poyang. They have played an important role in accommodating the Yangtze floods. In the last century, human activities, however, have led to severe shrinkage of the lake water area, especially Dongting lake. Soil erosion in the upper reaches of the river generated a large amount of sediment that has been silted in the middle basin. This, together with lake–coast reclamation, has dramatically altered the lake function for adapting floods since the last century.

In this study, on the basis of substantial data collected, we examine the historical Yangtze floods, the occurrences and related driving forces to enhance flood prevention and hazard mitigation in the near future.

2. Data and methodology

Discharge data (both maximum and mean) were collected from three major hydrological gauging stations, i.e. Yichang station (1865–1985), Hankou station (1865–1985), and Datong station (1950–1985), representing the upper, middle and lower reach of the Yangtze River, respectively (Fig. 1) (Changjiang Water Conservancy Committee, 1865–1985). Discharge data after 1985 are not publicly available. Multi-annual maximum water level and frequency of water levels of higher than 19 m during 1950s–1990s of Duchang hydrological gauging station, middle Yangtze, were collected from the Changjiang Water Conservation Committee (2001). Major flood characteristics for the six years (1870, 1931, 1935, 1954, 1996, 1998) recorded in Hankou hydrological gauging station, were also incorporated into the present database, including peak water level, maximum discharge, area of inundation, and flood duration (Changjiang Water Conservancy Committee, 2001). Data of daily discharge during the big flood in 1998 were cited from six major hydrological gauging stations (from upstream downwards: Cuntan, Yichang, Jianli, Luoshan, Hankou and Datong; Fig. 1A) (Changjiang Water Conservancy Committee, 1998). Landsat TM satellite images of Dongting and Jianghan Basin from 1986, 1996, and 2000 were used (TM4, TM3 and TM2) at same phase. Images of the water surface area of the Dongting lake from 1650s to 1970s were modified from Changjiang Water Conservancy Committee, 2001. Historical flood data of the Yangtze basin cited http://www.Chinawater.com.cn and Changjiang Water Conservancy Committee (2001) were incorporated into the present study.

3. Characteristics of Yangtze floods

3.1. The major features of recurrence

The first key feature of Yangtze floods is its recurrence. Over the last thousand years, the flood recurrence has been gradually shortened. For example, between 618 A.D. and 907 A.D. (Tang Dynasty),

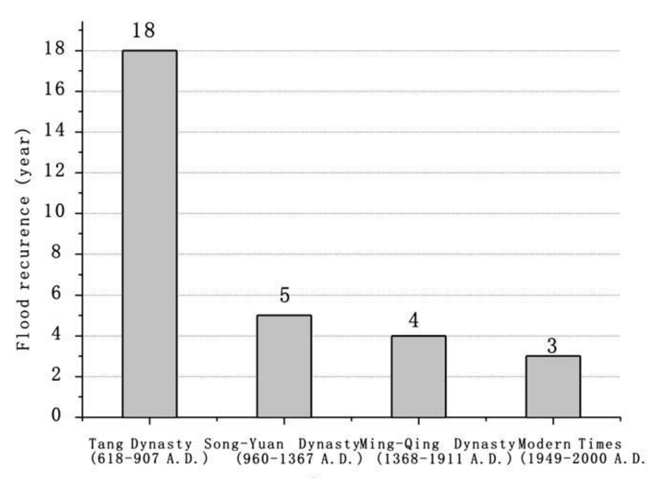

Fig. 2. Historical flood occurrence since Tang Dynastic (168–907 A.D.; data sources: Changjiang Water Conservancy Committee, 1999, 2001).

