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An investigation of enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts

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SUMMARY

Changes in lake hydrological regimes and the associated impacts on water supplies and ecosystems are internationally recognized issues. During the past decade, the persistent dryness of Poyang Lake (the largest freshwater lake in China) has caused water supply and irrigation crises for the 12.4 million inhabitants of the region. There is conjecture as to whether this dryness is caused by climate variability and/or human activities. This study examines long-term datasets of catchment inflow and Lake outflow, and employs a physically-based hydrodynamic model to explore catchment and Yangtze River controls on the Lake's hydrology. Lake water levels fell to their lowest during 2001–2010 relative to previous decades. The average Lake size and volume reduced by 154 km^2 and 11×10^8 m^3 during the same period, compared to those for the preceding period (1970–2000). Model simulations demonstrated that the drainage effect of the Yangtze River was the primary causal factor. Modeling also revealed that, compared to climate variability impacts on the Lake catchment, modifications to Yangtze River flows from the Three Gorges Dam have had a much greater impact on the seasonal (September–October) dryness of the Lake. Yangtze River effects are attenuated in the Lake with distance from the River, but nonetheless propagate some 100 km to the Lake's upstream limit. Proposals to build additional dams in the upper Yangtze River and its tributaries are expected to impose significant challenges for the management of Poyang Lake. Hydraulic engineering to modify the flow regime between the Lake and the Yangtze River would somewhat resolve the seasonal dryness of the Lake, but will likely introduce other issues in terms of water quality and aquatic ecosystem health, requiring considerable further research.

1. Introduction

The unique and valuable functions of lakes, such as their contributions to the freshwater demands of local communities, for recreation, as unique ecosystems, and their flood mitigation roles, are well recognized (Maltby and Ormerod, 2011; Zedler and Kercher, 2005). Lake hydrological condition is fundamental to the maintenance of these functions (Carter, 1986; Mitsch and Gosselink, 2000). Changes in climatic stressors and human activities may result in the alteration of lake water balances, causing significant changes in lake water levels and impairment of lake functions (Carter, 1986; Carpenter et al., 1992; Casanova and Brock, 2000). Hydrological changes may occur as floods and/or droughts occurring at modified severity and frequency, and potentially causing considerable socioeconomic loss and extensive degradation of the lake ecosystem (Yin and Li, 2001; Humphries and Baldwin, 2003; Shankman et al., 2006; Bond et al., 2008; Wantzen et al., 2008; Li et al., 2013).

A prominent example of hydrological modifications to lake functioning is the regime changes to Poyang Lake, the largest freshwater lake in China (Liu et al., 2013; Zhang et al., 2012). Poyang Lake is located at the south bank of the middle reaches of the Yangtze River, and is one of the few lakes that remain naturally connected to the Yangtze River. The Lake receives water inflows from its catchment, and discharges to the Yangtze River at Hukou (the junction of the Yangtze River and Poyang Lake) in the north. The combined effects of catchment inflows and the interaction with the River result in a considerable seasonal variation of some 10 m in the Lake water level. The significant seasonal fluctuations in Poyang Lake water levels and in the associated water surface area create extensive wetland ecosystems across an ephemeral

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region of some 3000 km^2 (Feng et al., 2013). These wetlands provide vital habitats for many species, in particular some rare and/or endangered birds (Wang et al., 2013). However, it has been well noted that Poyang Lake water levels have been declining significantly in the last decade (Min and Zhan, 2012; Liu et al., 2013), resulting in water supply and irrigation problems for the 12.4 million inhabitants of the surrounding region. For example, in 2003, 3.89 million hectares of arable lands were affected with an economic loss of ¥1.15 billion (equivalent to US$188 million) (JWCPDI, 2011). In addition, shallow groundwater wells used as the major water supply for many of the villages in the region failed to meet demand due to the decline of Lake water levels, creating a water crisis for some 5.7 million farmers (JWCPDI, 2011). Changes in the Lake's hydrological regime may also lead to substantial impacts on the surrounding wetland vegetation and ecosystem health more generally (e.g., Yu et al., 2011; Zhang et al., 2012; Feng et al., 2013).

The above problems have caused great concern for local governments. To resolve the dryness of the Lake and to minimize the impacts on local socio-economic development and Lake wetland functions, various management strategies are being proposed and discussed. These include optimized operation of the reservoirs in the Lake's catchment and manipulation of the Yangtze River flow via hydraulic engineering upstream of the River's connection with Poyang Lake. The construction of a dam at the Lake's outlet has also been proposed (Li, 2009). The dam would be open during the wet season, so that the Lake is fully connected to the Yangtze River. However, in dry seasons, the dam would be operated to retain water in the Lake and maintain the water level above threshold values.

Given the natural connection of the Lake to the Yangtze River, several studies were carried out to investigate the interactions of the River and the Lake, and how modifications to the interactions will affect Poyang Lake discharge and subsequently the hydrological and hydrodynamic conditions of the Lake. Hu et al. (2007) quantified the interaction of the Lake and the River using observed water levels and water fluxes at Hukou, and the ratio of the net storage change of Poyang Lake to the water flux into the Lake from the surrounding catchment. The analyses of these parameters showed that the controlling effect of the River is particularly strong from July to September when the Yangtze River reaches its peak flood season. The River acts to restrict discharge from the Lake at relatively high River stages, and flow reversals (River to Lake) can occur if the River's blocking effect is strong enough (Hu et al., 2007). Hu et al. (2007) further noted that in the occurrence of severe floods, the local catchment plays a primary role influencing the water level of the Lake, while the Yangtze River plays a complementary role of blocking outflows.

