# Inter-annual variations of Poyang Lake area during dry seasons: characteristics and implications

Mengfan Li, Qi Zhang, Yunliang Li, Jing Yao and Zhiqiang Tan

## ABSTRACT

Variations in a lake area constitute an important indicator of the modifications of the lake hydrology. This paper explores the inter-annual variations of the Poyang Lake area during the dry seasons occurring within the 1961 to 2010 period and further quantifies the severity of dryness recently endured during the 2000s. A physically based hydrodynamic model of Poyang Lake established the relation between the lake area and lake level. The lake area was calculated using the observed lake water level. Results indicated the average lake area in the dry seasons was 1,015 km$^2$. There was a considerable inter-annual variation of the minimum lake area that varied from 702.8 km$^2$ to 1,259.7 km$^2$. Poyang Lake experienced the most severe dryness in the 2000s, resulting in an average lake area during 2001 to 2010 of 124 km$^2$ less than that of the preceding period. During the dry seasons, the catchment of the river discharge is likely the primary cause of the changes in lake area. This study evaluated the inter-annual variations of the Poyang Lake over a period of 50 years. Our results may provide support for an integrated management of the lake-catchment system, securing the water supply.

**Key words** | dry seasons, hydrodynamic model, lake area, lake area–lake level relation, Poyang Lake

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## INTRODUCTION

Lakes are valuable economic resources (fresh water resources, cultivation, fishing) for the human population and play an important role in regional ecological and environmental issues (Beeton 2002; Lehner & Döll 2004). Lake areas are sensitive to climate change and human activity, and therefore provide an excellent indicator of climate/anthropogenic forcing and regional responses (Ma *et al.* 2010). Lake areas provide essential information on the characterization of hydrological dynamics (Hervé *et al.* 2011). Monitoring their inter-annual variation is critical to the understanding of the change in water balance (Huang *et al.* 2011). Consistent variations in lake area were shown to cause serious environmental problems, and to greatly affect the available freshwater resources. This leads to an adverse evolution of regional ecological environment and wetlands (Cui 2004; Fang *et al.* 2006; Moiwo *et al.* 2010; Du *et al.* 2011; Hu *et al.* 2015).

China has a large number of lakes having a rich cultural, ecological, and economic history. However, over the last half century, nearly 13% of Chinese lakes have undergone a remarkable reduction in lake area (Ma *et al.* 2010). The Poyang Lake, located in the middle reach of the Yangtze River, is the largest freshwater lake of China and is recognized internationally as an important wetland. The lake is a valuable resource of freshwater and provides the largest winter habitat for more than 90% of Siberian migratory birds (Kanai *et al.* 2002; Xia *et al.* 2010; You *et al.* 2014; Han *et al.* 2015). During the 1990s, severe flooding occurred (1992, 1995, 1997, and 1998), with the 1998 flood being the most severe ever recorded (Jiang & Shi 2003; Guo *et al.* 2012; Shankman *et al.* 2012). Winter droughts also occurred in 2003–04, 2006–07, and 2008–09 (Min & Zhan 2012; Ye

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*et al.* 2014). Furthermore, the Poyang Lake area and water level have been declining significantly since 2000 (Feng *et al.* 2012; Liu *et al.* 2013; Zhang *et al.* 2014). Rapid variations of the lake area during the dry seasons have caused serious problems in water supply for the local population. The reduction of the lake area also disturbed the wetland vegetation and, consequently, the habitat of migrating birds (Liu *et al.* 2006; de Leeuw *et al.* 2009; Raulings *et al.* 2010). To alleviate the environmental pressure caused by the rapid lake shrinkage, the local government proposed the Poyang Lake Hydraulic Project (PLHP) in March 2008. The PLHP would contain a 2.8 km-wide dam across the northern lake channel. This hydraulic dam would operate during the dry seasons to control the water flow from the Poyang Lake to the Yangtze River, and maintain a reasonable lake water level (Wang *et al.* 2015). However, the proposed PLHP stirred considerable debate related to the impact on the ecology and environment (Li 2009; Ge *et al.* 2010; Wang *et al.* 2015). Thus, improving our knowledge of the variations in the area of Poyang Lake is critical to rationally managing the lake–river system.