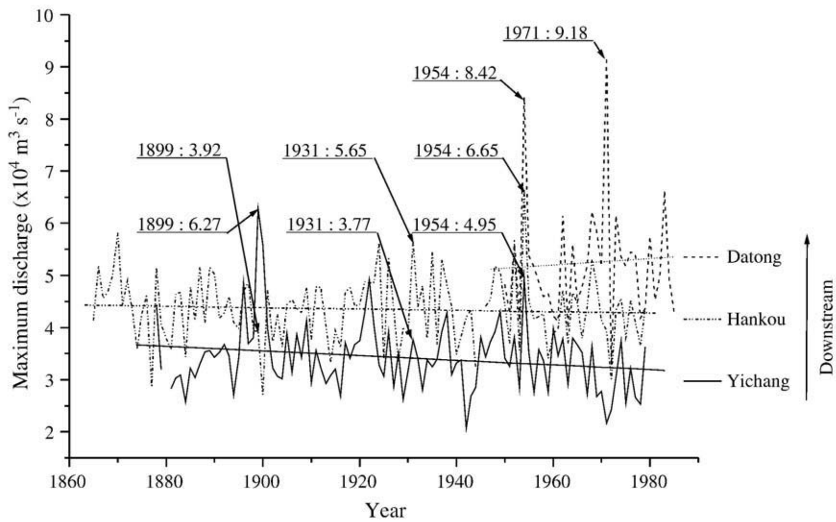

Fig. 3. Annual maximum discharge during 1865–1985 from the Yichang station, Hankou station and Datong station downstream. Straight lines show the linear trend of the maximum discharge. Also shown on the diagram is the maximum discharge of big floods in the years of 1899, 1931, 1954 and 1971.

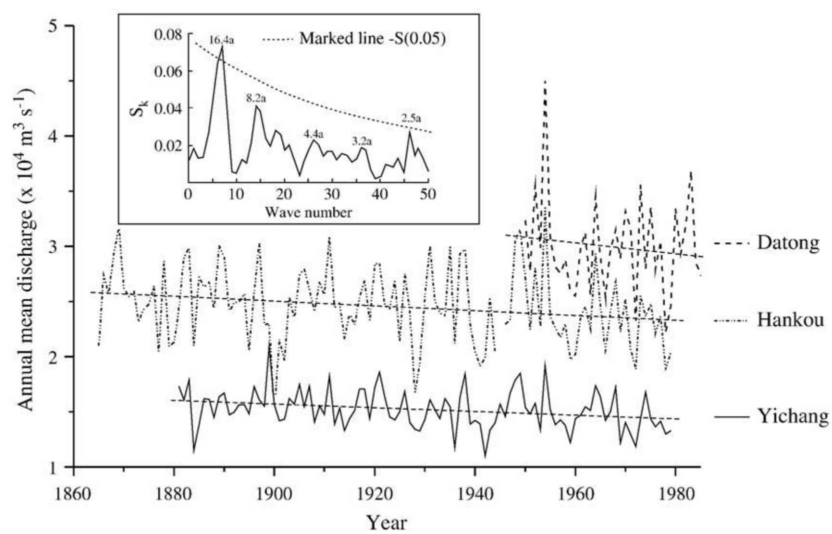

Fig. 4. Same with Fig. 3, but for the annual mean discharge. Inset shows the result of spectral analysis on the mean discharge of Hankou station with a significance level of 0.05.

the flood recurrence was about 18 years, but 4–5 years during 960–1911 A.D. (the Song Dynasty and the Qing Dynasty) (Fig. 2; Changjiang Water Conservancy Committee, 2001). After 1950, on average, the recurrence was 3 years. Jiang et al. (2003, 2007) recently concludes that the major floods in the Yangtze catchment have increased in the last decade.

Discharge fluctuations recorded at Yichang, Hankou and Datong hydrological gauging stations of the upper, middle and lower Yangtze basin (1865–1985) highlight the variation of maximum discharge in the catchment as a whole, ranging from 2×10^4 m^3 s^{-1} to 9×10^4 m^3 s^{-1} (Fig. 3). The database reveals that the yearly maximum discharge at the three stations has generally increased from $3–4\times10^4$ m^3 s^{-1} in the upper catchment, to $4–5\times10^4$ m^3 s^{-1} in the middle catchment, and to 5–6 10^4 m^3 s^{-1} in the lower catchment (Fig. 3). During 1865–1985, 11 floods of $>4\times10^4$ m^3 s^{-1} occurred in the upper Yangtze reaches, 17 floods of $>5\times10^4$ m^3 s^{-1} in the middle reaches, and 6 floods of $>6\times10^4$ m^3 s^{-1} in the lower reaches. Discharge of $4–6\times10^4$ m^3 s^{-1} is historically treated as the threshold of local flood occurrence (Changjiang Water Conservancy Committee, 2001).

