A modeling study of the influences of Yangtze River and local catchment on the development of floods in Poyang Lake, China

Xianghu Li, Jing Yao, Yunliang Li, Qi Zhang and Chong-Yu Xu

ABSTRACT

Poyang Lake, one of the most frequently flooded regions in China, connects with the Yangtze River and the five sub-tributaries in the local catchment. The lake's hydrological regime is complicated by a complex hydraulic connection and strong river–lake interaction, especially for the extreme hydrological regime. This study analyzes the relationships between the lake level changes and the flow regimes of Yangtze River and local catchment during the flood season and employs a physically based hydrodynamic model to quantify their relative contributions to the development of floods. The study found that the large catchment runoff and Yangtze River discharge were both significant contributors to flood development but that their contributions were unevenly distributed in time and space. The local catchment imposed more influence during the period of April–May and at the middle parts of the lake, and its influence decreased toward the north and south; in contrast, the most remarkable lake level changes were observed in July–August and at the northern lake for the Yangtze River cases, and these changes reduced from north to south. Moreover, Yangtze River imposed far stronger influences on the lake level changes than the catchment runoff and dominated the duration of floods to a great extent.

Key words | flood, hydrodynamic model, Poyang Lake, water level, Yangtze River

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INTRODUCTION

Floods cause considerable economic loss and serious damage to towns and farms and are one of the most common natural disasters recorded in the world, especially with their increased frequencies as an estimated impact of global warming (Christensen & Christensen 2003; Frei *et al.* 2006; Zhang & Li 2007; Nakayama & Watanabe 2008; Garcia-Castellanos *et al.* 2009; Nie *et al.* 2012; Gül 2013). It is evident from the literature that the frequency and number of hydro-meteorological hazards (i.e., floods) are on the rise compared with geophysically induced disasters (Ramos & Reis 2002; Krausmann & Mushtaq 2008; Adikari & Yoshitani 2009). Over the last several decades, many countries have suffered from severe flooding, such as the Brahmaputra River in Bangladesh, the Oder and the Vistula in Poland, the Elbe in Germany, the Mekong River in Vietnam, the Menam River in Thailand, the Indus in Pakistan, and the Yangtze River in China (Chowdhury 2003; Gupta & Sah 2008; Yu *et al.* 2009; Wang *et al.* 2010; Khan *et al.* 2011; Yi *et al.* 2012). The global cost of floods has reached a total of $470 billion since 1980 (Knight *et al.* 2011).

Similar to other countries, China is no exception to recurrent floods due to the strong influence of the East Asian monsoon (Liu & Liu 2002; Yu *et al.* 2009). Two-thirds of Chinese territory and over half of the total

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population are affected by a variety of flood events almost every year (Nakayama & Watanabe 2008; Wang et al. 2012); this is especially true in the Yangtze River basin, which is historically one of the most frequently flooded areas in China (Zhao 2000; Cai et al. 2001). Poyang Lake, the largest freshwater lake in China, is located in the middle and lower reaches of the Yangtze River and is one of the few lakes that remains naturally connected to the Yangtze River. During the past several decades, the Poyang Lake region has experienced as many as 17 major flood events, six of which can be categorized as severe floods (i.e., 1954, 1983, 1995, 1996, 1998, and 1999) (Li et al. 2015a). Moreover, it has recently been shown that the frequency and severity of the floods in Poyang Lake have increased since 1990 (Guo et al. 2008), owing to the southward shift of the major warm season rain bands to the south of the Yangtze River basin and the increased fluctuation of warm season rainfall in Poyang Lake catchment (Hu et al. 2007). The frequent large floods in Poyang Lake have caused extensive damage to the environment and the agricultural economy and have threatened the life of approximately ten million people in the surrounding region (Shankman & Liang 2003; Shankman et al. 2006; Li & Zhang 2015). For instance, a big flood event in 1998 resulted in several cities in the lakeside area being severely flooded, affecting more than 600 thousand people (Min 2002) and resulting in more than $5 billion in economic losses for the Poyang Lake region (Chen et al. 2002).

As is well known, explaining the triggering causes and affecting factors of floods is an important prerequisite of flood disaster prevention and mitigation (Nie et al. 2012). This is also indispensable for flood management in Poyang Lake and has raised extensive concern. Numerous studies have been carried out to investigate the triggering mechanism of Poyang Lake floods and their relationships with climatic characteristics and human activities. Usually, the severe flood events in Poyang Lake are mainly ascribed to the abnormal climate variability (Nakayama & Shankman 2013), i.e., during the flood seasons of 1998 and 1954, the average total precipitation was significantly higher than usual in the Yangtze River basin (with the most excessive rainfall of 300 mm and 220 mm, respectively, during June–July) (Nakayama & Watanabe 2008). Shankman et al. (2006) found that the most severe floods in Poyang Lake may have occurred during or immediately following El Niño events. Hu et al. (2007) and Guo et al. (2008) also found that the increase in flood frequency and severity in Poyang Lake in the 1990s was partially attributable to the southward shift of the major warm-season rain bands to the south of the Yangtze River basin. In contrast, Yu et al. (2009) examined the characteristics of historical floods in the Yangtze River basin and found that the intensifying anthropogenic activity in the last century was the key cause for recently human-induced floods. Many studies also noted that the landscape changes related to human activity have resulted in the loss of floodwater storage and were the main causes of an increasing severity of major floods (Yin & Li 2001; Piao et al. 2003; Zhao & Fang 2004; Zhao et al. 2005; Nakayama & Shankman 2013). Statistics indicate that the Poyang Lake has shrunk in volume from 37 billion m^3 in the 1950s to 28.9 billion m^3 in the late 1990s, with an accompanying decrease in area from 5,160 km^2 to 3,860 km^2 in this time (Shankman & Liang 2003). Shankman & Liang (2003) ascribed these declines to the land reclamation and levee construction in lake regions. Additionally, the sediment deposition due to deforestation in the five sub-tributary catchments has reduced the total volume of Poyang Lake by 4.8% between 1954 and 1997 (Min 1999). In addition, Hu et al. (2007) explained the occurrence of floods from the aspect of the interaction among the Yangtze River, Poyang Lake, and its catchment. Nakayama & Shankman (2013) investigated the effects of the Three Gorges Dam (TGD) and water transfer project on Yangtze River floods. Similarly, Gao et al. (2013), Guo et al. (2012), and Zhang et al. (2014) also examined the effects of TGD on Yangtze River flow and the hydrological regime of Poyang Lake. These studies showed that the Poyang Lake flood risk decreased moderately because the modulated river flow has distinctly weakened its blocking effect (Guo et al. 2012) by reducing the peak discharge of the Yangtze River, i.e., from approximately 7×10^4 m^3/s to 4×10^4 m^3/s, with a 40% decrease during the flood periods of 2010 (http://www.cjw.com.cn/); however, the model predicted that the TGD might increase the lake stage and flood risk during the spring and early summer months due to the release of water from the dam during this period (Nakayama & Shankman 2013).

Despite many studies concentrating more efforts to deal with the occurrence characteristics of severe floods in Poyang Lake region and their associated triggering causes in terms of climate variability and human activities (Min 1999; Cai *et al.* 2001; Shankman & Liang 2003; Shankman *et al.* 2006, 2012; Nakayama & Watanabe 2008; Li *et al.* 2015a), it remains unclear how the Yangtze River discharge and local catchment inflow impact the lake flood stages and their duration. In particular, the effects of the Yangtze River and the Poyang Lake catchment have not been quantified by considering the dominant hydrodynamic processes of the river–lake–catchment system, which is essential to real-time flood hazard prediction in such a complex system (Bates & Anderson 1996; Adhikari *et al.* 2010). It is necessary to extend the previous studies using scenario simulations to provide a generalized and quantitative interpretation of the influences of both the Yangtze River and the local catchment on the high lake level. Therefore, the objectives of the study are to: (1) analyze the characteristics of the lake level in typical flooding years and in dry years and identify their relationships with the flow regime changes of the Yangtze River and the sub-tributaries in the local catchment; and (2) quantify the effects of the local catchment runoff and Yangtze River flow on the flood stages based on the hydrodynamic model MIKE 21, and simulate its temporal and spatial distribution, as well as the duration changes of the high lake level.

