Hydrological evidence and causes of seasonal low water levels in a large river-lake system: Poyang Lake, China

Jing Yao, Qi Zhang, Yunliang Li and Mengfan Li

ABSTRACT

Seasonal variations in local catchments and connected rivers lead to complex hydrological behaviours in river-lake systems. Poyang Lake is a seasonally dynamic lake with frequent low levels in spring and autumn, which may be triggered by the local catchment and Yangtze River. Based on two typical years, a hydrodynamic model combined with long term hydrological observations was applied to quantify the spatiotemporal impacts of the local catchment and Yangtze River on spring and autumn low water levels in Poyang Lake. As a first attempt, this study explored the spatial differences of the two influences. Simulation results showed that the contributions of the catchment and the Yangtze River were approximately 70% and 30% in spring 1963, and 5% and 95% in autumn 2006, respectively. The area of catchment influence was mainly distributed in channels and southern floodplains, with relatively uniform water levels. The area impacted by the Yangtze River mainly spanned from the northern portion of the waterway to the central lake, with strong spatial variability. This study focused on two typical years; however, the results can be extended to explain common hydrological phenomena and improve future strategies of water resource management in this river-lake system.

Key words | hydrodynamic model, low water level, Poyang Lake, river-lake interaction, Yangtze River

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INTRODUCTION

Many natural lakes receive water inflows from catchments and discharge to large, connected rivers, forming river-lake systems. The volume of a lake is not only controlled by the lake bathymetry but also by the balance between water inputs and outputs, which largely depends on river-lake interactions over diurnal and annual cycles (Peters & Buttle 2010). There are a large number of river-lake systems around the world. Extensive floodplain lakes are associated with the Amazon River (South America), and the water in river-lake systems is derived from the rivers, local rainfall and runoff, exchanges with adjacent lakes, and so on (Engle & Melack 1993; Lesack & Melack 1995; Bonnet *et al.* 2008). For example, Lake Calado is connected to the Amazon River by a narrow channel, and its depth changes (1–12 m) are directly linked to the river's hydrograph (Engle & Melack 1993). Lake Wakatipu (New Zealand) is a similar system whose main inflow is from the Dart and Rees Rivers. It outflows to the Kawarau River, and the lake water level fluctuates within a 1.5 m range most of the time (Pickrill & Irwin 1982). Examples in other regions include Great Lake Saimaa and rivers connected to it in Finland (Tikkanen & Tikkanen 2002), the Lake Athabasca-Peace-Athabasca Delta system in Canada (Peters & Buttle 2010), the Tonle Sap Lake-Mekong River system in Cambodia (Dutta *et al.* 2007), and the St Clair River-Lake St Clair-Detroit River system on the border between the United States and Canada (Anderson & Schwab 2011). In

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such complex river-lake systems, the local catchment and river control the water resource and flood-drought potentials of the lake seasonally or jointly in different seasons, resulting in highly complex lake level fluctuations and flow regimes (Lai *et al.* 2013). Thus, understanding shortages of water resources is a challenge for the populations and ecosystems in these systems (Gemmer *et al.* 2008). It is important to properly understand and quantify the relative contributions of the local catchment and the river to dynamic changes in lake water levels.

Poyang Lake is the largest freshwater lake in China and is located in the middle reaches of the Yangtze River. The Poyang Lake catchment-Poyang Lake-Yangtze River system in China is an ideal example of a highly valued water resource with a particularly complex hydrological regime and topography. This system has experienced floods and droughts at a much higher frequency over the past 50 years as a result of naturally occurring climate variability coinciding with increased human activities (Shankman *et al.* 2006; Gemmer *et al.* 2008; Ye *et al.* 2011; Nakayama & Shankman 2013). As an internationally important wetland and the largest bird conservation area for migratory birds in the world, Poyang Lake has important ecological functions (Hui *et al.* 2008). The lake receives catchment runoff from five tributary rivers and subsequently discharges to the Yangtze River through the Hukou outlet in the north. During the flood season of the local catchment from April to June, Poyang Lake has the largest outflow to the Yangtze River and exerts a strong pressure on it (Guo *et al.* 2011). The Yangtze River affects Poyang Lake in a different manner, including the blocking effect of outflows from the lake to the river and reversing water flow into the lake when the blocking pressure is sufficiently large (Hu *et al.* 2007). The Yangtze River's blocking and/or reverse flow to Poyang Lake is strongest during the peak discharge of the Yangtze River from July to September (Guo *et al.* 2011). These two very different hydrological processes indicate different river-lake interactions in different seasons (Guo *et al.* 2012). Due to their variations and interactions, the water level and surface area vary considerably in their spatial and temporal patterns within and between years. Annual variations in water level can reach up to 18 m (Li *et al.* 2015a). The lake area varies from less than 1,000 km^2 in dry seasons to more than 3,000 km^2 in wet seasons (Feng *et al.* 2012a; Zhang *et al.* 2015). Spatial-temporal heterogeneity due to river-lake interactions in the system makes understanding the highly dynamic hydrological regime more challenging.

Aiming to gain deeper insight into the complex river-lake system, several studies were performed to investigate the lake water level and surface area influences of the river and lake. During the water level rise period (from April to June), the water level of Poyang Lake is mainly controlled by seasonal variations in catchment inflows (Shankman *et al.* 2006; Hu *et al.* 2007). Especially during the occurrence of severe floods, the lake catchment plays a primary role in determining the lake water level, while the Yangtze River plays a complementary role in blocking outflows (Hu *et al.* 2007). However, during the high water level period and recession period, the flow regime changes of the Yangtze River have a strong influence and can change the blocking force of the river on outflows from Poyang Lake (Hu *et al.* 2007). It further affects the lake level, water storage and associated seasonal variations (Guo *et al.* 2012). Liu *et al.* (2013) found that the lake area not only depended on water inputs from regional precipitation, evapotranspiration and discharge but also on the interactions between the lake and the Yangtze River.

Poyang lake has experienced a new and more severe dry condition since 2000 (Zhang *et al.* 2014). Compared to levels reported in previous decades, the lake water levels dropped to the lowest level from 2001 to 2010 (Zhang *et al.* 2014), and the lake area decreased significantly (Feng *et al.* 2012a). The higher frequency of extremely low water levels in recent years has affected not only the agriculture, transportation, and urban water supply but also wetland and aquatic habitats (Liu *et al.* 2015). The reasons for and spatial distribution of low water levels in such a complex river-lake system with seasonal variations in water level must be urgently investigated.

A number of studies of the low water level conducted analyses of climate changes, rainfall runoff, river-lake interactions and human activities. Feng *et al.* (2012b) used 12-year multi-source satellite data combined with corresponding hydrological data to evaluate Poyang Lake's inundation area and local precipitation, suggesting that the extremely low water level in spring 2011 was primarily caused by the significantly low local precipitation. Later, Liu *et al.* (2013)

examined the change in the lake size and proposed that the recent lake size decline was principally caused by a weakened blocking effect of the Yangtze River. Lai *et al.* (2014b) investigated channel changes using surveyed and remotely sensed data and found that sand mining increased the discharge ability of Poyang Lake into the Yangtze River, causing a lower water level in the winter dry season in recent years. Because of the advantage of spatial-temporal continuity, physically based hydrodynamic models can overcome the difficulties associated with data scarcity in statistical analyses and remote sensing methods. Based on long-term hydrological data sets and a hydrodynamic model, Zhang *et al.* (2014) argued that the 'empty effect' of the Yangtze River was the primary causal factor of the low water level during autumn in recent years in Poyang Lake. Similarly, Lai *et al.* (2014a) adopted a hydrodynamic model (CHAM) to quantify the impacts of catchment inflows and Yangtze River discharge on water level and surface area in Poyang Lake during the rising and falling flood stages in May and October, suggesting that both factors can significantly change lake water levels. Overall, the above-mentioned studies show that different seasonal low water levels may result from completely different drivers in this complex river-lake system, although extremely low water levels occurred frequently in recent years in Poyang Lake.