Fig. 2 reveals no indication either for the increasing tendency of the distribution of maximum discharge or flood magnitude. Actually, the maximum discharge of the upper Yangtze had slightly lowered in the last century, and that of the middle Yangtze had been quite stable, but that of the lower Yangtze had a minor increase (Fig. 3). Extreme discharge may or may not take place simultaneously throughout the drainage basin. For instance, the extreme discharges of 6.27×10^4 m^3 s^{-1} and 9.18×10^4 m^3 s^{-1} only occurred in the upper and lower catchments in 1899 and 1971, respectively, (Fig. 3), but were not recorded in the other parts of the catchment. But, the opposite case of basin-wide extreme discharge took place in 1931, when 3.77×10^4 m^3 s^{-1} discharge was recorded in the upper

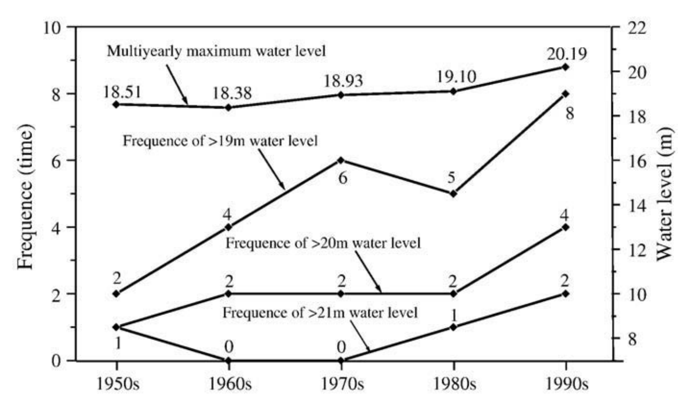

Fig. 5. Multi-annual peak water level and frequency of high water level in Duchang station, during 1950s–1990s.

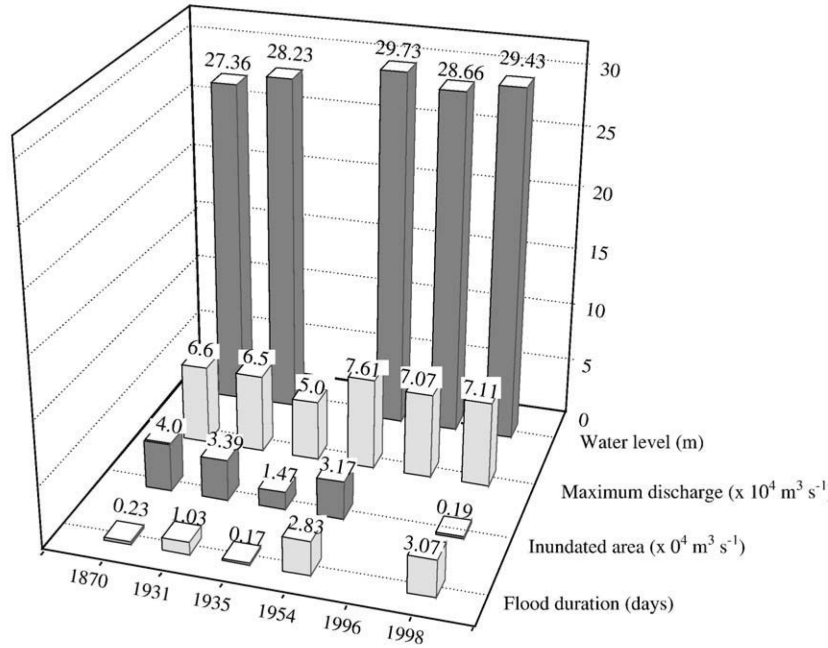

Fig. 6. Measurements of the six large floods since the late 19th century at Hankou hydrological gauging station.