The operation of the Three Gorges Dam (TGD) in the upper Yangtze River (~800 km upstream of Poyang Lake) since 2003 has complicated significantly the flow of the Yangtze River (Gao et al., 2013; Lai et al., 2014). TGD operations, including impounding and releasing water affected considerably the seasonal variation of discharge and water levels of the Yangtze River (Guo et al., 2012; Lai et al., 2014). Persistently drier conditions in Poyang Lake since TGD came into operation have raised great concerns regarding TGD impacts. Guo et al. (2012) extended the previous work of Hu et al. (2007) by including the TGD operation period of 2003–2008, in order to identify the effects of TGD on River flows. A method of "analogous years" was used to isolate and quantify the TGD effects. That is, for the specified year ("target year") in 2003–2008, the monthly precipitation of the target year was compared and contrasted with the monthly precipitation in each year from those before TGD operation. The year that had the minimum difference between its monthly precipitation and that in the target year was selected as the "analogous year". They found that the operation of TGD significantly modified the seasonal flow of the River. Although the TGD effects attenuate along the River, they modify the interaction between the River and Poyang Lake by weakening the River's blocking effect on the Lake, thereby increasing Lake discharge during July–September. By constructing statistical models using a semi-parametric approach based on generalized additive models (GAMs), Zhang et al. (2012) examined quantitatively the TGD's impacts on both the Yangtze River and Poyang Lake. Comparison of modeling results prior and after the TGD's operation for 2003–2008 indicated an average 2 m water-level drop at Hukou. This analysis revealed considerable impacts of the TGD on Poyang Lake, particularly a reduced water level over the dry period from late summer to autumn, resulting from rapid water impoundment in the TGD reservoir during this period.

A number of researchers have considered the changes in Poyang Lake bathymetry and the possible effects on the Lake hydrology and storage. For example, Shankman et al. (2006) identified for the period of 1954–1998, based on historical data, that human activities such as levee construction and land reclamation in the Lake region reduced the Lake's surface area from 5160 km^2 to 3860 km^2, and an associated Lake volume reduction from 37 to 28.9 billion m^3, worsening the severity of summer floods. Feng et al. (2011) found significant inter-annual variability of the bottom topography from 2000 to 2009 for part of the Lake, derived from MODIS 250-m resolution data. They attributed changes in the bottom topography to the combined effect of human activities (e.g., sand dredging, levee construction, operation of TGD) and weather events. How the changes in bottom elevation affect the water level in the Lake remains unknown and requires further research. More recently, Liu et al. (2013) revealed an abrupt change in the Lake size in 2006, using remote sensing data and Mann–Kendall test analysis. It was noted that neither the catchment precipitation nor the evapotranspiration fully accounted for this change.

Despite several efforts to evaluate changes in the flow regime of the Yangtze River and human activities in the Lake region, and their impacts on Poyang Lake, questions remain regarding the characteristics and causes of Lake dryness since 2000. In particular, the effects of the Yangtze River and the Lake catchment have not been quantified taking into account the dominant hydrodynamic processes of the Lake–River-catchment system. A better understanding of the system is essential to develop appropriate management responses to seasonal variations in Lake water levels, and to project future conditions under various land-use changes, engineering modifications and climate scenarios. This paper extends previous studies by examining the effects of both the River and the Lake catchment on the Lake's increased dryness in the last decade. The effects are assessed firstly by trend analyses of long-term records of Lake inflow and outflow. Subsequently, a physically based hydrodynamic model is applied to Poyang Lake for the first time to further characterize the causal factors. The objectives of this paper are to: (1) analyze the dryness of Poyang Lake in the 2000s, compared to long-term behavior; (2) analyze the trend and variations in the inflow and outflow of the Lake using Mann–Kendall testing, and explore commensurate changes in Lake volume and area; and (3) further explore the dominant factors that cause the recent dryness of the Lake using physically based mathematical modeling.

2. Materials and methods

2.1. Study area

Poyang Lake is located in the middle reach of the Yangtze River (N28°24′–29°46′, E115°49′–116°46′), to which it is connected via a channel in the northern extremity of the Lake (Fig. 1). The