During the 2000s, autumn water levels were the lowest in history (Zhang *et al.* 2014), suggesting frequent low autumn water levels. However, the maximum/minimum ratios of monthly inundation areas between 2000 and 2010 were over 2.5 in spring and over 3 in autumn (Feng *et al.* 2012a), indicating that spring is second to autumn in terms of low water level events. For example, in 2007 and 2011, low water levels occurred in spring (Feng *et al.* 2012a, 2012b), therefore, low water levels generally occur in spring and autumn in Poyang Lake. Although several studies have evaluated the influences of the local catchment and Yangtze River on recently low water levels in Poyang Lake, questions such as 'What are the different spatiotemporal impacts of the catchment and Yangtze River on seasonally extreme low water levels in this complex river-lake system?' remain unanswered and must be addressed. Addressing this question is of great scientific merit in understanding the causes of frequent spring and autumn low water levels in Poyang Lake. Based on two typical spring and autumn low water level events in Poyang Lake, this study explores the spatiotemporal impacts of the Yangtze River and local catchment on seasonal low water levels using a hydrodynamic model combined with long-term hydrological observations. The objectives of this paper are as follows: (1) to analyse the characteristics of typical extreme low water levels in spring and autumn in Poyang Lake; and (2) to characterize and quantify the relative spatiotemporal contributions of the local catchment and Yangtze River to spring and autumn extremely low lake levels. This study attempts to provide a reference for similar spring and autumn low water levels in complex river-lake systems. The outcome of this study aims to further the understanding of the potential impacts of climate variability and anthropogenic activities along the lake catchment and Yangtze River and provide scientific explanations for the considerable variations in the hydrological regimes of Poyang Lake. Water resource management should be performed from the catchment-lake-river perspective, considering staggered peaks of the Yangtze River and the local catchment in the system.

STUDY AREA

Poyang Lake is located in the middle reaches of the Yangtze River, with a latitude between 28°24′ and 29°46′N and a longitude between 115°49′ and 116°46′E (Figure 1(a)). The catchment of the Lake has an area of 1.62×10^5 km^2, and its topography varies from approximately 30 m (above mean sea level) in the lake floodplain area to 2,200 m in mountainous regions (Zhang & Werner 2015). The catchment has a subtropical monsoon climate with an average annual rainfall of 1,654 mm, an average temperature of 17.6 °C and an annual potential evapotranspiration of 1,049 mm/year (Zhang *et al.* 2014).

Poyang Lake spans 170 km from north to south and as much as 74 km from east to west (Lai *et al.* 2014a). Shaped by a combination of lacustrine and riverine morphological processes, the lake has a complex topography, including narrow channels, internal lakes and large areas of alluvial deltas (Lai *et al.* 2014a). The elevation of the lake bottom generally decreases from south (upstream) to north (downstream). There are two national nature reserves in the

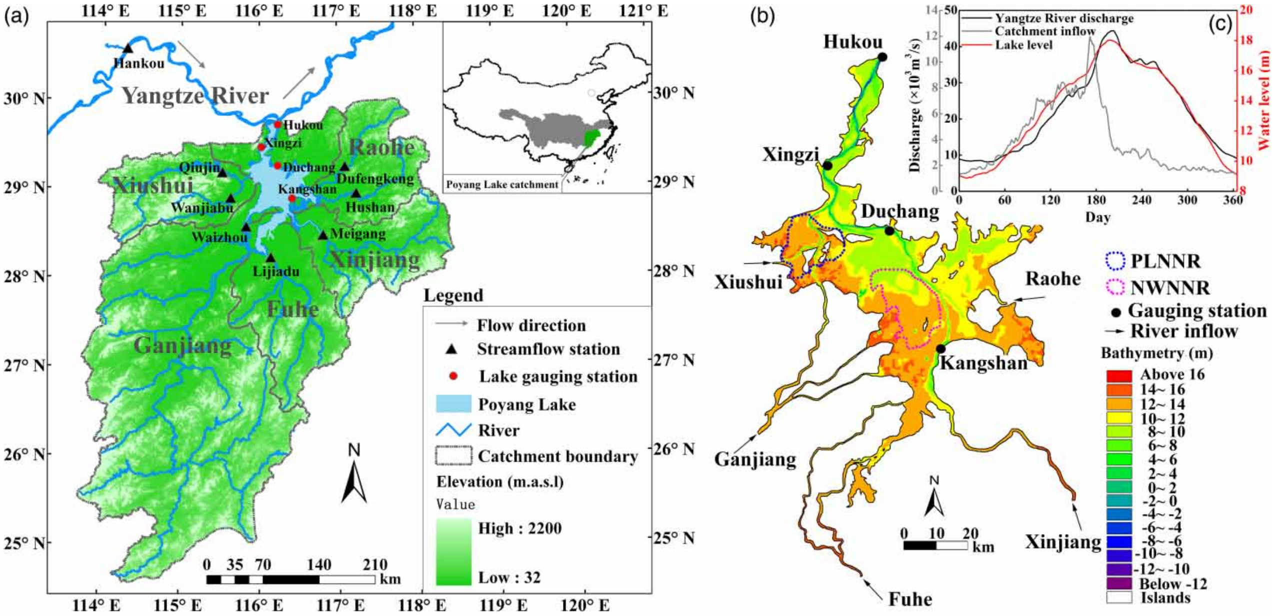

Figure 1 | (a) Location of the Poyang Lake catchment and Yangtze River; (b) Poyang Lake bathymetry, locations of the PLNNR and the NWNNR, lake gauging stations, and five major rivers within the lake area; (c) average annual variation in discharge to Poyang Lake from the catchment and Yangtze River discharge at Hankou and the lake water level at Xingzi.

central lake, the Poyang Lake National Nature Reserve (PLNNR) and the Nanji Wetland National Nature Reserve (NWNNR) (Figure 1(b)).

Poyang Lake receives water flows from five rivers in the catchment: the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers. It exchanges water with the Yangtze River via a narrow channel (Hukou outlet) at the northern end of the lake (Figure 1(a)). Figure 1(c) shows the average variation in discharge to Poyang Lake from the catchment, the Yangtze River discharge at Hankou station, and the lake water level at Xingzi gauging station, which is located at the north of the lake and approximately 39 km from the Yangtze River (Zhang *et al.* 2014). Catchment inflows vary considerably throughout the year, ranging between 1.4×10^3 and 12.0×10^3 m^3/s based on the average values from 1953 to 2010. The Yangtze River discharge also demonstrates evident seasonal variation, with a mean annual variation between 8.1×10^3 and 44.4×10^3 m^3/s from 1960 to 2010. However, a time lag exists in the peak discharge of the Yangtze River relative to the maximum catchment inflow. Generally, catchment inflows peak from April–June, which is before peak discharge reaches the Yangtze River in July–September (Guo *et al.* 2012; Gao *et al.* 2014). Seasonal variations and the time lag of the catchment inflows and Yangtze River complicate lake level and area fluctuations. Annual average fluctuations in water level vary by 8–18 m (Figure 1(c)). In the wet season, with the rise of the lake level, all floodplains are inundated. In the drier season, the lake level declines, and the lake shrinks to little more than a river.

MATERIALS AND METHODS

Data availability

Seven downstream gauging stations (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan and Dufengkeng; Figure 1(a)) were used to represent the catchment inflows from the five major rivers. Observed daily streamflows at these seven gauging stations were obtained from 1953 to 2010. Xingzi, Duchang and Kangshan gauging stations are located from the downstream to upstream ends of Poyang Lake (Figure 1(b)), reflecting different hydrological responses in the downstream, central and upstream parts of the lake to river inflows. Additionally, the Lake water levels of these gauging stations were used to assess modelling results. The water levels at Xingzi gauging station from 1960 to 2010 were chosen to represent the lake and analyse inter-annual variability. The Yangtze River gauging station of Hankou from 1960 to 2010 (Figure 1(a)), located 284 km upstream of the lake, was used to represent the hydrological conditions of the river. All data were obtained from the Hydrological Bureau of Jiangxi Province and the Hydrological Bureau of the Yangtze River Water Resources Commission of the Ministry of Water Resources of China.

Two typical seasonal low water level cases

To compare the impacts of the local catchment and the Yangtze River on seasonal low water levels, two typical extreme low water level cases in different seasons were selected. The mean water level and the lowest water level can partially reflect the duration and magnitude, respectively, of low water levels. Figure 2 highlights the spring and autumn variability in the mean and lowest water level variations in different years based on the water level at Xingzi gauging station. There was a significant decline in water level from July–October in the 2000s (Figure 2 (b)). Both the mean water level (12.23 m) and the lowest water level (8.62 m) in July–October 2006 were clearly the lowest. In addition to those in the 2000s, the corresponding values in 1960, 1972, 1978, 1986, and 1992 were considerably below the historic water level. From January to April, low water levels occurred in both the 1960s and 2000s. In 1963, the mean water level was 8.08 m (lowest in history) and the lowest water level was 7.16 m. The corresponding values in 2004 were 8.73 and 7.12 m (lowest in history). In addition during the 1960s and 2000s, in 1972, 1979, 1987 and 1999, the mean and the lowest water levels from January to April were all far below the average historic water level. These results showed that spring and autumn low water levels have generally occurred historically in Poyang Lake. For further exploration, Figure 3 shows daily hydrographs of water levels in the 1960s and 2000s at Xingzi gauging station. Among the maximum and minimum recorded water levels, the spring water levels in 1963 were the minimum levels over the longest duration. In autumn, a similar condition based on the lowest water level and longest duration was found in 2006. Therefore, 1963 and 2006 were chosen to represent the typical spring and autumn low water cases, respectively. Although these two cases are specifically demonstrated, they are representative of general and frequent spring and autumn low water levels in Poyang Lake.