Yangtze reach and 5.65×10^4 m^3 s^{-1} in the middle Yangtze; and in 1954, 4.95×10^4 m^3 s^{-1} was recorded in the upper reaches, 6.65×10^4 m^3 s^{-1} in the middle and 8.42×10^4 m^3 s^{-1} in the lower reaches (Fig. 3).

Statistical analysis indicates that the annual mean discharge of the three stations has slightly decreased over the last century (Fig. 4). The analysis reveals two prominent flood recurrences, i.e. 16.4 years and 2.5 years (at level: $S = 0.05$), identified from the annual mean discharge database of Hankou hydrological gauging station (Fig. 4). Interestingly, a decline of annual mean discharge occurred in downstream-most Datong hydrological station in the past half century, which contrasts with the increasing trend of maximum discharge at same time (Fig. 3).

3.2. Characteristics of major floods of the Yangtze catchment since late 19th century

The multi-annual maximum water level recorded at the Duchang hydrological gauging station ascends from 18.51 m in 1950s to 20.19 m in 1990s (Fig. 5). The figure demonstrates that the increasing trend is notable in the average maximum water level and also the frequency of the peak water level. For example, numbers of floods which have a peak water level higher than 20 m and 21 m are two and four in the 1990s, while in the 1950s, only one flood was observed with a peak water level over 20 m and 21 m (Fig. 5). During 1865–2000, six high-magnitude floods were recorded at Hankou station, respectively in the year of 1870, 1931, 1935, 1954, 1996 and 1998 (Fig. 6). Accordingly, the peak water level increased from 27.36 m in 1870 to 29.73 m in 1954, and further to 29.43 m in 1998. The highest discharge increased from $<6.60 \times 10^4$ m^3 s^{-1} before 1950s to $>7.00 \times 10^4$ m^3 s^{-1} after 1950s (actually, it reached 7.61×10^4 m^{3}s^{-1} in 1954; Fig. 6). Data also demonstrate that the inundated area in the middle Yangtze has been obviously reduced from about 4.00×10^4 km^2 in 1870, to 3.39×10^4 km^2 in 1931, 1.47×10^4 km^2 in 1935, 3.17×10^4 km^2 in 1954, and finally to 0.19×10^4 km^2 in 1998. In contrast, the duration of the peak water level has gone up from about 0.23 days in 1870, 1.03 days in 1931, 0.17 days in 1935, 2.83 days in 1954, and 3.07 days in 1998 (Fig. 6).

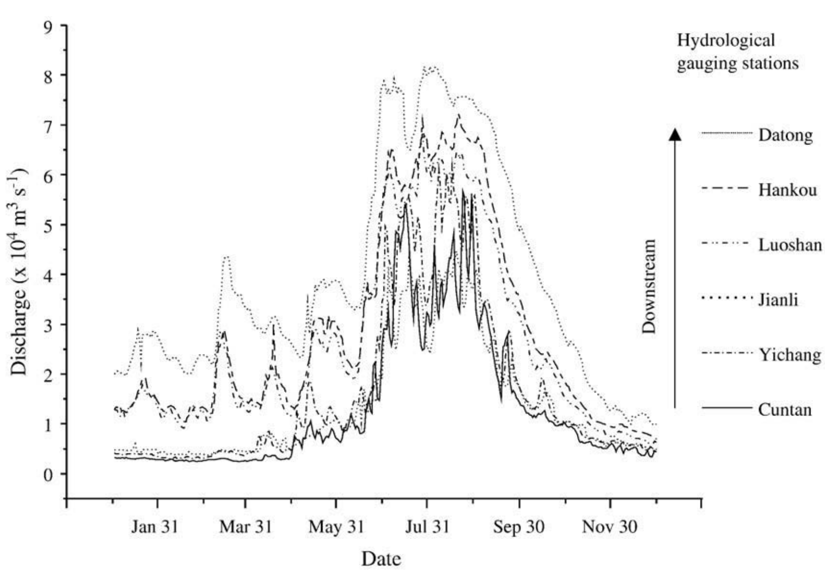

Fig. 7. Discharge fluctuations during the 1998 big flood.