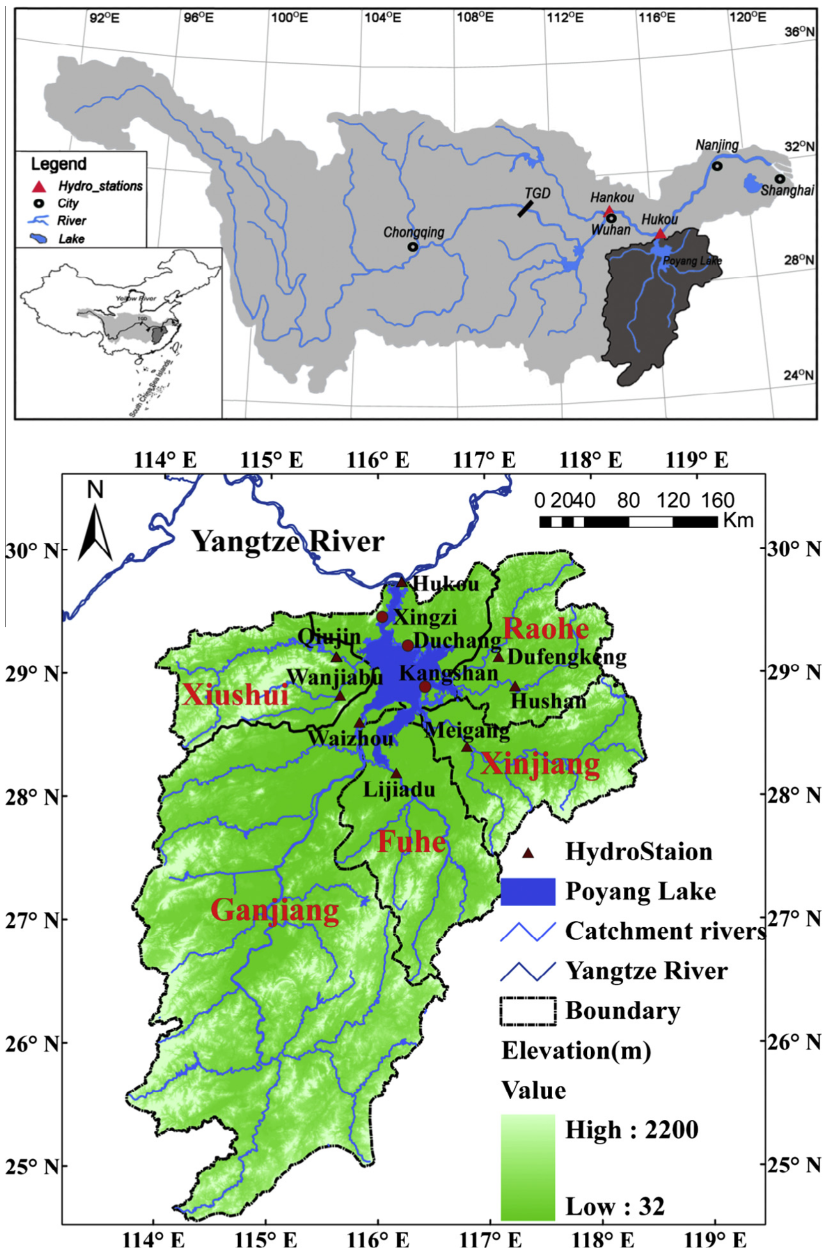

Fig. 1. The Poyang Lake catchment and its location in the Yangtze River. Hukou is the gauging station located at the junction of the Yangtze River and Poyang Lake's discharge channel that measures Lake discharge. The Lake catchment consists of five sub-catchments: Xiushui, Ganjiang, Fuhe, Xinjiang and Raohe. The most downstream river gauging station in each sub-catchment is indicated by triangles. Water level gauging stations in the Lake (Xingzi, Duchang and Kangshan) are marked as circles.

catchment of the Lake has an area of 16.2×10^4 km^2, and varies in elevation from 2200 m (above sea level) in mountainous regions to about 30 m in alluvial plains downstream of the major watercourses and around the Lake. The boundary of the catchment is almost identical to the administration boundary of Jiangxi Province, which has a population of 45 million (in 2012). Land use in the catchment consists of forest (46%), shrub land (25%), crop land (25%) and small areas of pasture, urban centers and open water (Ye et al., 2011). The soils in the catchment were classified by Ye et al. (2011) according to the Genetic Soil Classification of China. Eight major soil types are identified as: red soil (43%), latosol (23%), paddy soil (21%), yellow soil (7%), alluvial soil (3%), purplish soil (1.5%), yellow–brown soil (1%) and limestone soil (0.5%). Physical properties of the soils were obtained from a soil survey by Shi et al. (2004), with total porosity ranging from 0.41 to 0.52, field capacity from 0.32 to 0.36, and saturated hydraulic conductivity varying from 0.14 to 0.97 m/d.

The Poyang Lake catchment has a subtropical, monsoon climate. Climate data, covering a 49-year observation period from the 1960s, are available from 14 meteorological stations in the catchment. Annual rainfall is 1654 mm, of which 55% occurs in March to June. Temperatures are highly seasonal, with June–August average of 27.3 °C and December-February average of 7.1 °C, and annual average of 17.6 °C. The annual potential evapotranspiration is 1049 mm/year, with the highest rates occurring during May to September.

Poyang Lake receives inflows from five major rivers (Xiushui, Ganjiang, Fuhe, Xinjiang and Raohe) within the catchment, and discharges to the Yangtze River at Hukou (Fig. 1). Fig. 2 shows the monthly average runoff depth for the five rivers, and the monthly average Lake water level variation at Xingzi gauging station, which is situated in the northern arm of the Lake at about 39 km from the Yangtze River. Catchment runoff varies considerably throughout the year, with mean monthly runoff varying between 0.34×10^8

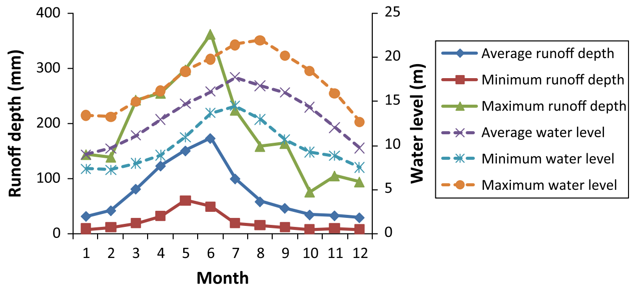

Fig. 2. Seasonal variations in catchment runoff depth and Lake water level. The runoff is the sum of gauged flows from the five main rivers in the catchment. Lake water levels are for Xingzi station. Runoff depths and water levels were calculated using 1953–2010 observations.

and 16.4×10^8 m^3/d, based on average values for the period 1953 to 2010. Both stream flows and Lake water levels demonstrate a distinct seasonal variation, with a time lag in the peak water level relative to the maximum catchment runoff. The catchment runoff starts to increase in February and peaks in June, while the Lake water level starts to rise in February and peaks in July, before dropping some 8.8 m (on average) to minimum values during December and January. Accordingly, the Lake area varies significantly. The historical maximum and minimum are about 4553 km^2 and 244 km^2, respectively (Tan et al., 2013).