2D hydrodynamic model

Poyang Lake is shallow and wide; therefore, vertical stratification in the water column can be neglected (Li & Yao 2015). Hence, a 2D depth-averaged hydrodynamic model of Poyang Lake was implemented using the MIKE 21 Flow Model (Li *et al.* 2014). MIKE 21 was developed by the Danish Hydraulic Institute (DHI) to simulate water

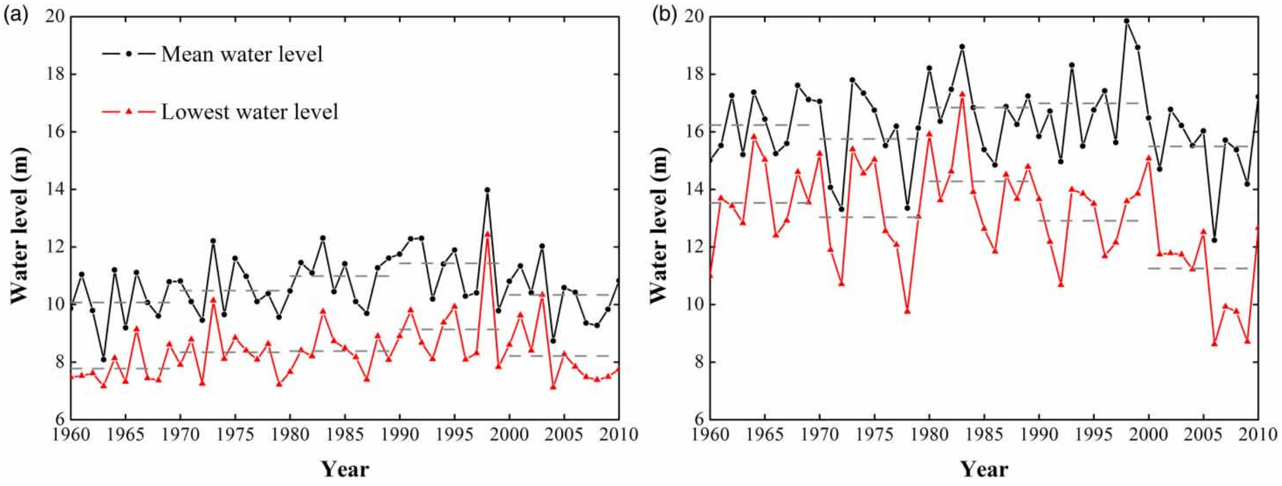

Figure 2 | Mean water level and lowest water level in (a) January–April and (b) July–October 1960–2010 at Xingzi gauging station.

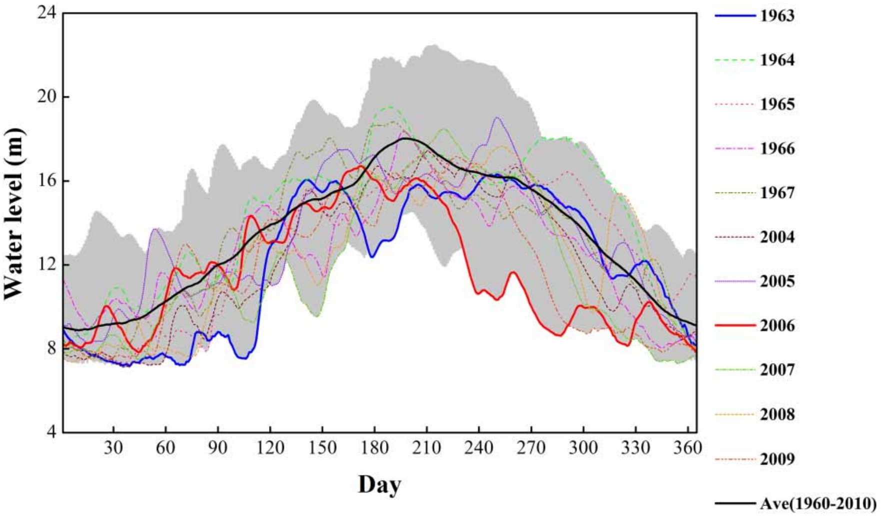

Figure 3 | Comparison of the daily hydrographs of water levels in the 1960s and 2000s at Xingzi gauging station. The grey area is the range of the maximum and minimum recorded water levels from 1960 to 2010.

environments in lakes, estuaries, bays, coastal areas and seas (DHI 2009a). It solves the vertically averaged and Reynolds-averaged equations, representing the conservation of mass and momentum based on a finite volume, unstructured mesh approach (DHI 2009a). The MIKE model has already been successfully applied to coastal oceans (Xing *et al.* 2012; Xu *et al.* 2016), gulfs (Babu *et al.* 2005; Patgaonkar *et al.* 2012), lagoons (Chubarenko & Tchepikova 2001) and lakes (Zeinoddini *et al.* 2009; Schoen *et al.* 2014).

The hydrodynamic model MIKE 21 used in the current study is an independent portion of a combined model that was used in a previous Poyang Lake-catchment investigation by Li *et al.* (2014). The grid has 11,251 nodes and 20,450 triangular elements, with approximate minimum and maximum element sides of 70 and 1,500 m, respectively, for differentiating lake topography at different scales (Li *et al.* 2014). The runoff from the ungauged area was calculated by simple linear extrapolation of the gauged runoff (Zhang *et al.* 2014). Daily catchment inflows from the five major rivers combined with runoff from the ungauged catchment area were specified as upstream boundary conditions (Zhang *et al.* 2014) at the outlets of the five sub-catchments (Figure 1(b)). Daily observed water levels at Hukou were used to define the downstream boundary condition. The time step was set to 5 s. The initial conditions were set as the lake water surface elevations obtained by interpolating the observed values at Hukou, Xingzi, Duchang, and Kangshan gauging stations (Figure 1(b)). Considering the seasonal drying and flooding of the Poyang Lake floodplains, 'Flooding and Drying facility' in MIKE 21 was included in the calculation. When the depths are small, the problem is reformulated, and when the depths are very small, the elements are removed from the calculation. The reformulation is performed by setting the momentum fluxes to zero and only considering the mass fluxes (DHI 2009b). In this study, a drying depth of 0.005 m, a flooding depth of 0.05 m, and a wetting depth of 0.1 m were selected. Water depths at element faces are compared to these depths to determine whether a grid cell should be inactivated, reactivated or only used to calculate the mass fluxes (Zhang & Werner 2015). Other details of the construction of the MIKE 21 model are described in Li *et al.* (2014).

Li *et al.* (2014) calibrated and validated the model against a variety of field observations from 2000 to 2008, including lake water level records and flow rate. The Nash-Sutcliffe efficiency coefficients (E_{ns}) of both the calibration and validation periods at all stations ranged from 0.80 to 0.98, suggesting a good agreement (Li *et al.* 2014). Other details of the calibration and validation processes were described by Li *et al.* (2014). The model was able to reproduce the major flow features of Poyang Lake and was adopted in various applications (Zhang *et al.* 2014; Li & Yao 2015; Li *et al.* 2015b; Zhang & Werner 2015).

In this study, further validation of water levels was performed using data from 1963, which was included in the simulation scenarios. Quantification of goodness-of-fit was assessed using statistical values, including the determination coefficient (R^2), Nash-Sutcliffe efficiency coefficient (E_{ns}) and root-mean-square error (*RMSE*). The R^2, E_{ns} and *RMSE* formulas were described by Li *et al.* (2015a). Table 1 shows the results of statistical parameters at the three gauging stations. The value of R^2 varies from 0.94 to 0.99, E_{ns} from 0.93 to 0.98, and *RMSE* from 0.31 to 0.43 m, indicating satisfactory model validation.