Table 1
Interpreted types and areas of wetland of the Jianghan plain and Dongting plain, middle Yangtze basin (modified after Ren, 2004).

Wetland	Area (km^2)	Percentage (%)
River channel	1733.89	6.17
Flood plain	616.39	2.19
Lakes	1544.51	5.50
Lake plain	2006.24	7.14
Polders	261.56	0.93
Rice paddy	17294.42	61.58
Wetland in total	23457.01	83.51
Others	4628.88	16.48

3.3. The big flood in 1998

The highest-magnitude flood in the past century was recorded at the Hankou station of the middle Yangtze in 1998 and had a recurrence of about 60 years (Fig. 7) (Xu et al., 2005). This flood has typical basin-wide characteristics: 1) the long duration of about 2.5 months lasted from early July to middle September, 1998; 2) high peak water discharge continuously increased as flood peaks downstream from $4.5–5.0\times10^4$ m^3s^{-1} in the upper catchment to $6.0–7.0\times10^4$ m^3s^{-1} in the middle catchment and to $7.5–8.0\times10^4$ m^3s^{-1} in the lower catchment; 3) flood peaks were initiated from the middle and lower Yangtze reaches, and more specifically, from the Dongting lake region of the middle Yangtze, and 4) a series of flood waves was generated by the rain zone shifting between the middle and upper reaches recorded by its hydrographic fluctuations through the river basin (Fig. 7).

4. Discussions and conclusion

The Yangtze floods that have been long associated with the development of Chinese history enable us to better understand its evolving characteristics, e.g. the shortened recurrence between floods at least since 618 A.D. (Fig. 2) (http://www.Chinawater.com.cn; Changjiang Water Conservancy Committee, 2001). Even though no clear signal exists to mark the increasing trend of monsoonal precipitation from the records of the maximum and annual mean discharge in the Yangtze catchment in the last century (Figs. 3, 4), the data analyzed in the present study support a remarkable increase in the flood frequency in the basin since 20th Centaury (Figs. 4–6). Slightly increasing trend of the maximum discharge recorded in the lower Yangtze in the past half century hints more likelihood of extreme seasonal rainfalls in relation to climate warming recently (Jiang et al., 2003). From the middle 1950s to 1990s, the magnitude of the annual peak water level recorded at the Duchang Hydrological gauging station in the middle Yangtze has continuously increased (Fig. 5), implying an intensification of human activities, especially the dramatic changes in land-use throughout the basin in the past decades as discussed below.

The two major flood recurrences (16.4 years and 2.5 years), recognized in the past 100 years as revealed by the mean discharge in the middle Yangtze, attract public attention for flood prevention and hazard mitigation (Fig. 4). An explanation for the longer recurrence of 16.4 years is not clear, but the shorter one with 2.5 years may relate to the El Nino year (Jiang et al., 2003). Herein, however, we emphasize anthropogenic forcings. The elevated peak water level, with longer duration can result from embankments/dykes in association with aggraded riverbeds in the middle and lower Yangtze catchments (Figs. 5, 6). Decrease in inundation area in the region would also come from various flood defense infrastructures that involve a huge capital outlay aimed at effective flood prevention (Changjiang Water Conservancy Committee, 2001). More than 2000 km of dykes have been built along the river bank and need intensive maintenance on an annual basis (Yin and Li, 2001).

The catastrophic basin-wide Yangtze floods, characterized by a 60-year recurrence in 1998, have provided an example of calling for caution on how to manage fluvial topography in relation to regional development. Monsoon precipitation, acting as the regional climatic control in the Yangtze basin during wet season, can often migrate within the catchment with time. We noted that rainfall pattern in the basin during catastrophic flooding may not be always oriented E–W trend as it is during the normal weather year. It can certainly migrate around the sub-basins with a short-time period (often 2–3 days; Changjiang Water Conservancy Committee, 2001). The huge rainfall initiated from the middle Yangtze (Dongting lake region) below Three Gorges Dam in 1998 is not isolated case during the historical flooding periods (Changjiang Water Conservancy Committee, 1999). This challenges how effectively the dam can mitigate floods, taking into consideration the geographic site of the dam in relation to seasonal rainfall occurrence. A series of flood waves with highest discharge (>80,000 m^3 s^{-1} recorded in the lower Yangtze catchment), triggered by the shifted rainfall pattern within the 2.5-month flood season, highlights the features of this catastrophic event (Fig. 7). We noted a similar case was recorded in 1954, when another historical big