2.2. Hydrological data

Observed daily stream flows at seven gauging stations are available for the period of 1950–2010 (Fig. 1 and Table 1). For sub-catchments of the Ganjiang, Fuhe and Xinjiang Rivers, only one gauging station at each main stream was selected to represent River discharge. For sub-catchments of the Xiushui and Raohe Rivers, gauging stations at tributaries (Wanjiabu station for the Xiushui River, Hushan and Dufengken stations for the Raohe River) were included to account for the runoff contributions to the main stream (Table 1). River gauging stations are upstream of the Lake's maximum inundated area, and hence Lake surface expansion does impact on these recordings. The total drainage area of these gauging stations is 137,143 km^2, leaving an area of 25,082 km^2 (15.5% of the whole catchment area, including the Lake surface) that is not gauged. Lake discharge is monitored at Hukou gauging station, which has a drainage area of 162,225 km^2.

The Lake water level gauging stations of Xingzi, Duchang and Kangshan were selected for assessment of modeling results. Xingzi station was selected as the most downstream and the closest to the Yangtze River, and was considered to best reflect the proximal effect of the River. Kangshan is located at the most upstream end of the Lake (110 km from the Yangtze River), and was selected because it is expected to respond primarily to catchment runoff. Duchang station is located in the central part of the Lake, and is expected to reflect the average condition of the Lake.

2.3. Mann–Kendall test

The Partial Mann–Kendall test (M–K test), also known as Kendall's statistic (Kahya and Partal, 2007), was applied to analyze trends in hydrological time series. It is a rank-based procedure, which is robust against the influence of extremes, and good for use with biased variables (e.g., Burn and Hag Elnur, 2002; Chen et al., 2007). For any samples of n variables, x_1, x_2, x_3, ..., x_n, n_i denotes the cumulative total of samples for which $x_i > x_j$ $(1 \leqslant j \leqslant i)$. The statistical parameter d_k was calculated as follows:

$$d_k = \sum_{i=1}^{k} n_i \quad (2 \leqslant k \leqslant n) \tag{1}$$

Under the null hypothesis of no trend, d_k is asymptotically normally distributed, with expected value $E(d_k)$ and variance $\mathrm{var}(d_k)$ as follows:

$$E(d_k) = k(k-1)/4 \tag{2}$$

$$\mathrm{var}(d_k) = k(k-1)(2k+5)/72 \tag{3}$$

The definition of the statistic index UF_k, under the above assumptions, is calculated as:

$$UF(d_k) = \frac{[d_k - E(d_k)]}{\sqrt{\mathrm{var}(d_k)}} \quad (k = 1, 2, 3 \ldots, n) \tag{4}$$

where $UF(d_k)$ is the forward sequence, and the backward sequence $UB(d_k)$ is calculated using the same equation but with a reversed series of data. The null hypothesis is rejected when any of the points in UF_k exceeds the confidence interval ±1.96. An increasing or decreasing trend is indicated at the 5% significance level. Because the presence of serial correlation can influence the identification of trends (Yue et al., 2003; Khaliq et al., 2009), it is necessary to do autocorrelation (serial correlation) analysis before the trend test.

The test statistics used here also enable the detection of the approximate time of trend occurrence by locating the intersection of the forward and backward curves of the test statistic. An intersection point of $UF(d_k)$ and $UB(d_k)$ located within the confidence interval indicates the beginning of a step-change point.

Table 1
List of hydrological gauging stations used in this study.[a]

Gauging station	Location	Coordinates	Gauged area (km^2)	Average annual runoff depth (mm)
Qiujin	Xiushui	(115.41°, 29.10°)	9914	921
Wanjiabu	Liaohe tributary of Xiushui	(115.65°, 28.85°)	3548	984
Waizhou	Ganjiang	(115.83°, 28.63°)	80,948	844
Lijiadu	Fuhe	(116.17°, 28.22°)	15,811	806
Meigang	Xinjiang	(116.82°, 28.43°)	15,535	1157
Hushan	Le'an tributary of Raohe	(117.27°, 28.92°)	6374	1117
Dufengken	Changjiang tributary of Raohe	(117.12°, 29.16°)	5013	927
Hukou	Junction of Poyang Lake and Yangtze River	(116.22°, 29.75°)	162,225	925
Xingzi[b]	Lake	(116.03°,29.45°)	–	–
Duchang[b]	Lake	(116.18°,29.27°)	–	–
Kangshan[b]	Lake	(116.42°,28.88°)	–	–

[a] 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.
[b] Lake water level gauging station.