Simulation scenarios

Seven 1-year scenarios based on two typical low water level events were performed to explore the relative changes in water levels (Table 2) according to catchment and Yangtze River variations. Scenario S1 represented the average condition from 1953 to 2010. Scenarios S2 and S5 were simulations of real conditions in 1963 and 2006, respectively. Scenarios S1, S2 and S5 were all used as reference cases for comparative purposes. Scenarios S3 and S6 were based on the average Yangtze River discharge condition from 1953 to 2010 (the same as Scenario S1), with catchment inflows from 1963 and 2006, respectively, allowing for evaluation of the effects of the catchment. Scenarios S4 and S7 were based on the Yangtze River discharges in 1963 and 2006, respectively, with the same average catchment inflows from 1953 to 2010 (both the same as Scenario S1), allowing assessment of the effects of the Yangtze River.

Table 1 | Quantitative assessment of model validation using the lake water levels in 1963

Gauging station	R^2	E_{ns}	*RMSE* (m)
Xingzi	0.99	0.98	0.36
Duchang	0.98	0.97	0.43
Kangshan	0.94	0.93	0.31

Table 2 | Descriptions of simulation scenarios

Model scenario	Catchment inflow (upstream)	Yangtze River discharge (downstream)
S1	1953–2010 average	1953–2010 average
S2	1963	1963
S3	1963	1953–2010 average
S4	1953–2010 average	1963
S5	2006	2006
S6	2006	1953–2010 average
S7	1953–2010 average	2006

If the upstream or downstream boundary conditions are changed relative to the reference case, simulation results may change accordingly. We assume that differences in results are caused by upstream or downstream differences. In this study, the average condition from 1953 to 2010 was defined as the reference case (S1), and its upstream and downstream boundary conditions were replaced with the respective catchment inflows from 1963 (S3 and S4). Therefore, the water level changes caused by the local catchment were calculated by subtracting S1 from S3, and those caused by the Yangtze River were calculated by subtracting S1 from S4. The same method was used to quantify the contributions of the lake catchment and the Yangtze River in 2006.

Notably, the water level at Hukou, as the downstream condition, is affected by both catchment inflow and Yangtze River discharge. In the hypothetical scenarios (S3, S4, S6 and S7), water levels at Hukou were not obtained from the observed data. Li *et al.* (2015a) adopted catchment inflows from five upstream rivers and discharge at Hankou gauging station (representing the Yangtze River) to build a back-propagation neural network (BPNN) model to simulate the lake water levels. The results showed that the BPNN model was best suited for simulations at Hukou of all the gauging stations in Poyang Lake. The R^2 and E_{ns} values of the training and testing phases at Hukou were all over 0.97, and the *RMSE* errors were lower than 0.59 m (Li *et al.* 2015a). As an efficient tool, the BPNN was adopted to calculate water levels at Hukou in the hypothetical scenarios.

RESULTS

Characteristics of typical low water levels in 1963 and 2006

Figure 4 shows the water level of Poyang Lake at Xingzi station, the Yangtze River discharge at Hankou station

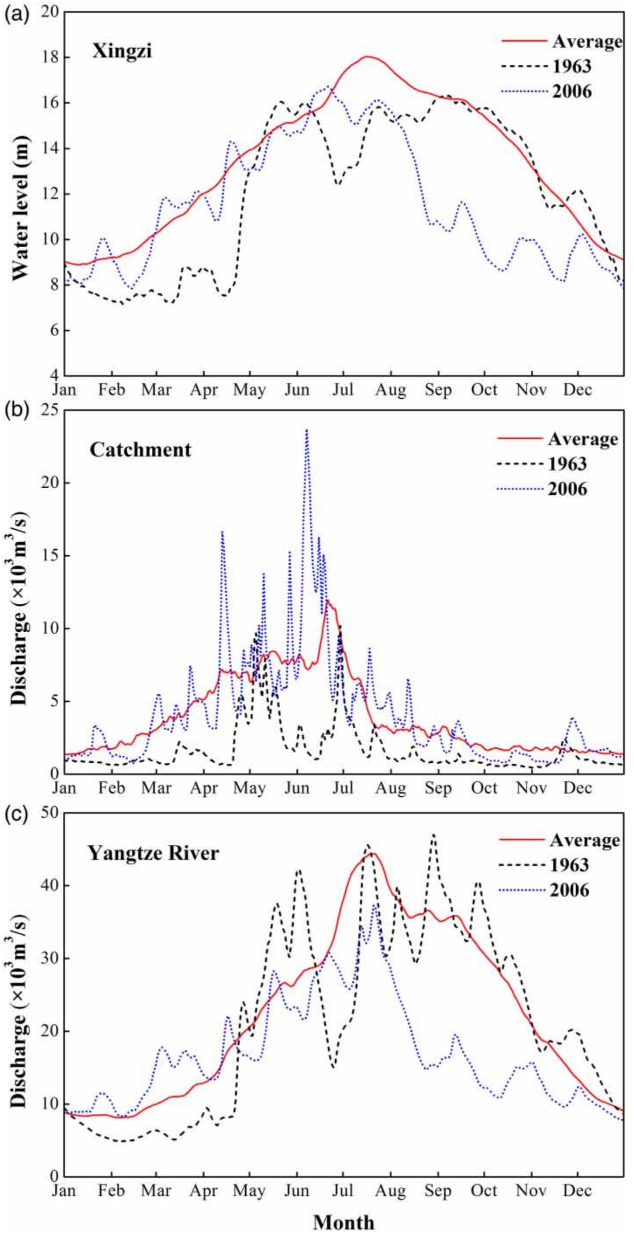

Figure 4 | Seasonal variations in the water level of Poyang Lake (Xingzi), the Yangtze River discharge (Hankou) and catchment inflows in 1963 and 2006, and the average condition: (a) from 1960 to 2010 at Xingzi; (b) from 1953 to 2010 for catchment inflows; and (c) from 1960 to 2010 at Hankou.

and the total lake catchment inflows from seven gauging stations in 1963 and 2006, as well as the historic average. In 1963, the water level declined significantly from January to April, with a maximum of 5.5 m and average of 2.6 m (Figure 4(a)). During the same period, the Yangtze River discharge and lake catchment inflows were both far below average conditions (Figure 4(b) and 4(c)). Specifically, the lake catchment inflows were below average throughout the year in 1963 (Figure 4(c)). In 2006, the water level of Poyang Lake dropped sharply during the recession period (July to November), with a maximum of 6.18 m and an average that was 4.02 m lower than the mean level. The Yangtze River discharge decreased by up to 50%, and its variation was remarkably comparable with the lake water level in the corresponding periods. However, there was no significant decrease in the lake catchment inflows relative to the average condition throughout the year. However, the inflows increased during the flood season.

It seemed that the Yangtze River might be responsible for the autumn low water level in 2006 and the dry conditions of both the lake catchment and Yangtze River may have caused the spring low water level in 1963, but the magnitude and domain of these effects were not clear.

Contributions of the lake catchment and Yangtze River to seasonal low water levels

Figures 5 and 6 show the comparisons of water levels among the seven designed scenarios. In spring 1963, the catchment inflows and Yangtze River discharge were both below the historic average (Figure 4(b) and 4(c)). Based on the simulation of 1963 (Scenario S2), the catchment inflows were replaced by the average condition (Scenario S4). Then, the original low water level from January to April increased obviously and approached the average condition (Scenario S1) (Figure 5). Particularly at Kangshan station, Scenarios S1 and S4 completely overlapped in this period (Figure 5(c)). The increase in catchment inflows greatly improved the spring low water level. Similarly, the average condition of the Yangtze River (Scenario S3) replaced the level in 1963 (Scenario S2), slightly increasing the spring water levels at Xingzi and Duchang stations (Figure 5(a) and 5(b)). However, the effect on water level diminished as distance upstream increased. At Kangshan station, there was almost no increase in water level (Figure 5(c)), suggesting that thewater level in the spring was mainly controlled by the catchment, but the Yangtze River also played a role downstream. Therefore, the spring low water level was largely attributable to the catchment and partly to the Yangtze River.