STUDY AREA AND DATA

Study area

Poyang Lake is located in the middle and lower reaches of the Yangtze River, China (28 °22′–29 °45′N and 115 °47′–116 ° 45′E); it receives water flows primarily from the five sub-tributaries in its catchment, i.e., Xiushui River, Ganjiang River, Fuhe River, Xinjiang River, and Raohe River, and discharges into the Yangtze River through a channel in its northern part (Figure 1). Among the five major rivers, the Ganjiang is the largest river in the region: it extends 750 km and contributes almost 55% of the total discharge into Poyang Lake (Shankman *et al.* 2006). Poyang Lake has an average water depth of 8.4 m and a storage capacity of 276×10^8 m^3 when the water level at Hukou is 21.71 m (http://www.poyanglake.net/pyhgk.htm). Generally, the lake water surface has relatively large gradients in dry seasons, i.e., the lake level in the south is 5–6 m higher than in the north (Figure 2(a)), and the water flows from the south and discharges (outflow) into the Yangtze River. During the wet season, the elevated water level of the Yangtze River may raise the northern lake level and block outflow from Poyang Lake and, in some cases, may cause backflow from the Yangtze River to Poyang Lake (Shankman *et al.* 2006).

The total drainage area of the water systems is 16.22×10^4 km^2, accounting for 9% of the drainage area of the Yangtze River basin. The topography in the catchment varies from highly mountainous and hilly areas (with the maximum elevation of 2,200 m above mean sea level) to alluvial plains in the lower reaches of the primary watercourses. Poyang Lake catchment has a subtropical wet climate that is characterized by a mean annual precipitation of 1,630 mm for the period 1960–2010 and an annual mean temperature of 17.5 °C. Five sub-tributaries in the Poyang Lake catchment make up the primary water sources of Poyang Lake. The amount of water flowing from the five rivers directly affects the volume and water level of Poyang Lake. Generally, the rainy season in the Poyang Lake catchment begins in April, and the water flows from the local catchment increase quickly from April to June, raising the water level of Poyang Lake (Figure 2(b)). This hydrograph of the Poyang Lake catchment explains the primary features of the first half of the annual variation of water level in Poyang Lake (Hu *et al.* 2007). From July to September, the runoff inflow decreases sharply; at the same time, the middle reach of the Yangtze River receives its annual peak precipitation, and its discharge increases. The rising discharge and water level of the Yangtze River block the outflow from Poyang Lake, possibly even causing backflow, and further elevates the lake level (Shankman *et al.* 2006; Hu *et al.* 2007). This blocking effect dominates the second half of the annual course of the lake level (Hu *et al.* 2007; Guo *et al.* 2012). As a result, the Poyang Lake water surface area can exceed 3,000 km^2, inundating low-lying alluvial plains surrounding the lake in the flood season (Shankman *et al.* 2006), but shrinks to $<$1,000 km^2 to form a narrow meandering channel during the dry season (Xu & Qin 1998) and exposes extensive floodplains and wetland areas.

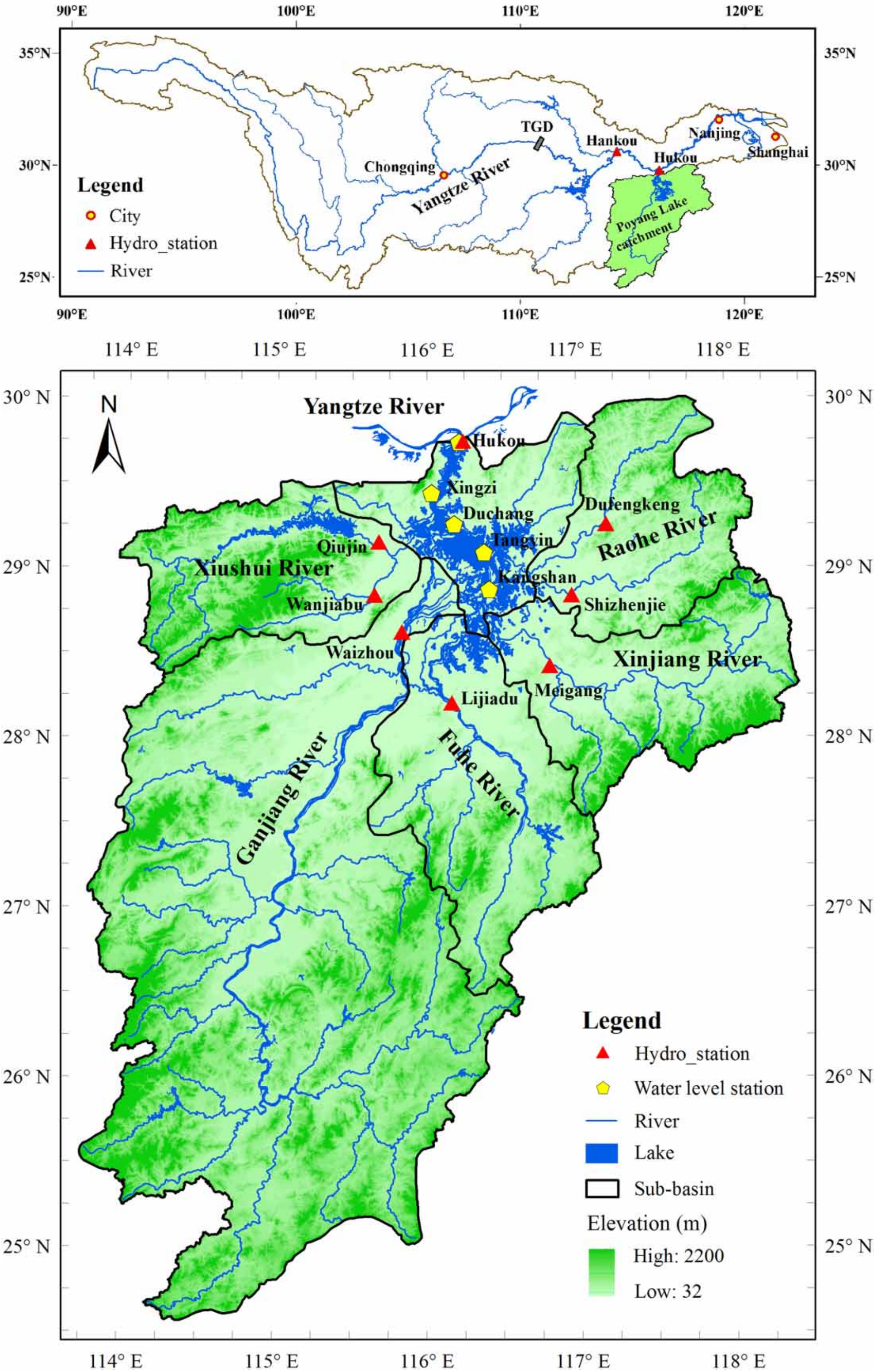

Figure 1 | Location of study area and the distribution of stations.

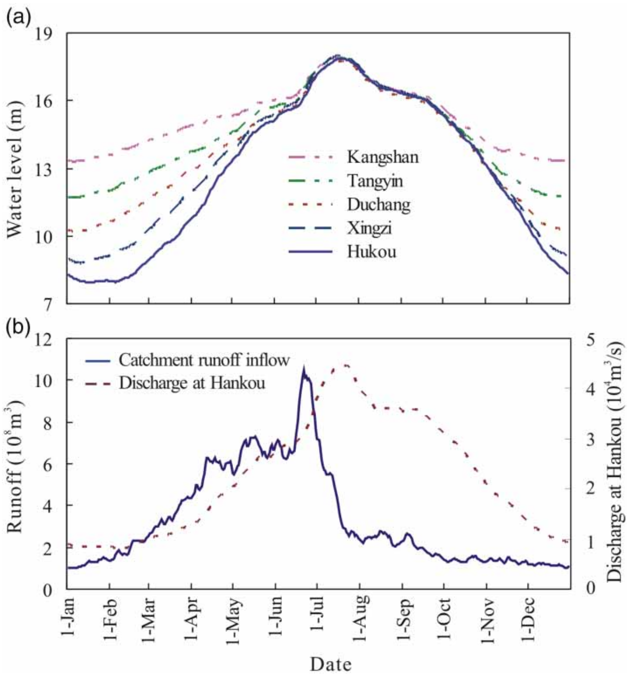

Figure 2 | Variation of average water level in Poyang Lake (a) and runoff inflow from five sub-tributaries and Yangtze River discharge at Hankou (b) during 1960–2010.