Previous studies, using bathymetric data, revealed the annual average area of Poyang Lake was 5,160 km$^2$ in 1954 and decreased to ~3,860 km$^2$ in 1992 (Min 2000). Several recent investigations have sought to define the variations in Poyang Lake's flooding area using remote sensing imagery. However, the data were limited to the 2000s period. For example, Feng *et al.* (2012, 2013) documented the inter-annual and intra-annual characteristics of Poyang Lake flooding for the period extending from 2000 to 2010, based on 620 images of the MODIS satellite 250 m-resolution data. The mean annual and minimum-flooded areas showed statistically significant declining trends. Wu & Liu (2014, 2015) investigated the spatial and temporal distribution of the lake flood variations related to drought conditions using 466 cloud-free MODIS images generated from 2000 to 2011. Liu *et al.* (2013) noted the recent shrinkage of Poyang Lake experienced a regime shift occurring in 2006, by examining 59 satellite images from 1973 to 2010. These previous efforts have failed to solve the remaining problems regarding the significance of the lake area shrinkage in the 2000s relative to earlier and longer time periods. It is essential to assess quantitatively the severity of the dry periods affecting Poyang Lake, so that a complete knowledge of the degree of variations in lake area since the last decade can be obtained. We will establish a comparison relative to the early periods when the impact of human activity was small.

There exist a number of approaches to calculate lake areas. Du *et al.* (2011) collected available maps and satellite imagery and used geographic information system (GIS) software to analyze the lake evolution in the middle reaches of the Yangtze River for the past century. More recently, satellite remote sensing is being widely used as an efficient tool to identify water surface area. Sima & Tajrishy (2013) applied satellite imagery to obtain the volume, area, and level data from the Urmia Lake (Iran) to estimate the water balance. Plug *et al.* (2008) examined six Landsat images collected from 1978 to 2001 to investigate the coverage changes of the Tundra Lake located in northwestern Canada. Ogilvie *et al.* (2015) employed the MODIS optical data to study the timing, duration, and extent of flooding across the plains of the Inner Niger Delta situated in Africa. Remote sensing is efficient in determining the water area. However, it is in certain cases limited by low time frequency (after screening for cloud-free images) and data unavailability for the preceding decades.

Physically based mathematical modeling will perform simulations and is an alternative method to establish the relations between lake area and lake level. For example, Wolfs & Willems (2014) studied the hysteretic behavior of the discharge–stage relation of the Dender River in Belgium by performing computer simulations using the MIKE 11 software. Patro *et al.* (2009) used a hydrodynamic model to simulate the flooded area of the Mahanadi River basin delta region in India. Chormański *et al.* (2009) confirmed the usefulness of the hydrodynamic model to simulate the inundated area and water depth of the Biebrze riparian wetland (Poland). Li *et al.* (2014) used the MIKE 21 software (DHI 2007) to reproduce the variations in lake level and corresponding lake area for the Poyang Lake. Zhang & Werner (2015) further looked at the hysteretic relation of the Poyang Lake volume, area, and level using a similar model to that of Li *et al.* (2014). Other similar investigations include the application of the Environmental Fluid Dynamics Code (Wang *et al.* 2015) and the Delft3D-FLOW (Zhang *et al.* 2015), also the Coupled Hydrodynamic Analysis Model (Lai *et al.* 2013) to study the hydrodynamics of the Poyang Lake–River system. The advantages of hydrodynamic models to capture the spatial and temporal variations in lake level and lake area at high resolution enabled us to adopt the existing Poyang Lake hydrodynamic model (Li *et al.* 2014) to establish the relation between lake area and lake level for a defined period. The relation was then applied to calculate the lake area for the entire period of study, based on the observed lake level.

This study will analyze the long-term variations of the Poyang Lake area during the dry seasons through the lake area–lake level relation. The main objectives are to: (1) establish the time evolution of the Poyang Lake area during the dry seasons for the period starting in 1961 and ending in 2010; (2) analyze the inter-annual variations of the lake area and quantify the severity of the lake area shrinkage during the last decade; and (3) discuss the possible mechanism causing the lake to dry and the potential impacts on the wetland ecosystem.

## MATERIALS AND METHODS

### Study area

Poyang Lake (28°24′–29°46′N latitude and 115°49′–116°46′E longitude) is located in the middle reach of the Yangtze River (Figure 1(a)). The lake flows into the Yangtze River by a natural narrow channel located to the north (Figure 1(b)). The lake receives surface runoff from the local catchment composed of five major rivers: Xiushui, Ganjiang, Fuhe, Xinjiang and Raohe. The lake bottom elevation decreases from south to north (Figure 1(a)) with a ~6.5 m variation calculated using the lake bathymetric data (Li *et al.* 2014). The lake has a catchment area of $16.22 \times 10^4$ km$^2$ (Shankman *et al.* 2006) and is affected by a subtropical monsoon climate characterized by annual precipitations of 1,654 mm and an annual potential evapotranspiration of 1,049 mm (Zhang *et al.* 2014). The annual cycle of precipitation generates 59.1% of the annual discharge from March to June, with only 13.7% from October to January (Ye *et al.* 2013). The ~8.8 m average variation of the maximum (June) and minimum (December and January) lake water levels produces significant modifications of the lake area (Zhang & Werner 2015). During the wet season, the lake level rises quickly and the lake area expands rapidly. During the dry season, the lake shrinks to a small area, exposing a large floodplain. The lake floodplain accommodates a wide range of migrating waterfowl during winter (Tang *et al.* 2016) and is ecologically important.