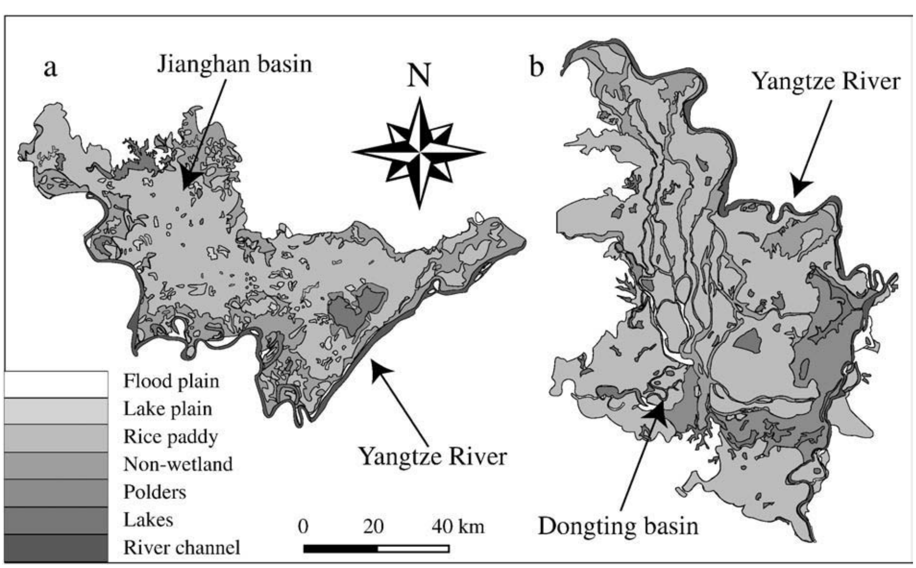

Fig. 8. Interpreted TM images for the changes of land-use. a: Jianghan basin; and b: Dongting basin (modified after Ren, 2004).