Data

The observed daily water levels of Poyang Lake at five hydrological stations (i.e., Hukou, Xingzi, Duchang, Tangyin, and Kangshan) are available for the period 1960–2010 and were used to identify the variation characteristics of the lake level and calibrate the hydrodynamic model parameters. The locations of these stations are shown in Figure 1. The records at Xingzi station are selected to stand for the lake level in the study because slight differences of the lake level can be observed at different stations during the flood season and also because Xingzi station is situated on the northern edge of the broad lake and away from the junction of the lake and the Yangtze River (Figure 1). The daily stream flows from the five sub-tributaries in the Poyang Lake catchment were measured at seven hydrological stations, i.e., Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Shizhenjie, and Dufengkeng stations (Figure 1), in the period 1960–2010 to reflect the amount of catchment inflow. Additionally, the water fluxes measured at Hankou station were collected to describe the variations of the Yangtze River flow and examine its effects on the outflow of Poyang Lake. These data have been widely used for different studies previously (Hu *et al.* 2007; Guo *et al.* 2008, 2012; Ye *et al.* 2011, 2013, 2016; Li *et al.* 2014; Li & Zhang 2015), and the quality of the data is quite reliable.

METHODS

Hydrological data treatment

Flood events were considered to occur in this study when the Poyang Lake stage at Xingzi station exceeded the level of 19.0 m, which is also the warning stage for the lake. To quantify the effect of the streamflow from the five sub-tributaries on the lake level, the total runoff from the Poyang Lake catchment to the lake was defined as the sum of the flow measured at Waizhou, Lijiadu, Meigang, Dufengkeng, Shizhenjie, Qiujin, and Wanjiabu hydrological stations (Figure 1). As the discharge data at Qiujin were missing during 1960–1982, the linear regression method with the observed discharge at Wanjiabu station was used to estimate the missing values. Moreover, the concept of anomaly was used in the study to conveniently reflect the variation of the runoff inflow from the local catchment and discharge of the Yangtze River, which is defined as the deviation at each month from the average water flow for the study period of 1960–2010 (see Equation (1)). Also, the anomaly was adopted in the analysis of lake level change as follows:

$$\Phi = X_i - \bar{X}_i \tag{1}$$

where Φ is the anomaly, X_i are the monthly hydrological variables, and $\bar{X}_i$ are the average monthly values during the study period.

The MIKE 21 model

The hydrodynamic model is a powerful tool to address the flow regime changes and hydraulic connection and interaction in complex river systems. Especially in Poyang Lake, the combined effects of catchment inflows and the interaction with the Yangtze River result in a considerable seasonal variation of some 10 m in the lake water level (Zhang *et al.* 2014); moreover, the complex flow patterns and hydrodynamic processes must be considered in modeling the lake behavior. Li *et al.* (2014) attempted to simulate the hydrodynamic processes of Poyang Lake by constructing a physically based mathematical model using MIKE 21 (DHI 2007). The model covered an area of 3,124 km^2, which was determined by examining the historic lake surface at high water levels. A digital elevation model of the study area used in model construction was generated based on the basic survey in 1998 by Jiangxi Hydrological Bureau and was updated with new data obtained recently. The modeling area was discretized into a number of triangular grids considering the heterogeneity of the lake bottom topography through a variable spatial discretization of 70–1,500 m (Li *et al.* 2014). The daily catchment inflows from the five sub-tributaries were specified as the upstream boundary conditions in the model, and the downstream boundary condition accounted for the connection of the lake to the Yangtze River and was specified as the daily water level at Hukou station. In the model, the hydraulic roughness (Manning number) was assumed to differ between the flat regions and the main channels, and the initial values ranged from 30 $m^{1/3}$/s to 50 $m^{1/3}$/s. A uniform value was assigned to the Smagorinsky factor (C_s) of eddy viscosity for the whole lake domain. Li *et al.* (2014) calibrated and validated the model against the observed water levels at four gauging stations in the lake (Xingzi, Duchang, Tangyin, and Kangshan station) and the discharge at Hukou station for the periods 2000–2005 and 2006–2008, respectively. The Nash–Sutcliffe efficiencies (E_{ns}) for both the calibration and validation periods at all gauging stations ranged from 0.80 to 0.98, and the determination coefficients (R^2) ranged between 0.82 and 0.99. The high values of these evaluation indexes demonstrated that the model produced excellent agreement with observations and achieved a satisfactory accuracy (for more details of model structure and simulation results, please refer to Li *et al.* 2014). The model was believed to be robust and capable of capturing the variations of the water level and was thus used in this study.

Scenarios of catchment runoff inflow and Yangtze River discharge in typical years

To accurately explore the relative contributions of the catchment and the Yangtze River to the lake level during the flood period, the following different scenarios of catchment runoff inflow and Yangtze River discharge in typical years (i.e., 1996 and 2006) were proposed in the study. Namely, scenario S0 was meant to represent the actual streamflow from the five sub-tributaries in the Poyang Lake catchment and the discharge at Hankou station, which was used as a reference case for comparative purposes. Scenarios S1, S2, and S3 (with the original discharge rates of the Yangtze River and 10%, 20%, and 30% increments of catchment runoff inflow, respectively, for 1996) emphasized the influences of the catchment runoff on the flood stage. Scenarios S4, S5, and S6 (with the original streamflow of the five sub-tributaries in the catchment and 10%, 20%, and 30% reduction of Yangtze River discharge, respectively, for 1996) emphasized the blocking effect of the Yangtze River. Similarly, in 2006, scenarios S7, S8, and S9 (with Yangtze River discharge increases of 10%, 20%, and 30%, respectively) were adopted to further investigate the blocking effects of the Yangtze River on the lake level during the flood season. The detailed scenario settings are summarized in Table 1. It is necessary to consider the rationality and existence of scenarios in reality, thus, the discharge scenarios at Hankou for the flooding year (1996) were designed to decrease the original streamflow but increase it for the dry year (2006).

The variation of the lake water levels at Hukou station, as the downstream boundary condition of the hydrodynamic model, must be input as a known variable in the scenario simulations. For this, the back-propagation neural network (BPNN) method was used to estimate the variation of the lake level at Hukou in each scenario. Li *et al.* (2015b)

Table 1 | Summary of scenarios setting in the hydrodynamic modeling

Scenario	Change of streamflow from the local catchment	Change of discharge rates of Yangtze River
S0	Observed streamflow	Observed discharge at Hankou station
S1, S2, S3	10%, 20%, and 30% of increment of streamflow from five sub-tributaries in 1996	Observed discharge at Hankou station in 1996
S4, S5, S6	Observed streamflow in 1996	10%, 20%, and 30% reduction of Yangtze River discharge in 1996
S7, S8, S9	Observed streamflow in 2006	10%, 20%, and 30% increment of Yangtze River discharge in 2006

attempted to simulate the variation of the Poyang Lake water level by using artificial neural network techniques. In his study, the period 1960–2000 was used for BPNN model training, and the period 2001–2008 was used to test the model's predictive capability; and an acceptable simulation result was received with the E_{ns} of 0.98, the R^2 of 0.98, and the root mean square error of 0.58 m. Thus, the model was reliable and directly applied in this study to estimate the variation of the lake level at Hukou for each scenario simulation. The details of the BPNN structures are provided in Li *et al.* (2015b) and are thus not repeated here.

RESULTS

Characteristics of catchment runoff and Yangtze river flow in typical flooding and dry years

To examine and understand the effects of the Yangtze River and local catchment on the flood stage of Poyang Lake, four years in which a severe flood event occurred, i.e., 1983, 1995, 1998, and 1999, were selected for study. The variations in the total runoff from the catchment, the discharge at Hankou, and their corresponding lake level anomalies during the wet season (April–September) of each year are shown in Figure 3. For comparison, four years with a low lake level in the flood season, i.e., 1963, 1972, 1978, and 2001, were also selected, and their corresponding results are shown in Figure 4. More detailed information for each years is shown in Table 1, including the peak lake level, date of the peak level, duration of the flood event, water flow from the catchment and discharge of the Yangtze River.