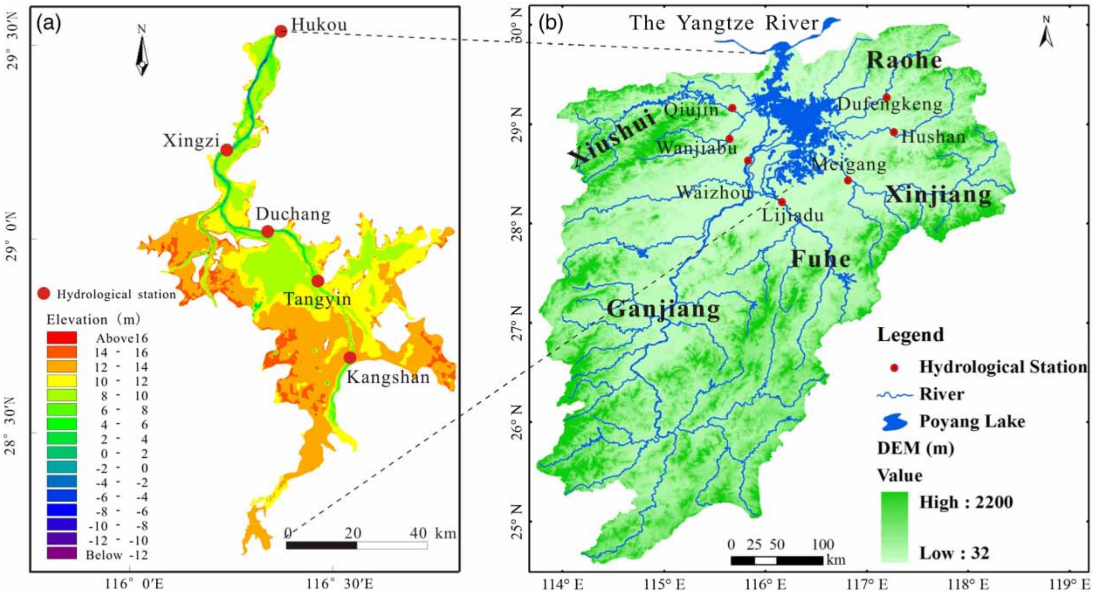

**Figure 1** | Poyang Lake catchment and river networks: (a) Poyang Lake bathymetry (*Source:* Li *et al.* 2014); (b) major rivers in the catchment. Water level observation points within the lake and river discharge gauging stations in the catchment are also marked.

## Data collection

The bathymetry of Poyang Lake was determined by the surveyed data obtained in 1998 with a resolution <100 m (Li *et al.* 2014). The total area of the lake submitted to computer simulation is 3,124 km$^2$. The hydrodynamic model was established using the following data. Where available, we used the observed daily stream flows at seven gauging stations installed in the Poyang Lake catchment (Figure 1(b)). The total drainage area of the gauging stations was 137,143 km$^2$, leaving an area of 25,082 km$^2$ not submitted to gauging. The runoff from the ungauged catchment area (25,082 km$^2$) was calculated by simple linear extrapolation of the gauged runoff to correct for water balance in the hydrodynamic simulation model. The determined runoff was added to the gauged inflows of the local catchment (see Zhang *et al.* (2014) for more details). The corrected daily catchment inflows from the five major rivers were set as the upper boundary condition of the simulation model. The daily water levels collected from the Hukou hydrological station were accepted as the lower boundary condition in connection with the Yangtze River. The daily precipitation and evaporation data of the lake area were incorporated in the model to simulate the direct rainfall input and evaporation from the water surface. The observed water levels determined at the Xingzi, Duchang, Tangyin, and Kangshan gauging stations (Figure 1(a)) and the outflow discharge at the Hukou gauging station (Figure 1(a)) were used to calibrate and validate the hydrodynamic model (Li *et al.* 2014). Moreover, the Poyang Lake water surface areas extracted from the MODIS satellite surface reflectance data (14 MODIS images taken in 2004) were applied to better constrain the modeling results (Li *et al.* 2014). Details of the model, including the calibration and validation, are presented in the section below.

Hankou station (114 °16′ E longitude, 30 °37′ N latitude) located 284 km upstream of Poyang Lake in the middle reach of the Yangtze River was chosen as the representative gauging station of the river discharge (Li *et al.* 2015). The Hankou station daily discharge monitored the effect of the Yangtze River on the lake area (see the section ‘Impacts of the local catchment and the Yangtze River’).