2.4. Simulation model

The distinct seasonal variation in Lake water levels results in not only considerable expansion and retraction of the Lake surface, but also complex flow patterns. In January and February, a stage difference of up to 6 m may develop in the Lake from upstream in the south (e.g. Kangshan station) to downstream in the north (e.g. Xingzi station), producing conditions in which hydrodynamic processes need to be considered in modeling Lake behavior. In response to this, Li et al. (2014) recently constructed a physically-based mathematical model for the Lake using the MIKE 21 code (DHI, 2007). The model covers an area of 3124 km^2, which was determined by examining the historic Lake surface under high water levels. The model utilizes a Digital Elevation Model (DEM) of the study area that was generated using data provided by Jiangxi Hydrological Bureau, surveyed in 1998 and updated with new data obtained in 2000.

Given the extensive area (about 3000 km^2) of periodic inundation, a proportion of the catchment (2%) fluctuates between regions of surface runoff and Lake storage. For this periodically inundated area, an option in MIKE 21 was used to account for incidental rainfall at all model elements, whereas evaporation applied only to the permanently wet elements. For dry elements, it was assumed that all rainfall was transformed to surface runoff (Li et al., 2014). Daily catchment inflows from the five main rivers were specified as upstream boundary conditions in the Lake model. Runoff from the ungauged catchment area was calculated using a simple linear extrapolation of the gauged runoff, and was added to the gauged inflows (see Section 3.3 for more detail). The connection of the Lake to the Yangtze River was simulated by specifying the downstream boundary water levels as those observed at Hukou. The model used a variable spatial discretisation of 70–1500 m, resulting in a total of 20,450 triangular elements. The time step was set to 5 s to limit the Courant-Friedrich-Levy number (DHI, 2007) for a stable solution. Outputs from the model included nodal water levels and velocities, and the outflows at Hukou.

Li et al. (2014) calibrated and validated the model against observed water levels for the periods 2000–2005 and 2006–2008, respectively, at four gauging stations in the Lake. The Nash–Sutcliffe efficiencies for both the calibration and validation periods at all gauging stations ranged from 0.80 to 0.98, suggesting a satisfactory accuracy (Li et al., 2014). The modeled flow rates at Hukou were also verified against observations, producing a Nash–Sutcliffe efficiency of 0.80 and 0.87 for the calibration and validation, respectively. In addition, the modeled seasonal variations in Lake water surface area were compared against remote sensing data, with relative errors of 3.3% and 16.8% for wet season (July 2004) and dry season (January 2004), respectively (Li et al., 2014).

3. Results

3.1. Lake water level changes

Fig. 3 shows the monthly average water levels at Xingzi for 1953–2010, showing clear seasonal and inter-annual variations. Although no significant trend is apparent from visual inspection, significant inter-annual variations are indicated by cumulative probability plots of water levels for different periods, using the long-term probability distribution as a reference (Fig. 4). The results demonstrate that, on average, Lake water levels were generally higher during the 1980s and 1990s, and were significantly lower during 2001–2010. Fig. 5 highlights variability in seasonal water-level variations across different decades, based on decadal averages of the daily water levels at Xingzi station, with comparison to the long-term condition. The water levels in July–August during the 1990s, and in October–November during the 2000s deviated considerably from the reference period. The high mid-year water levels for the 1990s are attributable to the large flood of 1998 (Shankman et al., 2006), when the water level reached the peak recorded value of 22.5 m on the 2nd August 1998. The low water levels of October–November (autumn dryness) during the 2000s are clearly the lowest in history, and these are the subject of current concerns. In the period 1953–2010, the annual average water level varied from 11.57 to 16.12 m, and the annual minimum water level varied from 7.12 to 9.49 m. Both the minimum values of 11.57 m and 7.12 m occurred in the 2000s. The results presented here indicate that the Lake has experienced a new and more severe dry condition since 2000.

3.2. Intra-annual variations of inflow and outflow

Changes in Poyang Lake's storage behavior are inextricably linked to the Lake water balance. Fig. 6 shows annual average flow rates and associated trends (from M–K testing) for catchment gauged inflows (sum of the flow gauging stations in Table 1), gauged outflows (at Hukou), and differences between the two. As previously noted, there is an area of 25,082 km^2 that is not gauged, and this produces larger outflows than inflows in Fig. 6. Fig. 6 illustrates that annual catchment inflows vary significantly between decades and the long-term linear trend is increasing slightly. The M–K test indicates a decreasing trend in catchment inflows before 1993 ($UF < 0$), while an increasing trend occurs thereafter.

The annual variations in outflow show largely similar trends to those of the catchment inflows, both of which have clearly decreased during the last decade (Fig. 6b). However, the difference between annual outflows and inflows is distinctly different (Fig. 6c), showing an increasing monotonic trend during the study period that is significant after 1999, when UF exceeds the critical value of 1.96.

Quantitative analyses were performed by considering the Lake's water balance, which can be expressed as:

$$Q = R_1 + R_2 + R_G + \Delta V \quad (5)$$

where Q is the outflow at Hukou, R_1 is the gauged runoff (Fig. 1 and Table 1), R_2 is the ungauged runoff, R_G is groundwater net inflow to the Lake, and ΔV is the change in Lake volume (positive for volume reductions). In Eq. (5), observation data are available for only Q and R_1. According to Feng et al. (2011), R_G is only 1.3% of the total water balance, and hence is neglected in the current analysis. We combine R_2 and ΔV and refer to this as the unknown water balance component R_X.