Previous studies (Guo *et al.* 2008) have noted that the first half of the annual variation in lake level was mainly influenced by the streamflow from the Poyang Lake catchment; this effect is well demonstrated in Figure 3(a) for the 1983 flood. It can be seen that the large runoff inflow continued through the major rainy season, reaching a total runoff of 866×10^8 m^3 during April–June, with a positive anomaly

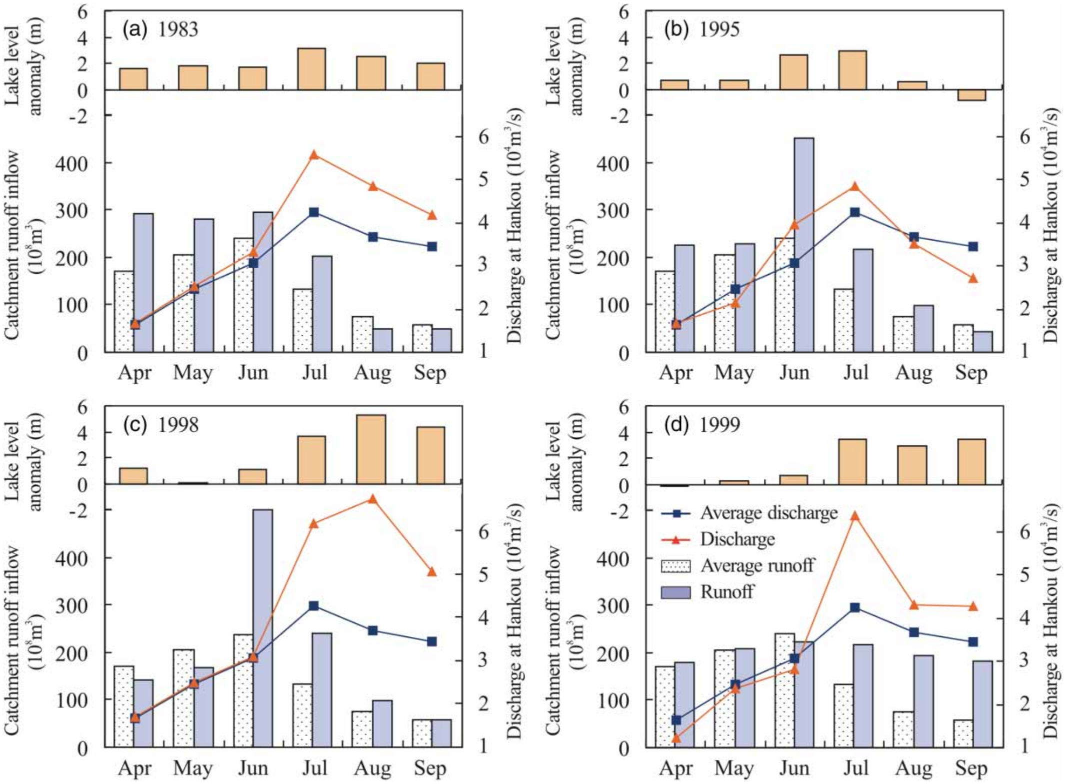

Figure 3 | Variation of the catchment runoff, Yangtze River discharge and corresponding lake level anomaly during April–September of the selected flooding years.

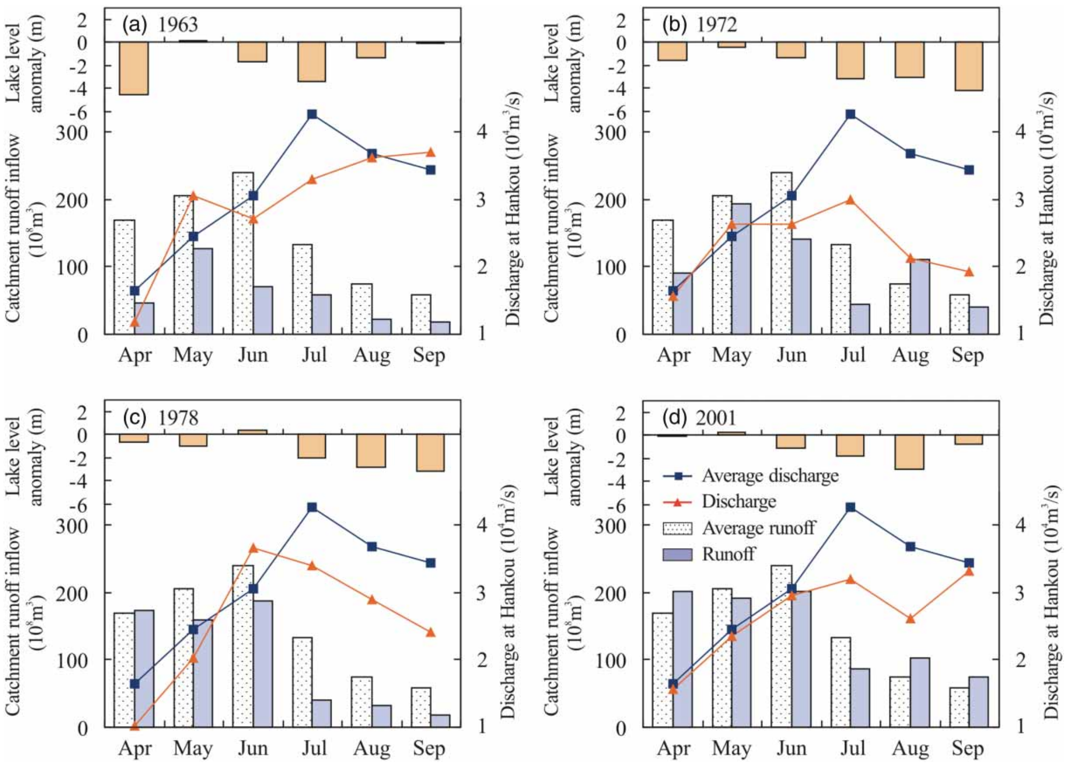

Figure 4 | Variation of the catchment runoff, Yangtze River discharge and corresponding lake level anomaly during April–September of the selected dry years.

of 252×10^8 m^3 (Table 2), resulting in a continuous rise in the lake level before the flood season. In July, the water flow from the catchment was also significantly above the usual level, with a positive anomaly of 69×10^8 m^3. More importantly, an abnormally large discharge and elevated water level in the Yangtze River in July blocked the outflow from Poyang Lake, which acted to further increase the lake level to 21.77 m on 13 July (Table 1). During the 1995 flood, although the runoff from the catchment in April and May was close to the average for those months, an abnormally large water flow in June caused a high total runoff during April–June as much as 905×10^8 m^3, with a positive

Table 2 | Summary of statistical indices for the flooding and dry years

Representative years		Peak lake level	Date of peak level	Duration[a] (day)	Runoff from catchment (10^8 m^3) Apr–Jun	Anomaly	Jul	Anomaly	Discharge at Hankou (10^4 m^3/s) Jul	Anomaly	Aug–Sep	Anomaly
Flooding years	1983	21.77	13 Jul	50	866	252	201	69	5.59	1.33	4.51	0.95
	1995	21.92	8 Jul	37	905	291	216	84	4.84	0.58	3.11	−0.45
	1998	22.50	2 Aug	94	811	197	240	108	6.14	1.89	5.88	2.32
	1999	21.97	21 Jul	73	616	2	217	85	6.36	2.11	4.29	0.73
	1996	**21.13**	**24 Jul**	**45**	**465**	**– 149**	**148**	**16**	**5.39**	**1.13**	**3.96**	**0.41**
Dry years	1963	16.22	4 Sep	–	244	−370	58	−74	3.29	−0.96	3.68	0.12
	1972	15.99	8 Jun	–	423	−191	44	−88	2.99	−1.26	2.03	−1.53
	1978	17.04	18 Jun	–	518	−96	39	−93	3.38	−0.87	2.65	−0.91
	2001	17.03	29 Jun	–	592	−22	87	−45	3.20	−1.06	2.96	−0.59
	2006	**16.72**	**21 Jun**	**–**	**693**	**73**	**136**	**4**	**3.10**	**– 1.15**	**1.79**	**– 1.76**

[a]Duration of lake level > 19 m.

anomaly of 291×10^8 m^3, which was even greater than the positive anomaly in 1983 (Table 1). It is also clear from Figure 3(b) that both the runoff from the catchment and the discharge of the Yangtze River in July were greater than normal, as occurred in the 1983 flood. A similar relationship between the flow regime of the Yangtze River and the local catchment and flood development in Poyang Lake was also observed in 1998 (Figure 3(c)). Considering the 1999 flood, the only difference with the other studied floods was that the monthly runoff from the catchment between April and June was closer to the average amount (Figure 3(d)), although the total water flow during the major rainy season exceeded the average by 2×10^8 m^3 (Table 1).