## Simulation model

The current hydrodynamic model was created by Li *et al.* (2014) for Poyang Lake, using the physically based mathematical model MIKE 21 (DHI 2007). A triangular mesh of variable cell size discretized the lake topography, resulting in a total of 20,450 triangular elements (Li *et al.* 2014). The elements’ size was adjusted by trial and error during the model build-up to minimize the numerical instabilities. The model was calibrated against the observed lake level, Hukou station flow rate, and lake water area for the period lasting from 2000 to 2005 (Li *et al.* 2014). Calibrated parameters include the hydraulic roughness values (Manning number; $M$) for different land types (i.e., 30 m$^{1/3}$/s, 35 m$^{1/3}$/s, and 50 m$^{1/3}$/s for the vegetal cover, mud, and permanent water area, respectively), and a Smagorinsky factor ($C_s = 0.28$) characterizing the eddy viscosity (Li *et al.* 2014). The Nash–Sutcliffe efficiency coefficient ($E_{\mathrm{ns}}$), coefficient of determination ($R^2$), and relative error ($R_e$) evaluated the model performance. The $E_{\mathrm{ns}}$ factor determining the calibration periods of daily water levels at the lake gauging stations varied from 0.88 to 0.97, the $R^2$ values ranged from 0.96 to 0.99, and the absolute values of $R_e$ were <3% (Li *et al.* 2014). We set the flow rates $E_{\mathrm{ns}}$, $R^2$, and $R_e$ values for the calibration periods at Hukou station at 0.80, 0.82. and −12%, respectively (Li *et al.* 2014). The results of the model were compared to the remote sensing data obtained for the wet and dry seasons having $R_e$ values of 3.3% and 16.8%, respectively (Li *et al.* 2014). More details of the model are given by Li *et al.* (2014), Zhang *et al.* (2014), and Zhang & Werner (2015).

The calibrated model was simulated to the year 2010 to capture the lake area during the extremely low lake level prevailing at the time. The three lowest lake levels at the Duchang station recorded from 1961 to 2010 were 7.99 m (2009), 8.05 m (2008), and 8.16 m (2010). The $E_{\mathrm{ns}}$ and $R^2$ values for the 2006 to 2010 validation period from all gauging stations concerning the daily water lake levels were all above 0.95, and the absolute values of $R_e$ were <3%. The flow rates $E_{\mathrm{ns}}$, $R^2$, and $R_e$ values at Hukou for the 2006 to 2010 period were 0.93, 0.95, and −1.8%, respectively. The results of the simulation for the Poyang Lake area were obtained for the period 2000 to 2010 to establish the relation between the lake area and lake level.

## The relation between the Poyang Lake area and lake level

Based on simulated results, the relations between the lake area and lake level at four gauging stations (Xingzi, Duchang, Kangshan, Hukou) during periods characterized by low lake levels from October to March are shown in Figure 2. We note the presence of the hysteretic effect in every instance. The relation at Duchang demonstrates the smallest degree of hysteresis, which is explained by its location near the center of the lake (Zhang & Werner 2015). Therefore, the data points collected at Duchang station were used to generate a linear regression equation (Equation (1)) (with an $R^2$ of 0.95 that is used to compute