Long-term (1953–2010) averages of Q and R_1 are 1489×10^8 m^3/year and 1228×10^8 m^3/year, respectively, with the difference of 261×10^8 m^3/year (21.3% of the inflow) being R_X (Table 2). Lake water components are also computed for different decades (Table 2). The results show that both Q and R_1 varied considerably at the decadal scale. The difference between the two (R_X) is found to have a higher correlation with the outflow Q than the inflow R_1, with correlation coefficients of 0.75 and 0.52, respectively. This implies that changes in water storage of the Lake flood plain is dominantly controlled by the Yangtze River. However, changes in the Lake bathymetry due to levee construction (Shankman et al., 2006) and sediment deposition (Shankman and Liang, 2003) were accompanying factors affecting the Lake storage capacity that are difficult to quantify using the current analysis. It is also noted that R_1 is smallest (1151×10^8 m^3/year) during the period 2001–2010. However, Q was higher during 2001–2010 than the periods 1961–1970 and 1971–1980. The R_X/R_1 ratio is greatest (24.1%) for 2001–2010 as a consequence.

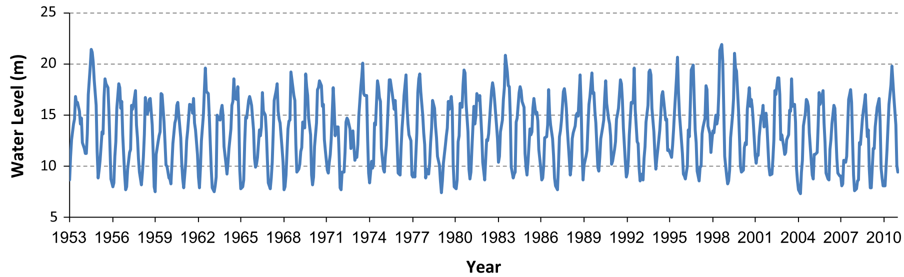

Fig. 3. Variation of monthly average water level at Xingzi for 1953–2010.

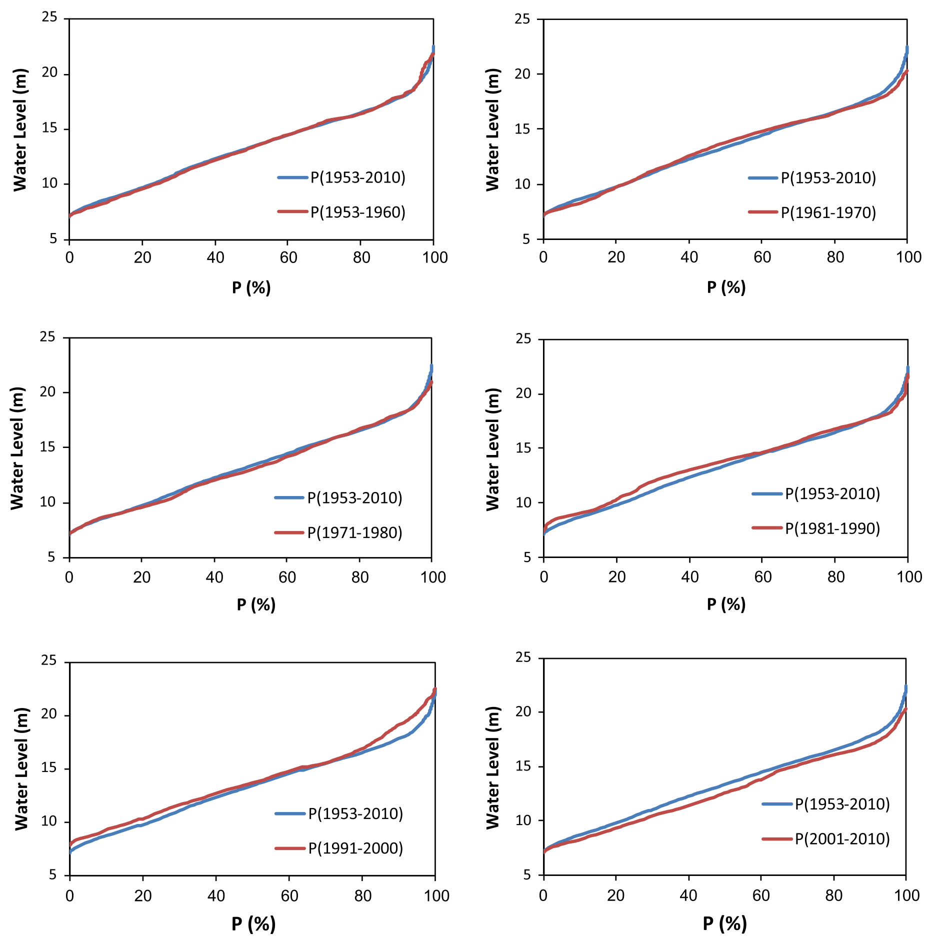

Fig. 4. Cumulative probabilities of water levels at Xingzi for different decades, compared to the reference period of 1953–2010.

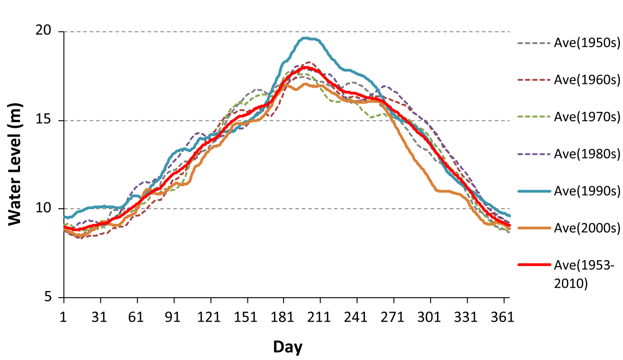

Fig. 5. Decadal averages of seasonal variations in water levels at Xingzi station.