Correspondingly, Figure 4 shows the variation characteristics of the total runoff inflow from the catchment, the discharge of the Yangtze River, and their effects on the lake level anomaly in non-flooding years. It can be seen that, in general, the total water flow from the catchment during April–June was smaller than the average, with negative anomalies ranging from -370×10^8 m^3 to -22×10^8 m^3 (Table 2). In addition, without exception, the discharge of the Yangtze River at Hankou and the runoff inflow from the catchment in July were abnormally lower than average. For example, the discharge anomalies at Hankou station in July were -0.96×10^4 m^3/s, -1.26×10^4 m^3/s, -0.87×10^4 m^3/s, and -1.06×10^4 m^3/s in 1963, 1972, 1978, and 2001, respectively. Further, the runoff inflow anomaly varied from -45×10^8 m^3 in 2001 to just -93×10^8 m^3 in 1978. As a result, the water level of Poyang Lake declined 2–4 m, with the maximal lake level no higher than 17.04 m during the flood seasons of these years (Table 2).

Through a comparison of Figures 3 and 4, in combination with the information from Table 2, several common features in the process of flood development in Poyang Lake can be identified: (1) the total runoff from the catchment during April–June was larger than the average and led to a continuous rise in lake level; (2) an abnormally large discharge from the Yangtze River in July elevated the water level and blocked the outflow from Poyang Lake; and (3) the large water inflow from the catchment resulted in a higher lake level in July when the level of the Yangtze River was also high. These features are all important indications for flood development, and if some of them arise, then there is a high probability that a flood may occur in Poyang Lake. The reverse is also true, a flood is inconceivable when none of these conditions arise.

Variation of catchment runoff and Yangtze River flow in 1996 and 2006

As mentioned above, flood development in Poyang Lake is affected by both the runoff inflow from the local catchment and the blocking effect of a large discharge of the Yangtze River. The common features have been summarized for the typical flooding years and dry years; however, several years, such as 1996 and 2006 in Table 1, had differing relationships between the total runoff inflow and Yangtze River discharge and lake level variation, compared to other years. Figure 5 shows the variation in the water flow

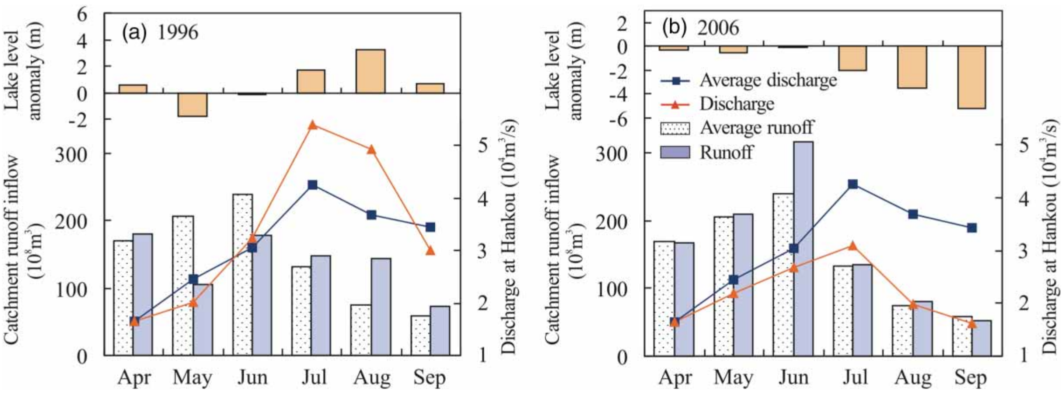

Figure 5 | Variation of the catchment runoff, Yangtze River discharge, and corresponding lake level anomaly in 1996 and 2006.

from the catchment, the discharge at Hankou, and the corresponding lake level anomalies during the wet seasons of 1996 and 2006. From Figure 5(a), it can be seen that the total runoff inflow from the catchment in April–June of 1996 was only 465×10^8 m^3, with a negative anomaly of -149×10^8 m^3, resulting in the lake level before the major flood season being lower than average; however, a flood event still occurred in this year with a maximal lake level of 21.13 m on 24 July (Table 2). Evidently, this flood event can mainly be ascribed to the effect of the Yangtze River water fluxes in July, amounting to a discharge of 5.39×10^4 m^3/s at Hankou station. This was nearly as large as that in the 1983 flood period and raised the lake level anomaly from negative to positive, reaching a total positive 1.73 m anomaly. Therefore, the abnormally large river flow of the Yangtze River was the principal driving force for the 1996 flood, blocking the outflow from Poyang Lake and elevating the lake level above the average.

An example of the opposite case is shown in Figure 5(b). It is clear that in 2006, the streamflow from the five sub-tributaries in the Poyang Lake catchment during April–June was very high, reaching 693×10^8 m^3 with a positive anomaly of 79×10^8 m^3, and was even greater than that in 1999. Nevertheless, such a large runoff inflow did not result in a rise in the lake level owing to the small discharge of the Yangtze River at that time. During the flood season, in particular, the abnormally low river flow, with a negative anomaly of -1.15×10^4 m^3/s in July and -1.76×10^4 m^3/s in August–September, accelerated the outflow from Poyang Lake and caused the lake level to drop 2–5 m, eventually leading to a serious autumn drought. Inspecting Figure 5, it is clear that the discharge of the Yangtze River imposes more influence on the development of floods in Poyang Lake than the runoff inflow from the local catchment. Thus, the strength of the blocking effect of the Yangtze River dominates the severity of the flood to a great extent.

Hydrodynamic modeling influences of the local catchment and Yangtze River

Hydrodynamic modeling was undertaken to further explore the relative contributions of the local catchment and the Yangtze River to Poyang Lake water level during the flood season of 1996 and 2006. Based on the previous analyses of the lake level (Guo *et al.* 2008; Li & Zhang 2015), the modeling was carried out from March to September (with March as a warm-up period) to save time and computing resources. The model results for the S0 case in 1996 were compared with the water level observations at Xingzi, Duchang, Tangyin, and Kangshan stations, producing E_{ns} of 0.998, 0.996, 0.986, and 0.992, respectively. The high values of E_{ns} demonstrated that the model produced an excellent agreement with observations and described the variation of water level well.

Figures 6 and 7 show the comparison of the simulated water level and its changes in 1996 for every scenario. It is seen that the water level of Poyang Lake rose with the increase of the streamflow from the five sub-tributaries in the local catchment and declined with the decrease of the Yangtze River discharge as expected; the average water level changes were 0.10 m, 0.17 m, and 0.24 m in scenarios S1, S2, and S3, respectively, and −0.50 m, −1.07 m, and −1.58 m in scenarios S4, S5, and S6, respectively. It is also found that the water level changes, regardless of whether these changes were increases or decreases, were distributed unevenly in different months. Specifically, the largest water level changes in scenarios S1, S2, and S3 were observed during April–May (except at Kangshan station) with the average increment of 0.11–0.14 m, 0.21–0.25 m, and 0.31–0.38 m, respectively, but they became small during July–August and were smallest in September. As for scenarios S4, S5, and S6, the seasonal distribution of water level changes was opposite to the former, i.e., the most significant decreases were presented during July–August (with the average decline of −0.58 to −0.78 m, −1.61 to −1.71 m, and −2.59 to −2.61 m in scenarios S4, S5, and S6, respectively), but they were trivial during April–May. Figures 6 and 7 further validate that the streamflow from the Poyang Lake catchment imposed more influence on the lake level during April–May than other periods, while the Yangtze River created a stronger blocking effect during July–August than other periods.