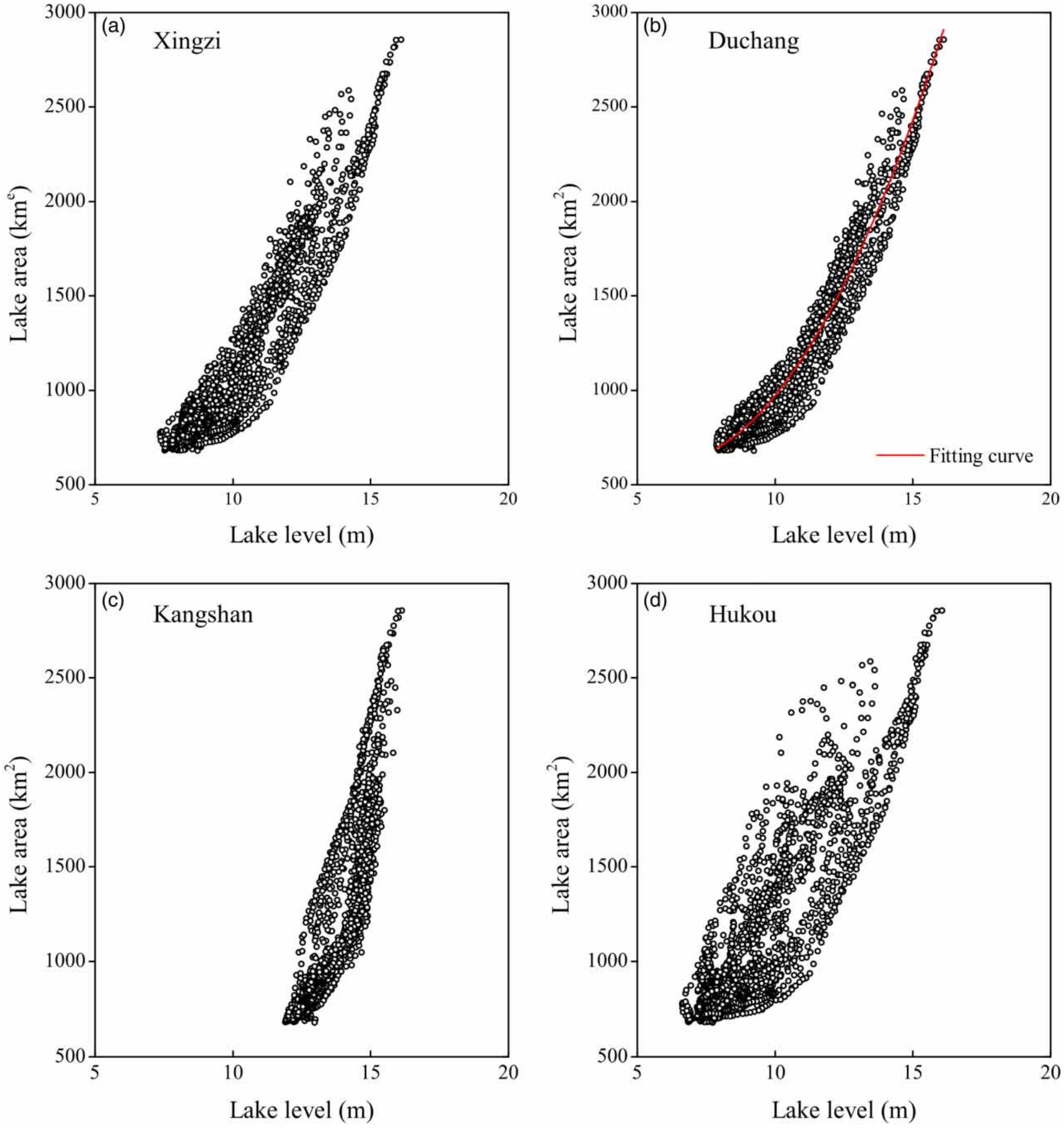

**Figure 2** | Computed lake area–lake level relations for Poyang Lake at (a) Xingzi, (b) Duchang, (c) Kangshan and (d) Hukou stations, for October to March during 2000–2010. The solid line represents the fitting curve for lake area-lake level relation at Duchang station (b).

the area of Poyang Lake from 1961 to 2010):

$$y = 22.55x^2 - 271.8x + 1434.9 \tag{1}$$

where $x$ is the observed lake level at the Duchang station; $y$ is the corresponding lake area.

### Determination of dry seasons

A cumulative probability analysis of the water levels at Duchang station allowed detection of the dry seasons (Figure 3). The water attaining a level having <25% probability to occur, e.g., 11.56 m, is adopted as the upper limit of the dry seasons. Thus, the dry seasons in this study were those when the water levels were less than 11.56 m. The year 2002 was excluded, since the water level was consistently >11.56 m for the entire year.

## RESULTS

Figure 4(a) illustrates the variations of the mean, minimum, and standard deviation (*SD)* of the Poyang Lake area during the dry seasons occurring from 1961 to 2010. During this period, the average lake area varied considerably, averaging 1,015 km$^2$. The *SD* ranged from 13.9 km$^2$ (minimum in 1997) to 161.7 km$^2$ (maximum in 1971), which indicated an important multi-year variability of the lake area. For example, the average lake area for 2008 was 834.5 km$^2$, which was 429 km$^2$ (34.7%) less than that of 1997 (1,277.7 km$^2$). Moreover, the minimum lake area varied from 702.8 km$^2$ (on January 28, 2009) to 1,259.7 km$^2$ (on November 13, 1997) resulting in a large difference of ~550 km$^2$. In addition, the average and minimum lake area remained consistently low in 2007–2010, e.g., 866 km$^2$ and 714 km$^2$, respectively (Figure 4(a)). An extremely small lake area (~714 km$^2$) characterized the 2007 to 2010 years, but not before the 2000s.