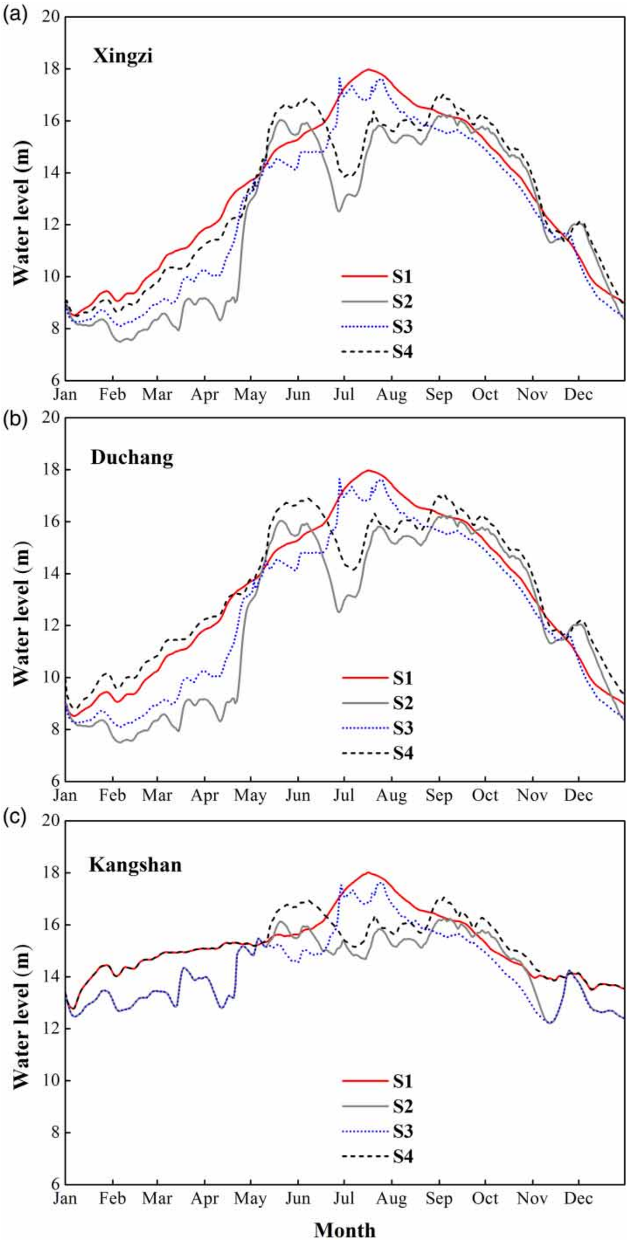

Figure 5 | Comparison of water levels in Scenarios S1, S2, S3, and S4 for (a) Xingzi, (b) Duchang, and (c) Kangshan.

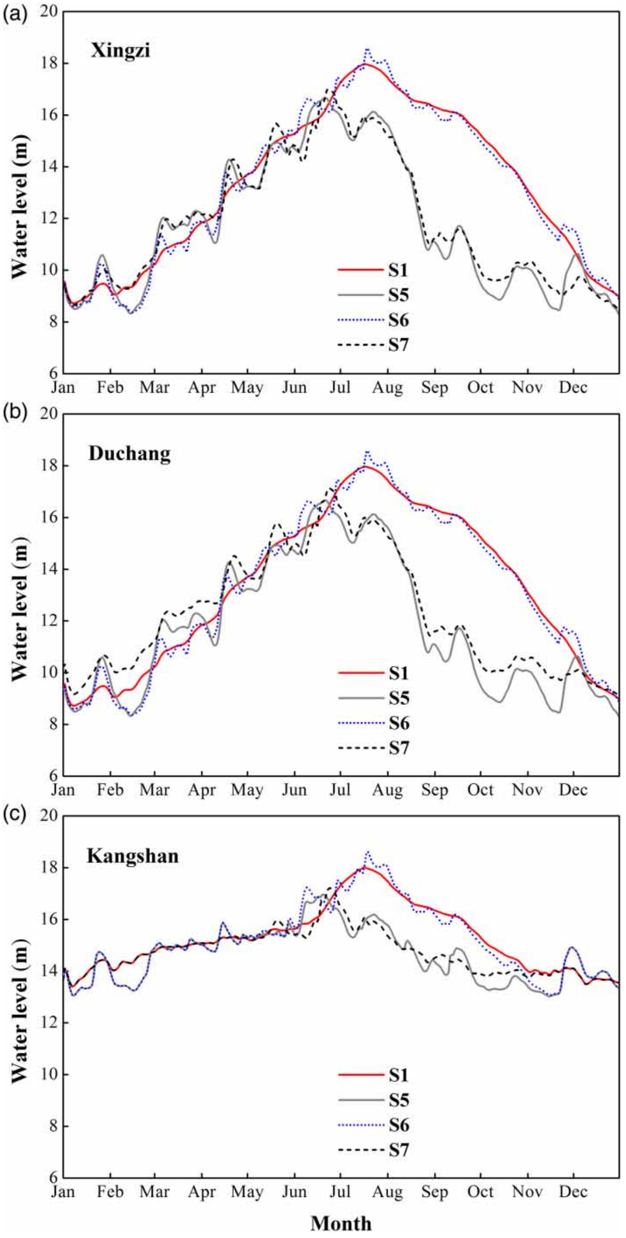

Figure 6 | Comparison of water levels in Scenarios S1, S5, S6, and S7 for (a) Xingzi, (b) Duchang, and (c) Kangshan.

Similarly, based on the 2006 simulation (Scenario S5), the catchment inflows were replaced with the average condition (Scenario S7). Then, the autumn low water level increased only between the end of August and mid-November (Figure 6). On the contrary, with the average condition of the Yangtze River, Scenario S6 reached the average level in autumn (Figure 6). This was consistent with the results shown in Figure 4(b) and 4(c), in which there was a significant decrease in discharge from the Yangtze River but not in catchment discharge in 2006. This again suggests that the autumn low water level in 2006 mainly resulted from the dry conditions in the Yangtze River.

Note that during the high water level period (May to September), the water levels followed a similar trend as they did under the same Yangtze River conditions (Scenarios S1 and S3/S2 and S4) except for differences in peak levels (Figure 5), which were attributed to the significant reduction in catchment inflows in 1963 compared to the average inflow. Similar patterns could be observed beginning in mid-June in Scenarios S1 and S6 (S5 and S7) (Figure 6), with insignificant variation in water levels due to the relatively small differences in catchment inflows between the 2006 and average values (Figure 4(c)). In Scenarios S2–S4, the critical point when the water level shifted from catchment-dominated to Yangtze River-controlled occurred in early May (Figure 5), while it was delayed until mid-June in Scenarios S5–S7 (Figure 6). This is likely due to the time difference between the peak flow of the Yangtze River and the local catchment. Both the Yangtze River and local catchment flows peaked in May 1963, which was more than one month earlier than the peaks in 2006 (Figure 4(b) and 4(c)).

To quantify the contributions of the catchment and Yangtze River to two typical low water level events in Poyang Lake, the periods of January to April 1963 and July to November 2006 were chosen to represent the spring and autumn low water level periods, respectively. Figure 7 shows the daily variations of mean water level decrease caused by the lake catchment and Yangtze River during the two periods (January–April 1963 and July–November 2006). The catchment and Yangtze River contributed maximums water level reductions of 2.6 and 1.1 m and average water level reductions of 1.3 and 0.2 m, respectively, from January to April 1963 (Figure 7(a)). Based on the difference between the water level in spring 1963 and the average condition (4.2 m maximum and 1.7 m on average, Figure 5, S1 minus S2), the percentages of the catchment and Yangtze River contributions to low water level were approximately 70% and 30%, respectively. The impacts of the catchment and Yangtze River varied spatially. For example, the Yangtze River minimally contributed to the low water level at Kangshan, but it reduced the water level at Xingzi by 0.5 m, which was nearly half of the contribution of the catchment at Xingzi (1.2 m, Figure 7(a)). Opposing patterns were found in autumn 2006 (Figure 7(b)). From July to October 2006, the impact of the catchment on water level was limited, fluctuating around zero, and the Yangtze River decreased the water level at Xingzi by a maximum of 5.4 m and average of 3.7 m on average (Figure 7(b)). Compared to the water level difference between autumn 2006 and the average condition (5.8 m maximum and 3.9 m on average, Figure 6, S1 minus S5), the percentage of the Yangtze River contribution to low water level was almost 95%. From September to October, the averaged water level decrease at Xingzi and Duchang due to the Yangtze River reaching up to 4 m. However, from the beginning of the recession period of the water level in early August, the impact of the Yangtze River on the water level at Kangshan