Moreover, the hydrodynamic simulation revealed that the spatial distribution of the water level change was also uneven. Figure 8 shows the variation of the water level changes at different stations in the lake, using scenarios S3 and S6 as examples. It is obvious that, during

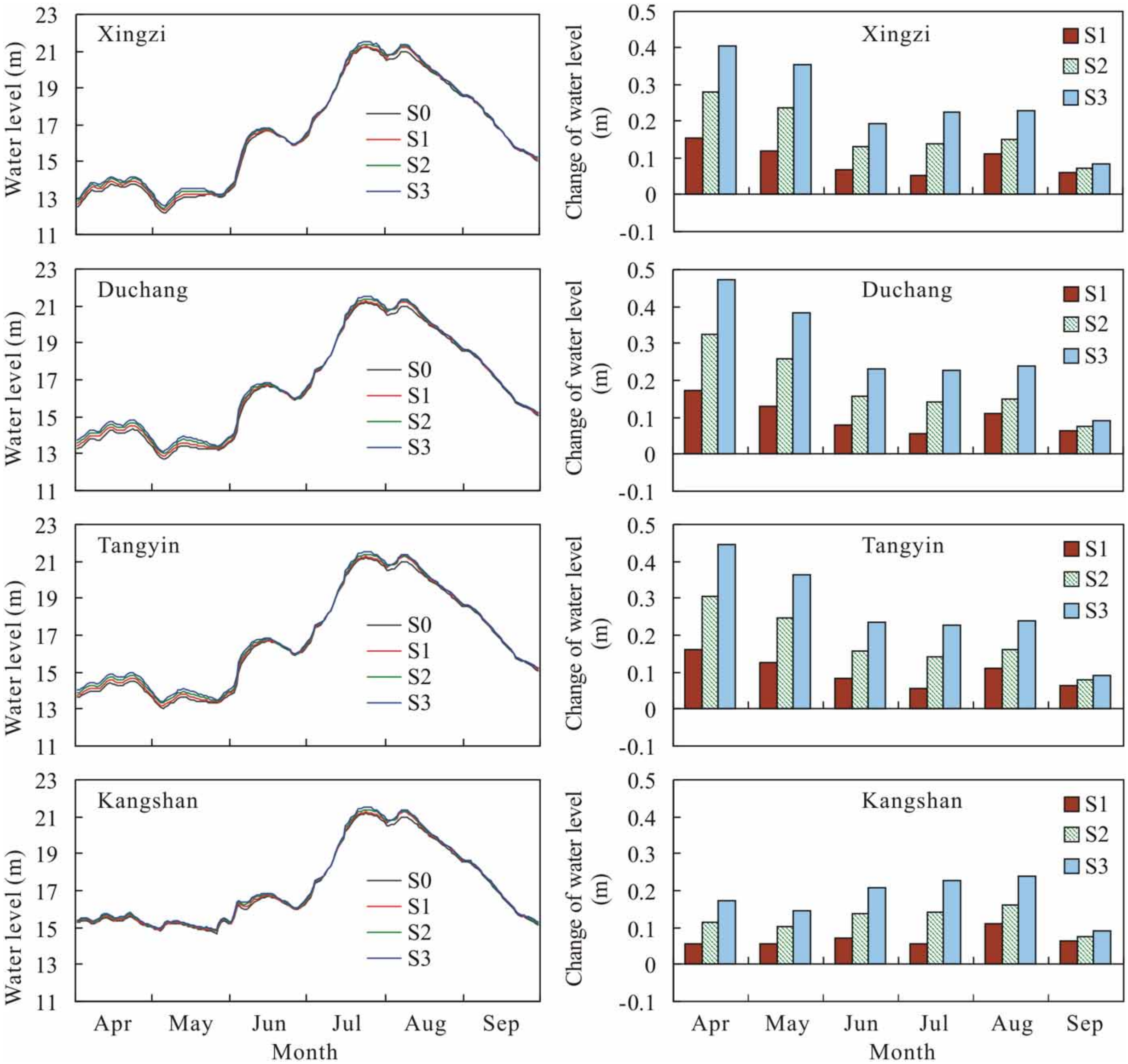

Figure 6 | Comparison of simulated water level and its changes in 1996 for scenarios S1, S2, and S3.

April–June, the increment of the water level in case S3 was more significant at Duchang and Tangyin than at Xingzi and Kangshan, but the decline of the water level in case S6 was the most remarkable at Xingzi and showed a gradual attenuation from Xingzi to Kangshan. Additionally, this pattern could be extracted more clearly from the spatial distribution of the average water level changes, which were derived from the outputs of the hydrodynamic model. As Figure 9(a) shows, the largest water level change in April for scenario S3 was observed at the middle parts of Poyang Lake with an approximately 0.7 m rise, and the increments were generally reduced toward the north and south. Whereas the average water level change in scenario S6 was more remarkable at the northern parts of the lake, the declines reduced from −1.0 m at the northern parts of the lake to −0.1 m at the southern parts (Figure 9(b)). During July–September, almost uniform water level changes were observed at different stations in both scenarios S3 and S6 because the lake surface is almost horizontal during the flood season.

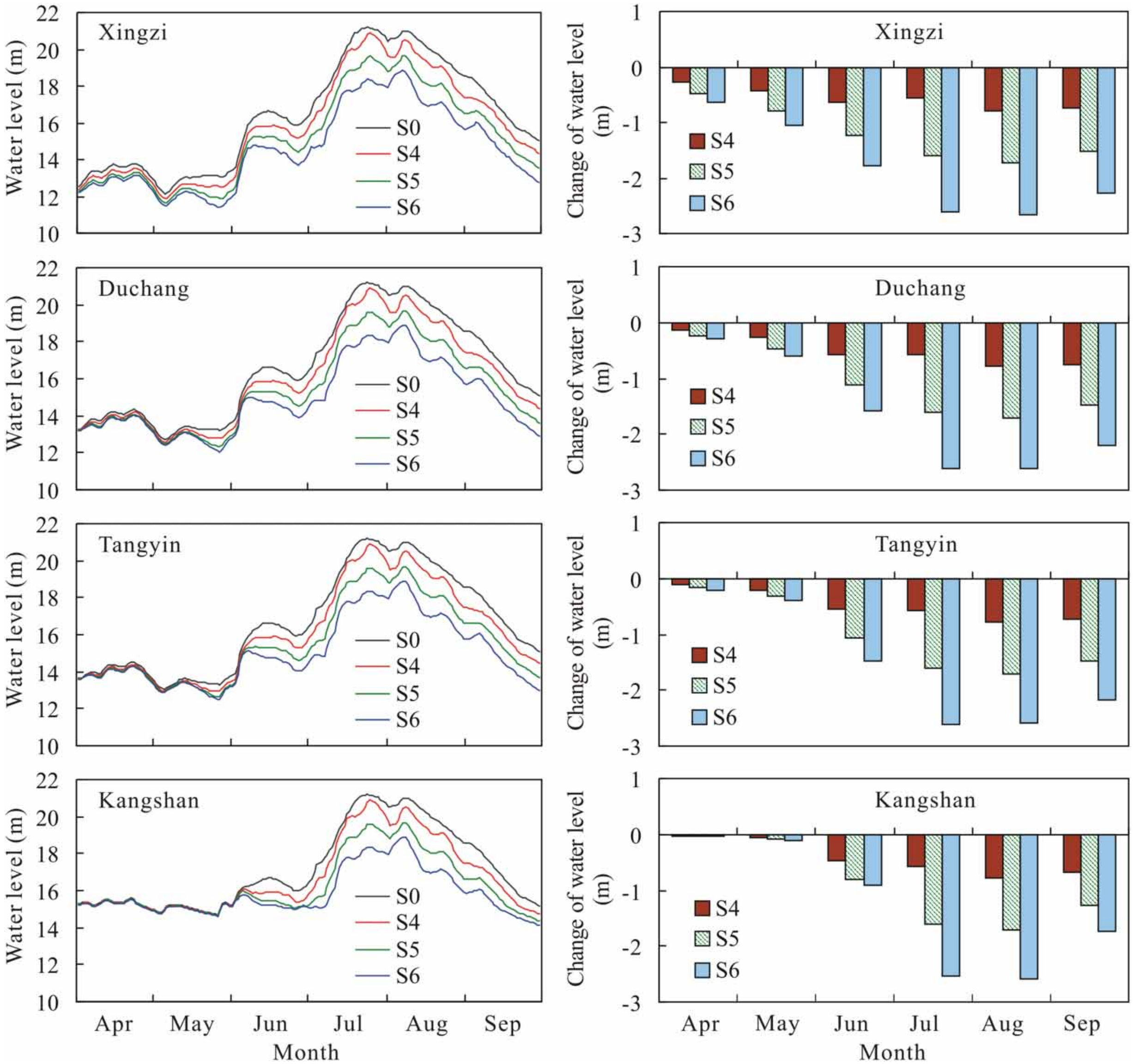

Figure 7 | Comparison of simulated water level and its changes in 1996 for scenarios S4, S5, and S6.