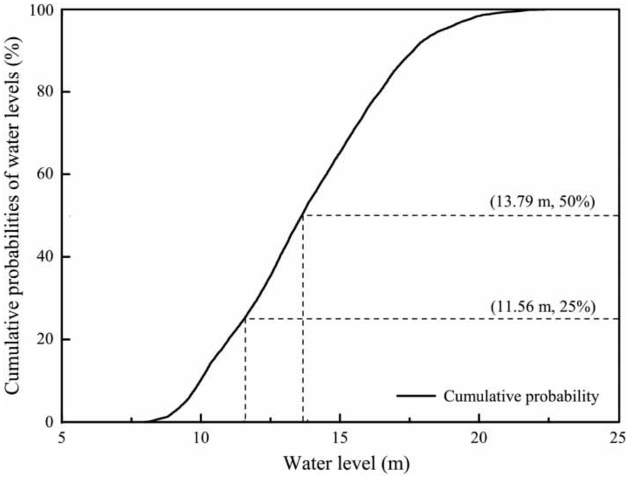

**Figure 3** | Cumulative probabilities of water levels at Duchang station for 1961–2010. The dashed lines represent water levels at the cumulative probability of 50% (13.79 m) and 25% (11.56 m).

Lake area averages over decades were also calculated. The largest decadal average lake area occurred in the 1990s and the lowest in the 2000s. The decadal average lake area in the 2000s (950 km$^2$) decreased by 166 km$^2$ relative to that in the 1990s (1,116 km$^2$). It decreased by more than 124 km$^2$ compared to that obtained from 1961 to 2000. Figure 4(b) depicts the difference in long-term average lake area relative to that of anomalous values. The average lake area anomalies became almost negative during the 2000s, indicating the lake was submitted to severe dry condition in the 2000s relative to other periods. Although the lake dryness was well reflected in the observed lake water levels, the changes in lake area provided additional information on the magnitude of water loss.

The discharges of the catchment (Figure 4(c)) and the Yangtze River (Figure 4(e)) are presented in Figure 4(d) and 4(f), along with the anomalous discharges. The figures establish a comparison of the impact of the local catchment and Yangtze River on the lake area variations. The detailed discussion on the correlation of the catchment and Yangtze River with the lake area is presented in the section below.

## DISCUSSION

### Impacts of the local catchment and the Yangtze River

Previous studies revealed the strong control exerted by the Yangtze River and local catchment on the hydrological status of Poyang Lake (Hu *et al.* 2007; Guo *et al.* 2012; Zhang *et al.* 2014; Li *et al.* 2015). Here, we further analyze the discharges of the local catchment and Yangtze River