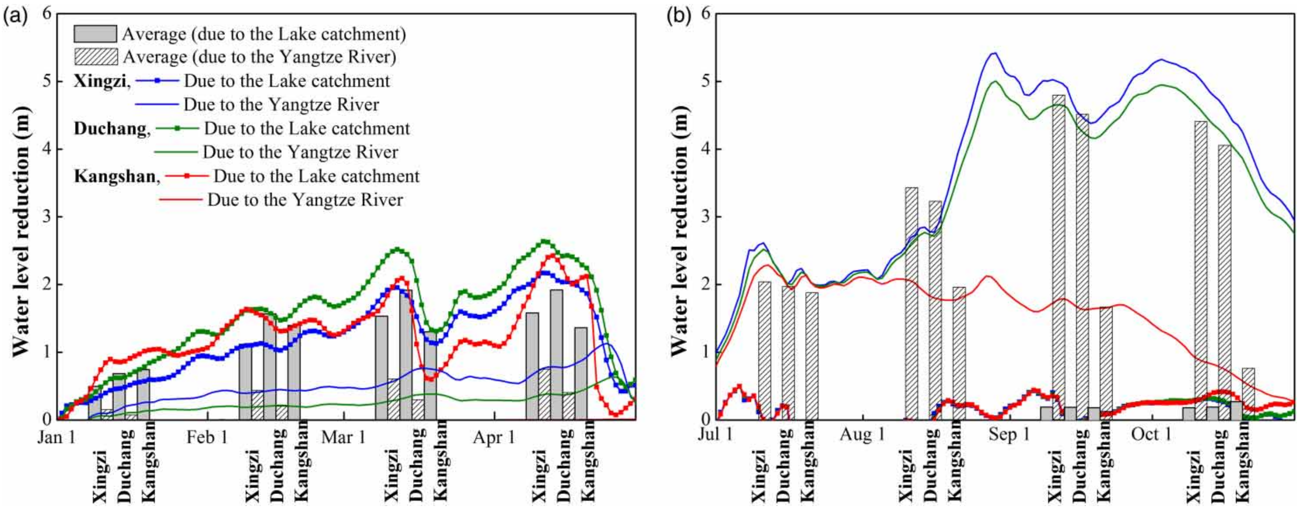

Figure 7 | The decreased water levels caused by the lake catchment (dotted lines) and Yangtze River (solid lines) in (a) spring 1963 and (b) autumn 2006. The decreased water levels caused by the lake catchment were calculated by subtracting S3 from S1 (S6) in 1963 (2006). The decreased water levels caused by the Yangtze River were calculated by subtracting S4 from S1 (S7) in 1963 (2006).

rapidly decreased from 2 to 0 m. Generally, the influences of the catchment and Yangtze River on the water levels were different in magnitude and spatial variability.

The areal influences of the lake catchment and Yangtze River on low water levels

The impacts of the catchment and Yangtze River on the water level varied spatially. Figure 8 shows the monthly mean domain of the whole lake influenced by the catchment and Yangtze River in spring 1963 and autumn 2006. There was an evident spatial gradient in the distribution of water level changes from January to April and from July to October. In spring 1963, the impact of the catchment was mainly concentrated in main channels rather than in the marshland (Figure 8, January–April). With the water level rise, the lake centre, southwest alluvial delta and east lakebay were also influenced. During the low-water period, the water level reduction caused by the catchment was generally lower than 2 m. In the PLNNR, only the channels were affected, and the decreased water levels were mainly lower than 0.5 m. In the NWNNR, the decreased water levels in the affected regions (middle and south) were mostly lower than 1 m. Regarding the impact of the Yangtze River, the whole lake was inundated during the high-water period in 2006 (Figure 8, July). The water levels of the whole lake exhibited different degrees of reduction. The water level of the northern channel connected to the Yangtze River decreased by 2–3 m. The level decreased by 1–2 m in the rest of the lake, including in the PLNNR and NWNNR (Figure 8, July). From the beginning of the water recession, there was an obvious spatial gradient in the distribution of water level changes (Figure 8, August–October). The impact of the Yangtze River became weaker from north to south. In August, the water levels in the PLNNR in the northern lake decreased by 2–3 m, while those in the southern NWNNR decreased by 1–2 m (Figure 8, August). In the most affected regions, spanning from the lake centre to the Hukou outlet, including the PLNNR and northern NWNNR, the water level decreased by 5–8 m, and the lakeshore area of this region was even exposed (Figure 8, September). Meanwhile, the water recession process accelerated due to the lower water level. In October, the Yangtze River had almost no influence on the southern and western NWNNR, and its impact shifted to the river channel.

DISCUSSION

As a major step forward, this work quantifies the relative contributions of the catchment and the Yangtze River to spring and autumn low water levels in two typical years using a hydrodynamic model. Previous studies have indicated that the spring water level is mainly influenced by the catchment and the effect of the Yangtze River is relatively weak (Shankman *et al.* 2006; Hu *et al.* 2007). In this study, both the catchment inflow and Yangtze River discharge decreased obviously in spring 1963 compared to the average value from 1953 to 2010. However, the Yangtze River could contribute up to 30% of the spring low water level, which is much higher than previous estimates, improving the knowledge of the causes of spring water levels. Similar studies have been performed to compare different types of low water levels. Zhang *et al.* (2015) compared the causes of low water levels in Poyang lake in the 1960s (1963–1967) and 2000s (2007–2009) at an inter-annual timescale, indicating that catchment inflows in the 1960s and 2000s decreased evidently; however, the Yangtze River discharge decreased sharply during low water levels in the 2000s and increased during low water levels in the 1960s. Due to the different timescales considered, their findings are not comparable with those of this study. Wu & Liu (2014) used MODIS data to demonstrate changes in water inundation areas in response to two typical low water level events in autumn–winter 2006 and spring–summer 2011, indicating that the low water level in 2006 was mainly induced by the Yangtze river and the level in 2011 resulted from the complicated interactions of the catchment and Yangtze river. Compared with previous qualitative studies, this study was performed to quantify the relative contributions of the catchment and Yangtze River at the seasonal timescale.

It was found that the variations in patterns of high water levels were caused by the Yangtze River, but peak values depended on the catchment inflows. The critical time of water level change from a catchment-dominated to river-controlled system was influenced by the starting