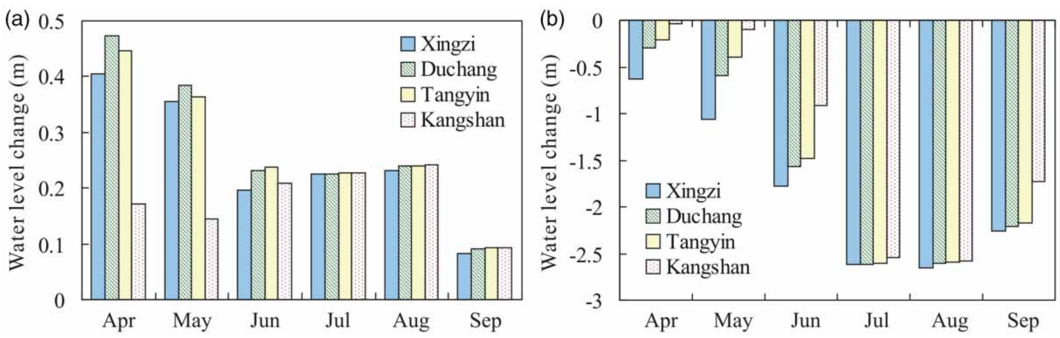

Figure 8 | Variation of water level changes at different stations in scenarios S3 (a) and S6 (b).

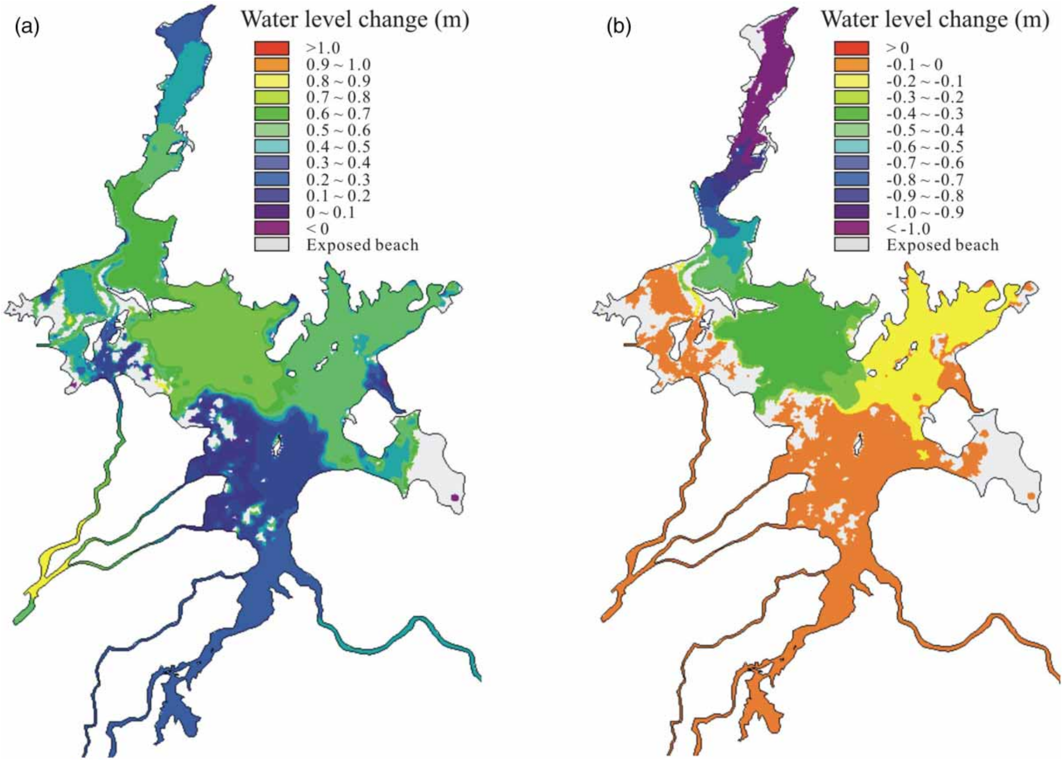

Figure 9 | Spatial distribution of average water level changes in April for scenarios S3 (a) and S6 (b).

In addition, the study was also extended to investigate the duration changes of the high lake level, which resulted from the impacts of the local catchment runoff and Yangtze River flow. Table 3 shows the changes of duration as well as the start/end date of the high lake level at Xingzi station in different scenarios. It is seen that with the increase of streamflow from the local catchment, the duration of the high lake level lengthened, regardless of whether the level was above 19.0 m, 20.0 m, or 21.0 m; further, the date of floodwater receding was delayed for 1–4 days, but the starting date was almost unchanging. In contrast, the decrease of the Yangtze River flow led to a distinctly shorter duration of the high lake level as expected, and some of them were reduced to 0 because the highest lake level did not exceed the threshold level. It also resulted in several days' delay of the floodwater

Table 3 | Changes in duration, start/end date of high lake level in different scenarios

	Duration (day)			Start date			End date		
Scenarios	**19 m**	**20 m**	**21 m**	**19 m**	**20 m**	**21 m**	**19 m**	**20 m**	**21 m**
S0	45	33	5	13 Jul	16 Jul	22 Jul	26 Aug	17 Aug	26 Jul
S1	46	34	8	13 Jul	16 Jul	22 Jul	27 Aug	18 Aug	29 Jul
S2	47	35	9	13 Jul	16 Jul	21 Jul	28 Aug	18 Aug	29 Jul
S3	47	35	10	13 Jul	16 Jul	21 Jul	28 Aug	19 Aug	30 Jul
S4	42	22	0	13 Jul	20 Jul	–	23 Aug	11 Aug	–
S5	20	0	0	22 Jul	–	–	10 Aug	–	–
S6	0	0	0	–	–	–	–	–	–

rising and advanced the date of the floodwater receding by at least 3–16 days.

Similarly, in 2006, the simulated water level and its changes in scenarios S7, S8, and S9 are shown in Figure 10. It is seen that the increase of the Yangtze River discharge elevated the lake level as expected, and the average water level rose 0.32 m, 0.66 m, and 0.98 m in scenarios S7, S8, and S9, respectively. However, these changes were also distributed unevenly in both time and space, as found in the 1996 scenario simulations. Specifically, the lake level change was stronger during July–August, with an average increment of 0.45–1.31 m, compared to that in April–May (approximately 0.14–0.71 m). Additionally, more notable changes of the lake level were observed at the northern parts of the lake, i.e., the increment reduced from 0.37–1.06 m at Xingzi to 0.06–0.25 m at Kangshan during April–May.