Table 2 also reveals that the lowest decadal-average water level of 12.74 m, and corresponding Lake volume of 35×10^8 m^3 (using the Lake storage curve of Tan et al. (2013)), occurred during 2001–2010. This is a reduction of 11×10^8 m^3 (23.9%) compared to the average for 1971–2000, and a reduction of 14×10^8 m^3 (28.6%) compared to that for 1991–2000. Liu et al. (2013) established a relationship between Lake surface area and the water level at Hukou from remote sensing images, for 1973–2010. By employing their surface area function, it is calculated that the Lake surface area for 2001–2010 reduced by 154 km^2 (6.3%) and 226 km^2 (9.0%), compared to the periods 1971–2000 and 1991–2000, respectively.

3.3. Hydrodynamic modeling assessment

Hydrodynamic modeling was undertaken to further explore the relative contributions of the catchment and the Yangtze River to

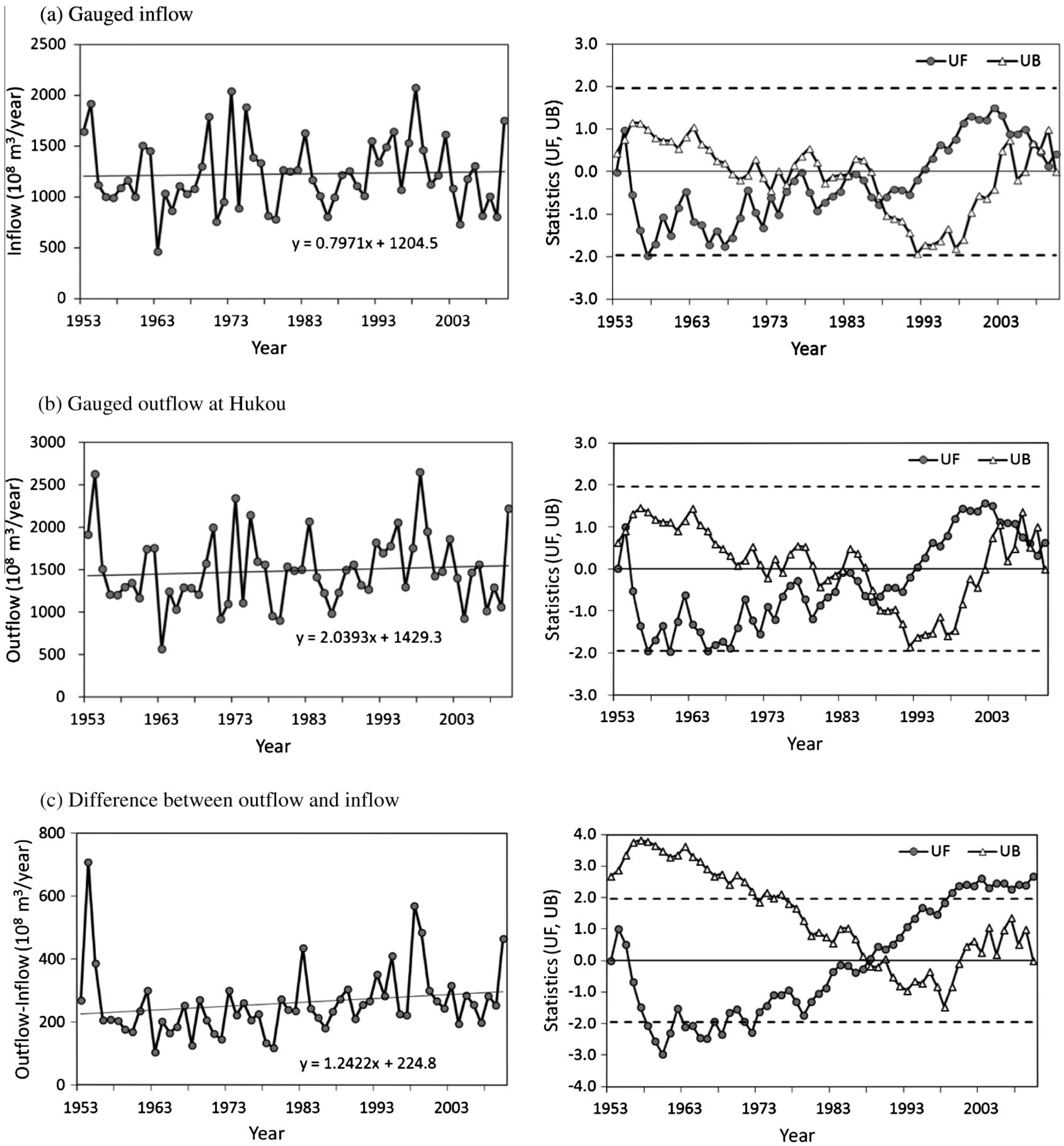

Fig. 6. Variations of annual flow rates (left figures) and corresponded trend analyses using M–K testing (right figures): (a) gauged catchment inflow, (b) outflow at Hukou, and (c) difference between outflow and inflow. The *UF* and *UB* in the right figures are the calculated statistics of M–K testing of annual flow rates, in the forward and backward directions, respectively. The horizontal dashed lines denote the ±95% confidence interval.