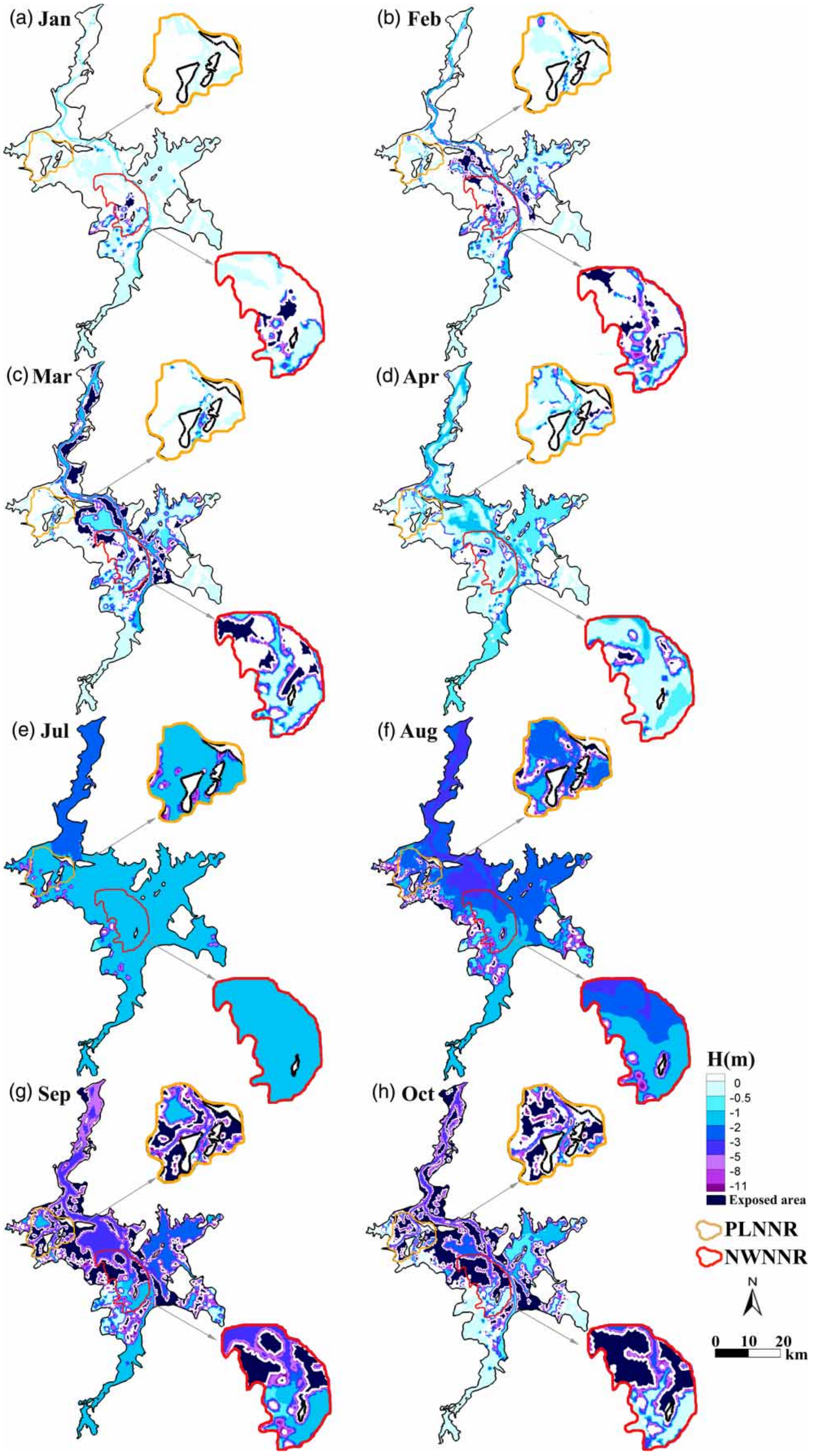

Figure 8 | Distributions of monthly mean water level changes for Poyang Lake, the PLNNR and the NWNNR caused by (a)–(d) the lake catchment from January to April, respectively, 1963 (S3 minus S1) and (e)–(h) the Yangtze River from July to October, respectively, 2006 (S7 minus S1) compared with the average condition.

times and intervals of peak flow from the Yangtze River and the local catchment. The flood season of the catchment is April–June, and that of the Yangtze River is July–September. In most cases, the Yangtze River effect became relatively strong only when the catchment effect weakened (Hu *et al.* 2007). If the peak flow is particularly rapid or delayed, it can lead to changes in river–lake interactions, replacing the main factor controlling water level. Ultimately, the occurrence time and magnitude of peak water level will change accordingly. Shankman & Liang (2003) noted that high catchment inflows later than normal during the summer, and therefore concurrent with high Yangtze River discharge, will increase the probability of floods. Therefore, further research should be considered to explore how the catchment and Yangtze River act at high water levels.

Compared with the analysis based on gauging stations of the lake, it better captures the spatial variations of the lake from a hydrodynamic perspective. We found that the temporal variations in water level changes caused by the lake catchment in spring and by the Yangtze River in autumn correspond to the water level rise and recession processes, respectively, with an evident spatial gradient. In other words, the domain controlled by the lake catchment was mainly concentrated in channels initially. Then, it spread due to rising water level. Conversely, the domain controlled by the Yangtze River gradually shrank from the whole lake to the channels and the northern portion of the lake during the recession period. Therefore, the PLNNR and northern NWNNR were mainly controlled by the Yangtze River, and the southern NWNNR was mainly controlled by the catchment. This finding has significant implications for different management strategies in the two nature reserves. Furthermore, there were clear differences in the spatial distribution patterns of water level produced by the lake catchment and Yangtze River, of which the latter appeared to have stronger spatial variation. Lai *et al.* (2014a) found that catchment inflow variations led to relatively uniform changes in water level in the whole lake, unlike the spatially heterogeneous distribution of water level changes produced by the Yangtze River flow variations. Their result is in agreement with the findings of the current study. Although controls of both the lake catchment and Yangtze River were restricted in the channel, their spatial distributions vary significantly (Figure 8, February and October). Except for in channels and permanently inundated regions, the domain of catchment control was the southwest alluvial delta (Figure 8, February), and that of Yangtze River control was mainly in the north (Figure 8, October). Zhang & Werner (2015) explored hysteretic effects in Poyang Lake, determining that both the floodplain and permanently inundated region contribute to Poyang Lake's volume–stage hysteretic effects. Furthermore, variation in catchment inflow was the major factor affecting hysteresis, rather than the influence of the Yangtze River. Hence, the complex topography and unsymmetrical patterns of the lake catchment and Yangtze River can explain the variable spatial distribution of their effects on channels and surrounding areas in this study.

The topography of Poyang Lake has undergone some changes over the past 50 years. The hydrodynamic model used in this study is based on a digital elevation model (DEM) from 1998 (Li *et al.* 2014), which may produce deviations in simulations of 1963 and 2006. From 1960 to 1998, a lake area of over 850 km^2 was reclaimed (Ye *et al.* 2012), resulting in the lake volume decreasing by approximately 15% (Min 2000). After 1998, reclaimed land was restored as lake. Since 2000, due to widespread sand mining, the bed channel elevation of the Hukou outflow channel has decreased significantly (de Leeuw *et al.* 2010; Lai *et al.* 2014b). Lai *et al.* (2014b) examined the impact of sand mining on the low water level and showed that the discharge ability of Poyang Lake into the Yangtze River at low water levels in the dry season has increased 1.5–2 times. As a result, the average water level at Xingzi decreased by 0.66 m in the dry season from 2008 to 2012 compared to that from 1955 to 2000 (Lai *et al.* 2014b). According to Lai *et al.* (2014b), we calculated that the average water level at Xingzi decreased by 0.18 m on average and by a maximum of 0.53 m from July to October 2006. These values accounted for approximately 4.5% and 8.6% of the average and maximum decreased water levels, respectively, far less than the impact of the Yangtze River. However, this influence will increase as the water level decreases from October to March. Furthermore, sand mining occurs mainly in northern channels and has less impact on the nature reserves. On the other hand, the model used in this study excluded the main stream of the Yangtze River. The variations in the river and catchment were reflected by the downstream boundary condition (Hukou) in the BPNN model. As a limitation of the model, the downstream boundary condition was not based on another hydrodynamic model. However, the spatial response of the lake water level to the local catchment and Yangtze River was reflected and is credible.

CONCLUSIONS

This study combined extensive hydrological data and a physically based hydrodynamic model to quantify the relative influences of the local catchment and Yangtze River in spring 1963 and autumn 2006 on low water levels in Poyang Lake. A quantitative spatial distribution of decreased water levels was presented.

Water levels during high and recession periods were mainly controlled by the Yangtze River discharge, while water levels during the rising period were mainly dominated by catchment inflow. The impacts of the catchment and Yangtze River were approximately 70% and 30%, respectively, on the low water level in spring 1963. Additionally, the Yangtze River contributed to almost 95% of the lower water level in autumn 2006. In spring 1963, the domain controlled by the lake catchment was mainly concentrated in channels and southern alluvial deltas. In autumn 2006, the control of the Yangtze River extended to the entire lake, with the maximum influence occurring in the north outlet waterway. The PLNNR and northern NWNNR were mainly controlled by the Yangtze River, and the southern NWNNR was mainly controlled by the catchment. Compared with the relatively uniform spatial distribution of the catchment's impact on water levels, the impact of the Yangtze River appeared to result in stronger spatial variation.

Overall, this study highlights the effects of the catchment and Yangtze River on seasonal variations in lake water levels and allows us to understand the potential impacts of climate variability and anthropogenic activities in the Yangtze River and Poyang Lake catchment. Moreover, it suggests that water resource management in such a complex river-lake system should be performed from a system perspective. Finally, this study provides a reference that can be used in similar river-lake systems to quantify the hydrologic drivers and examine river-lake interactions.

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REFERENCES

Anderson, E. J. & Schwab, D. J. 2011 Relationships between wind-driven and hydraulic flow in Lake St. Clair and the St. Clair River Delta. *J. Great Lakes Res.* **37**, 147–158.

Babu, M. T., Vethamony, P. & Desa, E. 2005 Modelling tide-driven currents and residual eddies in the Gulf of Kachchh and their seasonal variability. *Ecol. Model.* **184**, 299–312.

Bonnet, M. P., Barroux, G., Martinez, J. M., Seyler, F., Moreira-Turcq, P., Cochonneau, G., Melack, J. M., Boaventura, G., Maurice-Bourgoin, L., León, J. G., Roux, E., Calmant, S., Kosuth, P., Guyot, J. L. & Seyler, P. 2008 Floodplain hydrology in an Amazon floodplain lake (Lago Grande de Curuaí). *J. Hydrol.* **349**, 18–30.

Chubarenko, I. & Tchepikova, I. 2001 Modelling of man-made contribution to salinity increase into the Vistula Lagoon (Baltic Sea). *Ecol. Model.* **138**, 87–100.