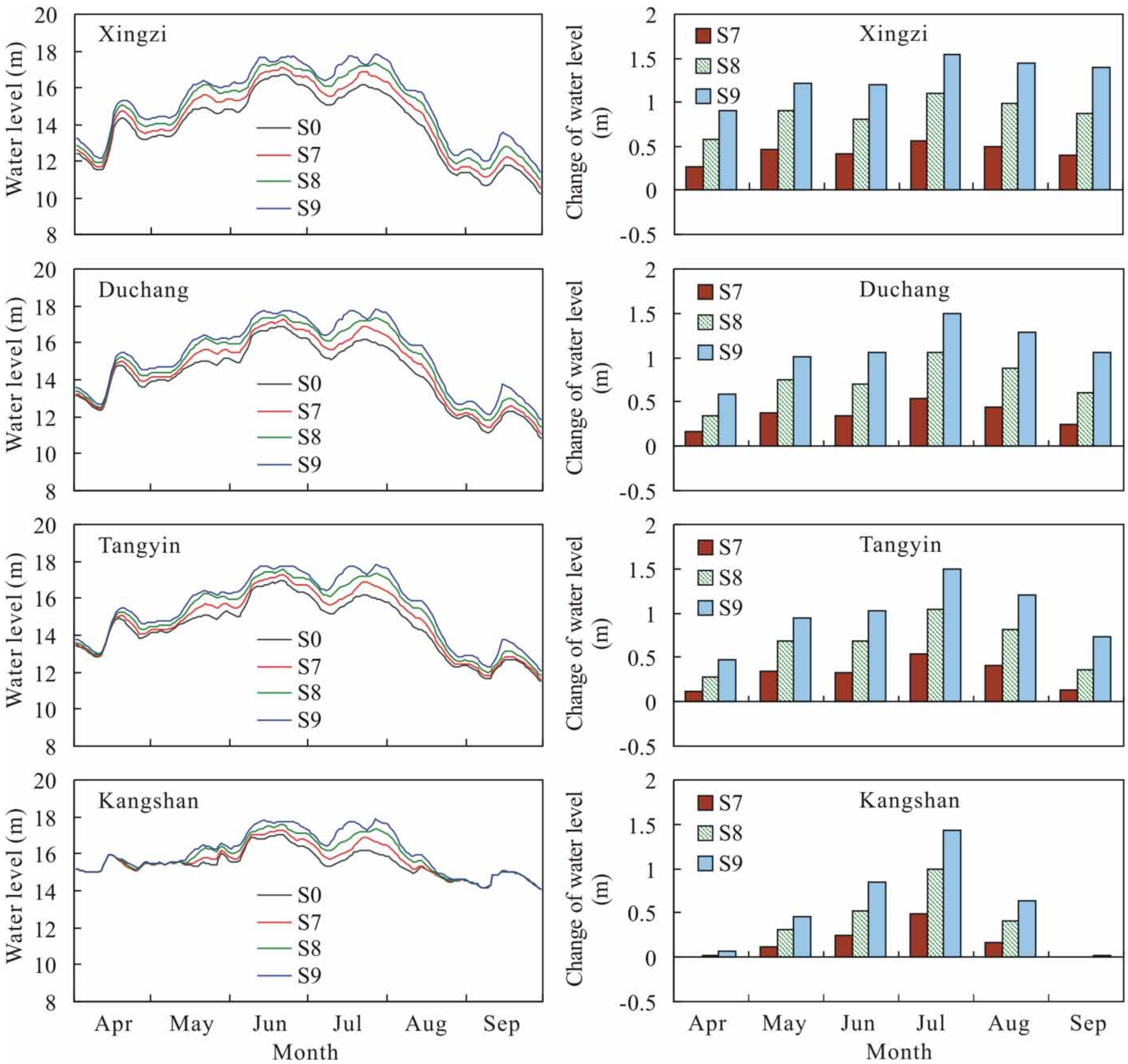

Figure 10 | Comparison of simulated water level and its changes in 2006 for scenarios S7, S8, and S9.

DISCUSSION

An examination of the characteristics of Poyang Lake water level in typical flooding years and a comparison with that in dry years found that the large catchment runoff and Yangtze River discharge were both significant contributors to flood development in Poyang Lake, and their concurrence may more easily trigger floods. Model simulations further revealed that the influence exerted by the catchment was most significant during April–May, when the lake level change ranged from 0.12 to 0.34 m, but the influence of the catchment was trivial (average 0.08–0.23 m) in the flood season; in contrast, the Yangtze River imposed greater influences during July–August, resulting in a lake level change as much as 0.68–2.61 m. This is in agreement with the findings of other studies. Many studies have shown that the water level of Poyang Lake is a result of the joint effects of the local catchment runoff and the Yangtze River discharge and that the Yangtze River imposes a greater influence on the development of floods in Poyang Lake than does the local catchment runoff (Min 2002; Shankman *et al.* 2006, 2012; Hu *et al.* 2007; Nakayama & Watanabe 2008; Guo *et al.* 2012; Lai *et al.* 2014a, 2014b; Zhang *et al.* 2014). Shankman *et al.* (2006) ascribed the high water levels in Poyang Lake during the flood season to a higher Yangtze River stage, and they further noted that a large catchment runoff generated later in summer than normal could increase the probability of lake floods. Hu *et al.* (2007) also noted that the catchment runoff raised the lake level and enhanced the impact of the local catchment on the lake during the spring–early-summer months, when the Yangtze River had a very low water level. In contrast, during July–September, the Yangtze River exerted frequent and substantial effects on the lake when the Yangtze River experienced its largest annual flows (Hu *et al.* 2007). This change pattern primarily resulted from the flow regimes of the five sub-tributaries in the local catchment and the Yangtze River; Hu *et al.* (2007) and Guo *et al.* (2012) explained that the hydrograph of the Poyang Lake catchment explains the primary features of the first half of the annual variation of the lake level but the second half of the annual course of the lake level is mainly controlled by the discharge of the Yangtze River. Similar conclusions were also reached in a study by Zhang *et al.* (2014).

The hydrodynamic simulation also revealed that the lake level change was the most remarkable at the middle parts of Poyang Lake for the catchment scenarios (S1, S2, and S3), but at the northern parts for the Yangtze River scenarios (S4, S5, and S6) during April–June, and during July–September, the almost uniform water level changes were observed in both scenarios. Lai *et al.* (2014a) also examined the impacts of alterations in the lake inflow and the Yangtze River flow on water levels in Poyang Lake and found that the Lake inflow alterations caused approximately uniform water level change in Poyang Lake, whereas the Yangtze River alterations mainly affected the northern lake. These findings are in agreement with the findings of the current study, except for the spatial disparities in the catchment scenarios. The possible causes for this difference between the findings include the different scenario designs, the spatial resolution of hydrodynamic simulation, and the time scale of the statistical analysis. Thus, further intensive investigation and a comparative study of an elaborate simulation are necessary in future studies.

In addition, several scenario simulations were used in the present study to examine the effects of the local catchment and the Yangtze River. However, the discharge scenarios at Hankou for the flooding year (1996) were designed to decrease the original streamflow, considering the rationality and existence of scenarios in reality when we evaluate the blocking effect of the Yangtze River (S4, S5, and S6). Such a treatment resulted in opposite changes of the lake water level compared with that in the catchment scenarios (S1, S2, and S3). To evaluate the effect of such treatment on the results, we also compared and examined the relationships between the increased and decreased discharge scenario of the Yangtze River with a low scale of change (10%) and the results are shown in Figure 11. The simulation results demonstrated that the increase of the Yangtze River discharge elevated the lake level as expected. Moreover, a similar distribution of the lake level changes with its counterparts (scenario S4) was observed, i.e., the increments of the lake level were significant during July–August but trivial in April–May, and the lake level changes reduced from the northern parts to the southern parts. Therefore, the effect of the opposite scenarios design was weak, and the above conclusions derived from the scenario simulations were conclusive.

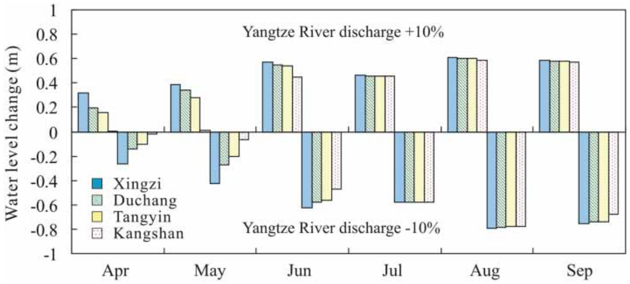

Figure 11 | Comparison of lake level change in the increasing and decreasing discharge scenario of Yangtze River.

CONCLUSIONS

This paper analyzed and compared the relationships between the water level changes of Poyang Lake and the flow regime changes of the Yangtze River and sub-tributaries in the local catchment in typical flooding and dry years and quantified their relative contributions during the flood season based on the hydrodynamic model MIKE 21. The study demonstrated that the large catchment runoff and Yangtze River discharge were both substantial contributors to flood development in Poyang Lake, and their concurrence may more easily trigger floods; however, a flood is impossible when both of them are low. The hydrodynamic simulation revealed that the lake level change, regardless of whether it resulted from the local catchment runoff or the Yangtze River discharge, was distributed unevenly in different months and areas in the lake. The influences exerted by the local catchment were most significant during April–May, when the lake level change ranged from 0.12 to 0.34 m, but were trivial (average 0.08–0.23 m) in the flood season. In contrast, the Yangtze River imposed a greater influence during July–August and caused a lake level change as much as 0.68–2.61 m. At the same time, the water level at the middle parts of Poyang Lake was more sensitive to the local catchment runoff change, but the northern parts were more sensitive to the Yangtze River alteration. In addition, the Yangtze River imposed far stronger influences on the rise and decline of a high lake level than did the local catchment runoff and dominated the duration of the flood to a great extent.

This paper adds additional knowledge to the previous studies and is the first study to employ a physically based hydrodynamic model to quantify the relative contributions of the local catchment and Yangtze River to the lake level during the flood season. The outcomes of this study enhance our understanding of the causes of floods in Poyang Lake. The above-mentioned conclusions also indicate that understanding the effects of the East Asian monsoon and prediction of the impact of specific distributions of rainfall, i.e., upstream of the Yangtze River or Poyang Lake catchment only, is necessary for flood prediction, mitigation, and management in Poyang Lake. In addition, efforts should be made to quantify the influences of intensive human activities in the next study.

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