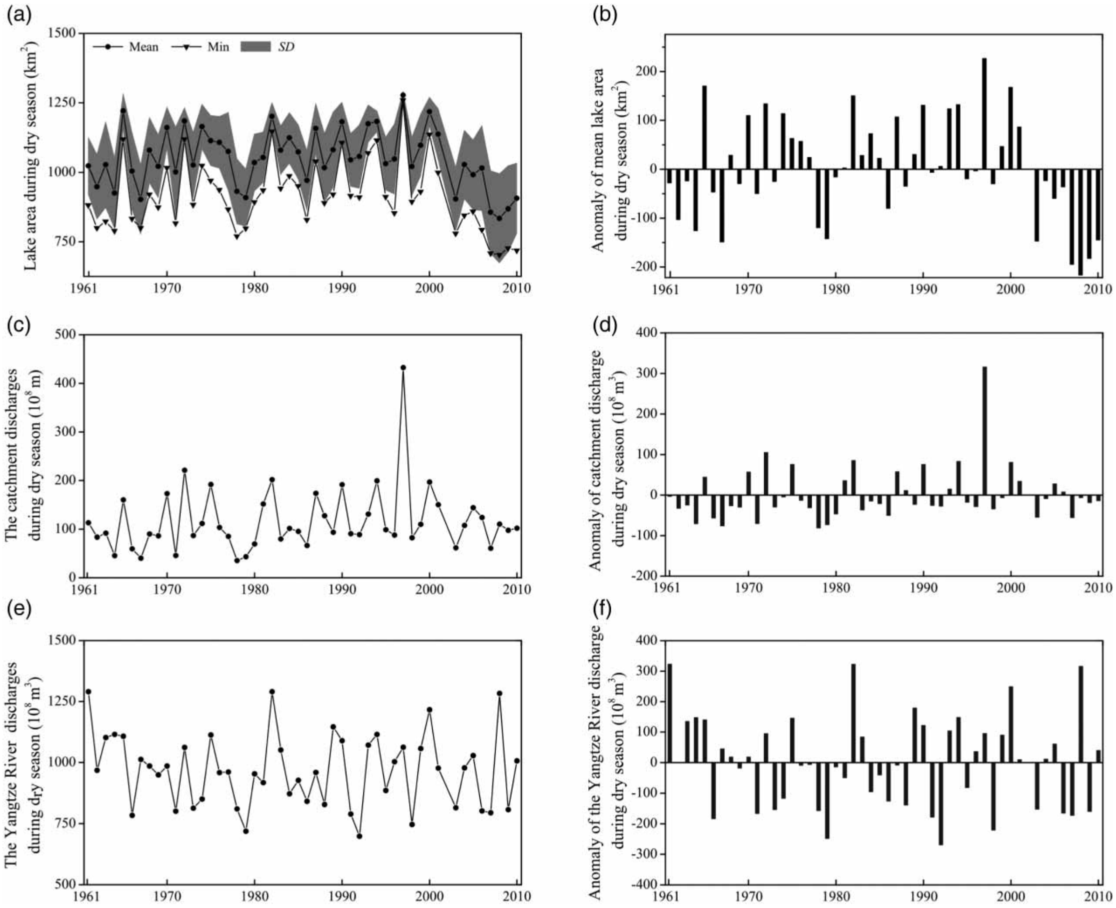

**Figure 4** | Variations of lake area, catchment discharges, and Yangtze River discharges, during dry seasons. The right column shows the corresponding values of anomaly. (a) Mean, minimum, and standard deviation (*SD* of the mean values) values of lake area. Mean value of lake area represents the average area for the dry season of a particular year, and the *SD* represents the variations of lake area in each dry season. (b) Anomaly of mean lake area. (c) Catchment discharges. (d) Anomaly of catchment discharges. (e) Yangtze River discharges at Hankou station. (f) Anomaly of Yangtze River discharges.

to explore the relative significance of their correlations with the variation of lake area (Figure 4(a), 4(c), and 4(e)). The correlation of the lake area with the catchment discharge is better with an $R^2$ value of 0.51 than that of the Yangtze River ($R^2 = 0.13$). Figure 4(b) indicates 26 years, during the 1961 to 2010 period, when the lake area anomalies were negative. Among the 26 years, 23, the exceptions being 1988, 2005, and 2006, presented negative anomalies for the catchment discharges (Figure 4(d)). Moreover, only 15 years were characterized by negative river discharge anomalies (Figure 4(f)). These results indicate the catchment discharge had generally a greater impact on the lake area than the Yangtze River discharge during the dry seasons. However, it should be acknowledged that the above correlation relationship is only statistically meaningful. We recognized the above correlations reflect the statistics over a 26-year period and may not be appropriate to explain the hydrological status of a specific year.

Furthermore, human activity contributed significantly along with climate change to the discharge variations. For example, the operation of the Three Gorges Dam in the upper Yangtze River caused more water to flow out of Lake Poyang (Zhang *et al.* 2012; Feng *et al.* 2013). Intensive sand mining within the lake significantly modified the lake bathymetry, and hence increased the risks of drought, in particular during the dry periods (Min & Zhan 2012; Lai *et al.* 2014). The increase in human activity combined with natural factors considerably affects the hydrological systems of the Yangtze River basin. Understanding the interactions of social-economic development with the evolution of hydrological systems is a great challenge for the near future, as noted in Wagener *et al.* (2010).

## Impacts on wetland ecosystem

The significant shrinkage of the lake water area in the 2000s modified the spatial distribution of the wetlands, referring to the area under periodic flooding. Model simulations demonstrated the wetland area was smallest in 2001, median in 2003, and largest in 2008. The three years were therefore selected to demonstrate the expansion of wetlands to the lower lake region in response to the reduction of water surface area. Figure 5 compared the wetland distribution at the lowest water level for the three selected years and shows an enlargement of the wetlands across the entire lake region. Important changes in wetland area were observed at the Poyang Lake National Nature Reserve and the Nanji Wetland National Nature Reserve.

Our results confirm the coverage of wetland vegetation rapidly increased during the 2000s and intruded into the lake lower region, reacting to changes in lake water area (Han *et al.* 2015; Hu *et al.* 2015). Modification to the hydrological regimes also transformed the structure of wetland vegetation. For example, Hu *et al.* (2015) and Xu *et al.* (2015) observed a degradation in plants growing in high marshlands and an accelerated expansion of plants in mid-marshlands. We need to pay particular attention to the strong interaction between the expansion in wetland vegetation and the hydrological regime given the rapid and significant modifications of the hydrological conditions of Poyang Lake.

## Uncertainties in lake bathymetry variations

The Poyang Lake bathymetry varied considerably due to natural erosion/deposition cycles and human activity (e.g., land reclamation, returning land to lake, sand mining, etc.) during the past decades (Ma *et al.* 2003; Min 2004; Shankman *et al.* 2006; Lai *et al.* 2014; Wu *et al.* 2015). The lake bathymetry used in this study was surveyed in 1998 and may not represent the bathymetry prevailing in earlier times. However, we established the lake area–lake level relation for the low lake level conditions (e.g., 7.99 m to 11.56 m). Land reclamation mainly occurred in the shallow margins of the lake (beyond the lake level of 22 m) (Shankman *et al.* 2006). Therefore, the bathymetric changes