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

DHI 2009a *Mike 21 Flow Model FM. Hydrodynamic Module, User Guide*. Danish Hydraulic Institute of Water and Environment, Hørsholm, Denmark, pp. 1–99.

DHI 2009b *Mike 21 and Mike 3 Flow Model, FM Hydrodynamic and Transport Module Scientific Documentation*. Danish Hydraulic Institute of Water and Environment, Hørsholm, Denmark, pp. 1–56.

Dutta, D., Alam, J., Umeda, K., Hayashi, M. & Hironaka, S. 2007 A two-dimensional hydrodynamic model for flood inundation simulation: a case study in the lower Mekong river basin. *Hydrol. Process.* **21**, 1223–1237.

Engle, D. L. & Melack, J. M. 1993 Consequences of riverine flooding for seston and the periphyton of floating meadows in an Amazon floodplain lake. *Limnol. Oceanogr.* **38**, 1500–1520.

Feng, L., Hu, C., Chen, X., Cai, X., Tian, L. & Gan, W. 2012a Assessment of inundation changes of Poyang Lake using MODIS observations between 2000 and 2010. *Remote Sens. Environ.* **121**, 80–92.

Feng, L., Hu, C. & Chen, X. 2012b Satellites capture the drought severity around China's largest freshwater lake. *IEEE J.-STARS.* **5**, 1266–1271.

Gao, J. H., Jia, J., Kettner, A. J., Xing, F., Wang, Y. P., Xu, X. N., Yang, Y., Zou, X. Q., Gao, S., Qi, S. & Liao, F. 2014 Changes in water and sediment exchange between the Changjiang River and Poyang Lake under natural and anthropogenic conditions, China. *Sci. Total Environ.* **481**, 542–553.

Gemmer, M., Jiang, T., Su, B. & Kundzewicz, Z. W. 2008 Seasonal precipitation changes in the wet season and their influence on flood/drought hazards in the Yangtze River Basin, China. *Quatern. Int.* **186**, 12–21.

Guo, H., Hu, Q. & Zhang, Q. 2011 Changes in hydrological interactions of the Yangtze River and the Poyang Lake in China during 1957–2008. *Acta Geographica Sinica* **66**, 609–618 (in Chinese).

Guo, H., Hu, Q., Zhang, Q. & Feng, S. 2012 Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008. *J. Hydrol.* **416–417**, 19–27.

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

Hui, F., Xu, B., Huang, H., Yu, Q. & Gong, P. 2008 Modelling spatial-temporal change of Poyang Lake using multitemporal Landsat imagery. *Int. J. Remote Sens.* **29**, 5767–5784.

Lai, X., Jiang, J., Liang, Q. & Huang, Q. 2013 Large-scale hydrodynamic modeling of the middle Yangtze River Basin with complex river-lake interactions. *J. Hydrol.* **492**, 228–243.

Lai, X., Huang, Q., Zhang, Y. & Jiang, J. 2014a Impact of lake inflow and the Yangtze River flow alterations on water levels in Poyang Lake, China. *Lake Reserv. Manage.* **30**, 321–330.

Lai, X., Shankman, D., Huber, C., Yesou, H., Huang, Q. & Jiang, J. 2014b Sand mining and increasing Poyang Lake's discharge ability: a reassessment of causes for lake decline in China. *J. Hydrol.* **519**, 1698–1706.

Lesack, L. F. W. & Melack, J. M. 1995 Flooding hydrology and mixture dynamics of lake water derived from multiple sources in an Amazon floodplain lake. *Water Resour. Res.* **31**, 329–345.

Li, Y. & Yao, J. 2015 Estimation of transport trajectory and residence time in large river-lake systems: application to Poyang Lake (China) using a combined model approach. *Water-Sui* **7**, 5203–5223.

Li, Y., Zhang, Q., Yao, J., Werner, A. D. & Li, X. 2014 Hydrodynamic and hydrological modeling of the Poyang Lake catchment system in China. *J. Hydrol. Eng.* **19**, 607–616.

Li, Y. L., Zhang, Q., Werner, A. D. & Yao, J. 2015a Investigating a complex lake-catchment-river system using artificial neural networks: Poyang Lake (China). *Hydrol. Res.* **46**, 912–928.

Li, Y., Zhang, Q. & Yao, J. 2015b Investigation of residence and travel times in a large floodplain lake with complex lake-river interactions: Poyang Lake (China). *Water-Sui* **7**, 1991–2012.

Liu, Y., Wu, G. & Zhao, X. 2013 Recent declines in China's largest freshwater lake: trend or regime shift? *Environ. Res. Lett.* **8**, 014010.

Liu, X., Qian, K. & Chen, Y. 2015 Effects of water level fluctuations on phytoplankton in a Changjiang River floodplain lake (Poyang Lake): Implications for dam operations. *J. Great Lakes Res.* **41**, 770–779.

Min, Q. 2000 Study on the relationship between shape, water regime and innings of Poyang Lake. *Adv Water Sci.* **11**, 76–81 (in Chinese).

Nakayama, T. & Shankman, D. 2013 Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. *Global Planet. Change* **100**, 38–50.

Patgaonkar, R. S., Vethamony, P., Lokesh, K. S. & Babu, M. T. 2012 Residence time of pollutants discharged in the Gulf of Kachchh, northwestern Arabian Sea. *Mar. Pollut. Bull.* **64**, 1659–1666.

Peters, D. L. & Buttle, J. M. 2010 The effects of flow regulation and climatic variability on obstructed drainage and reverse flow contribution in a Northern river-lake-Delta complex, Mackenzie basin headwaters. *River Res. Appl.* **26**, 1065–1089.

Pickrill, R. A. & Irwin, J. 1982 Predominant headwater inflow and its control of lake-river interactions in Lake Wakatipu. *New Zealand Journal of Marine & Freshwater Research* **16**, 201–213.

Schoen, J. H., Stretch, D. D. & Tirok, K. 2014 Wind-driven circulation patterns in a shallow estuarine lake: St Lucia, South Africa. *Estuarine, Coastal and Shelf Science* **146**, 49–59.

Shankman, D. & Liang, Q. 2003 Landscape changes and increasing flood frequency in China's Poyang Lake region. *The Professional Geographer* **55**, 434–445.

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

Tikkanen, M. T. & Tikkanen, M. 2002 Long-term changes in lake and river systems in Finland. *Fennia – Int. J. Geography* **180**, 31–42.

Wu, G. & Liu, Y. 2014 Satellite-based detection of water surface variation in China's largest freshwater lake in response to hydro-climatic drought. *Int. J. Remote Sens.* **35**, 4544–4558.

Xing, F., Wang, Y. P. & Wang, H. V. 2012 Tidal hydrodynamics and fine-grained sediment transport on the radial sand ridge system in the southern Yellow Sea. *Mar. Geol.* **291–294**, 192–210.

Xu, F., Tao, J., Zhou, Z., Coco, G. & Zhang, C. 2016 Mechanisms underlying the regional morphological differences between the northern and southern radial sand ridges along the Jiangsu Coast, China. *Mar. Geol.* **371**, 1–17.

Ye, X., Zhang, Q., Bai, L. & Hu, Q. 2011 A modeling study of catchment discharge to Poyang Lake under future climate in China. *Quatern. Int.* **244**, 221–229.

Ye, X. C., Li, X. H. & Zhang, Q. 2012 Temporal variation of backflow frequency from the Yangtze River to Poyang Lake and its influencing factors. *J. Southwest Univ. National (Nat. Sci. Ed.)* **34**, 69–75 (in Chinese).

Zeinoddini, M., Tofighi, M. A. & Vafaee, F. 2009 Evaluation of dike-type causeway impacts on the flow and salinity regimes in Urmia Lake, Iran. *J. Great Lakes Res.* **35**, 13–22.

Zhang, Q. & Werner, A. D. 2015 Hysteretic relationships in inundation dynamics for a large lake-floodplain system. *J. Hydrol.* **527**, 160–171.

Zhang, Q., Ye, X., Werner, A. D., Li, Y., Yao, J., Li, X. & Xu, C. 2014 An investigation of enhanced recessions in Poyang Lake: comparison of Yangtze River and local catchment impacts. *J. Hydrol.* **517**, 425–434.

Zhang, Z., Chen, X., Xu, C., Hong, Y., Hardy, J. & Sun, Z. 2015 Examining the influence of river-lake interaction on the drought and water resources in the Poyang Lake basin. *J. Hydrol.* **522**, 510–521.

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