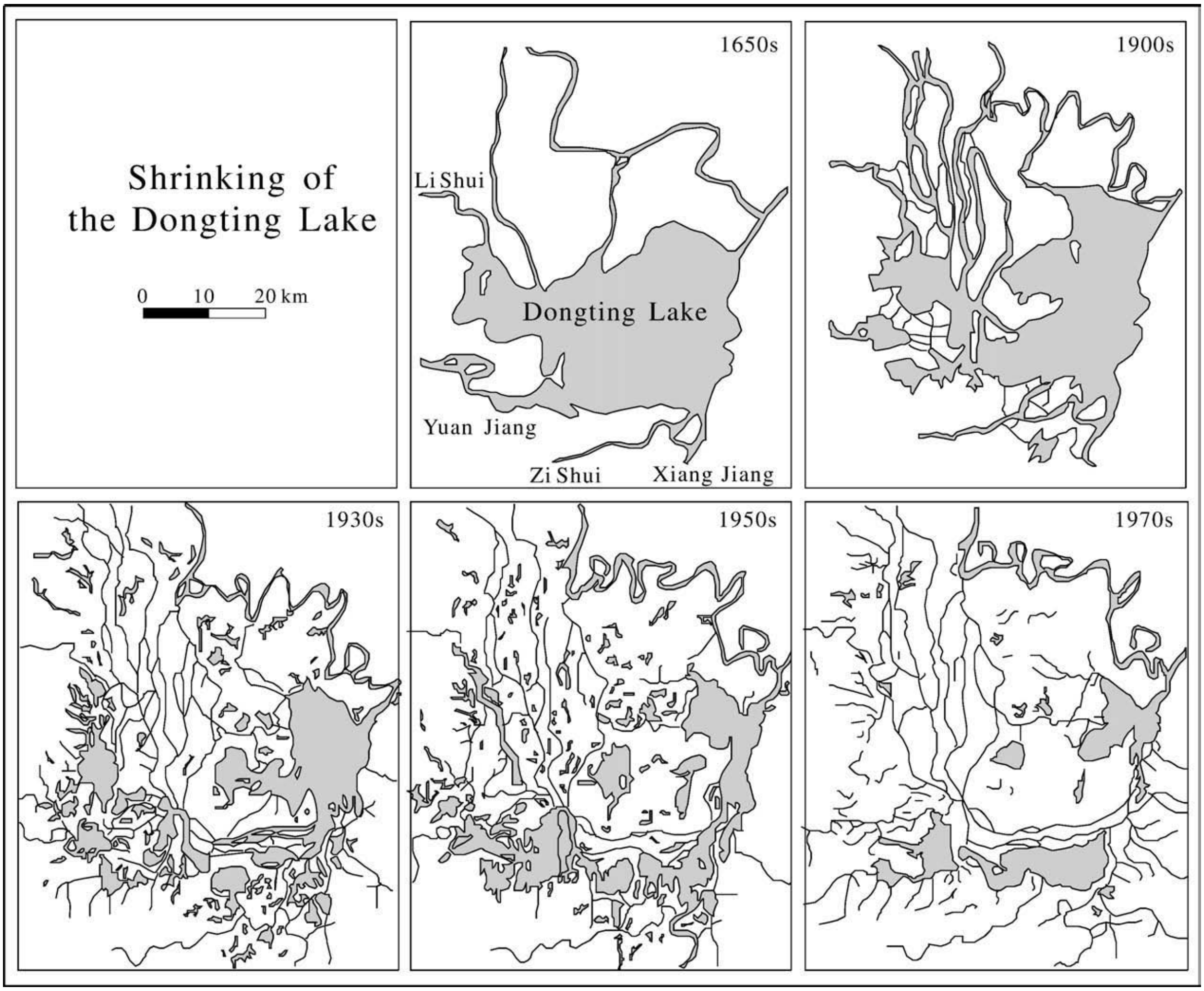

Fig. 9. Shrinkage of Dongting Lake during 1650s–1970s (sources: after Changjiang Water Conservancy Committee, 1999).

flood occurred in the Yangtze basin (Changjiang Water Conservancy Committee, 2001).

The raised peak flow levels in the river channel through time can come from the high dykes constructed along the river channel to protect the land properties, rather than an increase in precipitation (Table 1; Fig. 8a,b). The land-use of the Yangtze drainage basin has been dramatically altered in the past century (Changjiang Water Conservancy Committee, 1999). Deforestation predominated in the upper and middle Yangtze basin in the 20th century (Deng, 2000), which directly causes the extensive soil erosion from a large area (55×10^4 km^2), accounting for almost one third of the total drainage area (Deng, 2000). Our interpretation of Landsat satellite TM data, pertaining to the 1986, 1996 and 2000, revealed significant land-use changes during the past two decades in the middle Yangtze catchment from lake, wetland, and flood plain to rice paddies (Fig. 8a,b; Table 1). The lakes that prevailed in the earlier history in the middle Yangtze basin have presently been largely converted to farmland (>60%, Table 1; Ren, 2004). Dongting Lake in the middle Yangtze plain, which was the largest freshwater lake in China, no longer is the largest because of the decrease in its water area from >6000 km^2 in the late 19th century to about 2400 km^2 nowadays. Consequently, the lake can store less water during the Yangtze floods (Fig. 9) (Tan, 1998; Li, 1999; Changjiang Water Conservancy Committee, 1999; Du et al., 2001; Nakayama and Watanabe, 2008; Wang et al., 2008).

Climate and human forcings combined have been imposed on the flood occurrence in the Yangtze basin. The historical case of this study proposes policy-friendly land-use in the future administration of the catchment.

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