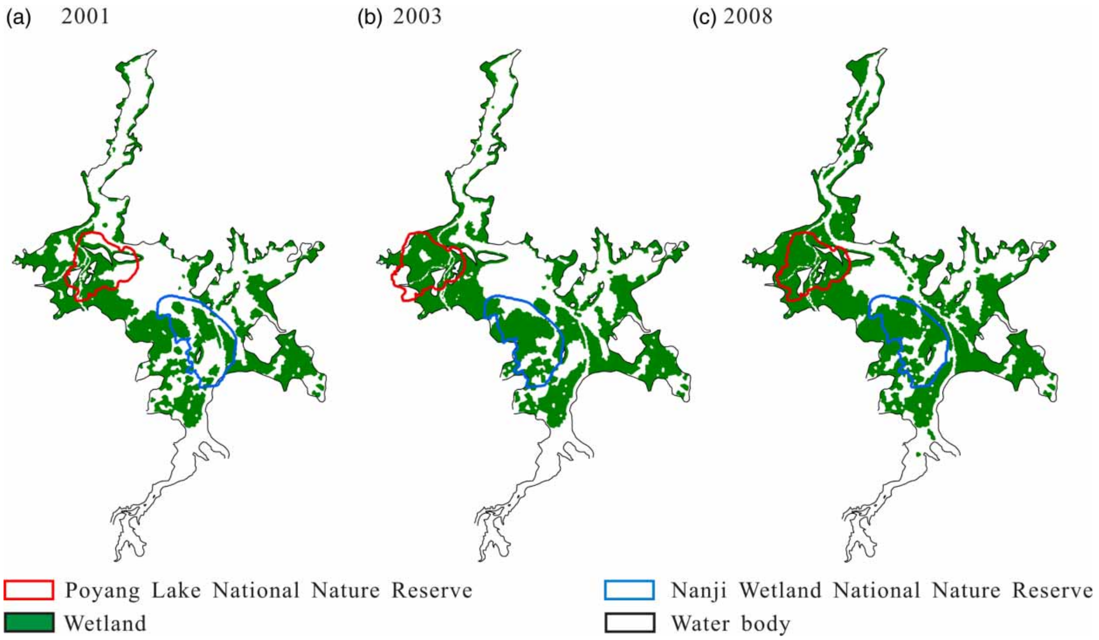

**Figure 5** | Simulated lake wetlands' distribution corresponding to the lowest water levels measured at Duchang station: (a) for 2001 at 10.15 m water level; (b) for 2003 at 8.72 m water level; (c) for 2008 at 7.99 m water level. The filled area represents wetland regions (refers to the area under a periodic inundation) and the white area water surface. *Note:* the wetland regions here may contain some villages and farmlands.

attributed to land reclamation should not affect the results of this study. Recently, the lake bathymetry was also modified by extensive sand dredging (Lai *et al.* 2014; Wu *et al.* 2015; Zhang *et al.* 2016). The dredging activities occurred mainly along the northern flow channel (Lai *et al.* 2014) and slightly enlarged the channel cross-sections, increasing the conveyance capacity of the lake (Lai *et al.* 2014). These changes could affect the results of our study and should be taken into consideration in future studies.

## CONCLUSIONS

This study presented long-term variations in the Poyang Lake area for dry seasons occurring from 1961 to 2010. The average lake area for the 1961 to 2010 period was 1,015 $km^2$, and the minimum lake area varied from 702.8 $km^2$ to 1,259.7 $km^2$. Regarding the last 50 years, the lake experienced the lightest dry conditions during the 1990s and the most severe during the 2000s. The lake area shrank by 124 $km^2$ from 2001 to 2010, compared to that for 1961–2000. This paper improved upon the previous studies by constructing a time sequence for the lake area data collected for the past 50 years, and quantifying the dry condition of the 2000s.

Using a simple correlation analysis, our work showed the lake area during dry seasons correlated significantly with the catchment inflows. This indicates any decrease in rainfall in the catchment could result in a decline of the lake area during the dry seasons. This also implies that optimized operation of the hundreds of reservoirs located in the catchment could help resolve the problem of dry conditions. Furthermore, the proposed construction of a hydraulic dam near the lake outlet may also be an adequate measure to maintain the lake water at an appropriate level. The dam would mitigate the impacts of unusual dryness on the wetland ecosystems and water supply for local residents and agricultural activity.

Application of the physically based hydrodynamic model in determining the lake area was successful. Poyang Lake presents a highly dynamic lake–floodplain system, and the model demonstrated the capability of capturing the temporal and spatial lake area variations at a satisfactory resolution. We could apply this model to similar lake systems around the globe as an alternative method to investigate hydrological changes when other data sources are limited.

## ACKNOWLEDGEMENTS

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