Table 2
Averaged water balance components for different periods.

Period	Q (10^8 m^3/year)	R_1 (10^8 m^3/year)	R_X (10^8 m^3/year)	R_X/R_1 (%)	Water level at Xingzi (m)
1953–1960	1533	1242	291	23.4	13.31
1961–1970	1369	1164	205	17.6	13.33
1971–1980	1417	1212	205	16.9	13.22
1981–1990	1429	1172	257	21.9	13.67
1991–2000	1769	1431	338	23.6	13.87
2001–2010	1428	1151	277	24.1	12.74
1953–2010	1489	1228	261	21.3	13.36

Poyang Lake water-level trends. Based on previous analyses of Lake and River interactions (Hu et al., 2007; Guo et al., 2012), it was concluded that the drainage effect of the River on the Lake normally occurs during July–October. It is therefore likely that the Lake's enhanced recession, which occurs during this period, is at least partly attributable to changes in River water levels. To explore this further, the contribution of the River to enhanced Lake recession during 2001–2010 was evaluated using three 1-year MIKE 21 scenarios (S1, S2 and S3). S1 is meant to represent the average condition for 1953–2010, and was used as a reference case for comparative purposes. S2 allows for an evaluation of the effects of catchment inflows, and S3 is intended to assess the effects of the Yangtze River.

In S1, Lake stresses (R_1, R_2 and Hukou water leve1s) were adopted that represent an annual sequence of time-varying daily averages for the period 1953–2010. Since the long-term average of ΔV can be regarded as nearly zero, R_2 is 261×10^8 m^3/year (neglecting R_g), on average (Table 2). R_2 is then distributed (i.e. variable) throughout the year using a daily weighting factor calculated from the R_1 daily flow time series, assuming that the annual variability in R_2 is relatively similar to that of R_1. In S2, daily variations in Lake inflows are averages for the period 2001–2010. R_2 was calculated using Eq. (5) for 2001–2010 (ΔV was estimated using the Lake storage curve and the water levels at Xingzi). The downstream boundary condition in S2 is the same as in S1. Lake inflows (R_1 and R_2) in S3 are the same as in S1, and the downstream boundary condition represents average daily water levels at Hukou from the observation period 2001–2010.

Model results for the S1 case were compared with water level observations (averages from 1953 to 2010) at Xingzi, Duchang and Kangshan stations (Fig. 7a), producing Nash–Sutcliffe efficiencies of 0.998, 0.973 and 0.872, respectively. The model results demonstrate a better agreement during high water levels than during low water levels. The reason was that the complex Lake bathymetry and the interactions between wetlands and the Lake storage may exert more influence on the prediction of low water levels than high water levels (Li et al., 2014). Nevertheless, the model is generally capable of capturing the rising and recession periods of water levels with satisfactory agreement. It is also noted that the model's agreement with observations reduces in the upstream direction, as expected given that the water level at Hukou is assigned observed values. Model results for the three scenarios are also compared in Fig. 7(b), (c) and (d). The model predictions for S3 are the closest to the observed values for the respective periods of averaging, especially during Lake water level recession. This indicates that the Lake water levels are more sensitive to the River stage during the recession period, compared to the rising period. That is, the Yangtze River appears to have a strong effect on Lake water level variations, in particular during high water levels and recession periods. The enhanced autumn dryness in Poyang Lake during 2001–2010 is therefore attributable mainly to the drainage effect of the River, rather than changes in catchment inflows during this period. The simulations produce impacts in the Lake, caused by the River, that are attenuated in the Lake's upstream direction, but nonetheless propagate to the upstream extremity of the Lake, as indicated in Fig. 7(b), (c) and (d).

4. Discussion

Examination of the long-term Lake water level observations found that the Lake encountered the lowest water levels during 2001–2010. This is in agreement with the findings of others. Min and Zhan (2012) analyzed the long-term water level changes at Duchang station (Fig. 1), and concluded that the severity of Lake dryness was most apparent during 2001–2010, especially in the period 2006–2010. Our analysis of catchment inflows and Lake outflows by trend testing and water budget analyses found that both the inflows and outflows decrease at a rate of 41×10^8 m^3/year and 52×10^8 m^3/year, respectively, after the 1998 flood. Using MODIS imagery to estimate the monthly change in Lake volume and gauged catchment inflows, Feng et al. (2011) estimated the Lake outflows using water balance calculations, and obtained a declining trend of 57×10^8 m^3/year for Lake outflow during 2000–2009, in agreement with the findings of the current study.

The dryness of Poyang Lake, in terms of reductions in Lake volume and Lake surface area, was quantified for the 2000's. The Lake volume was found to be lower on average by 14×10^8 m^3 for the period 2001–2010, compared to that for 1991–2000. The reduction in Lake volume was the underlying cause of the high ratio of the difference between the outflow to the inflow. Loss of water storage in the Lake also resulted in shrinkage of the annual average surface area by 226 km^2, compared to that for 1991–2000. Liu et al. (2013) examined the change in Lake surface area using Landsat images for the period 1973–2011, and found that the Lake area started to decrease after 1998, dropping abruptly by some 311.6 km^2 in 2006, and remaining a reduced extent since then. Feng et al. (2012) obtained the inundation area for Poyang Lake using

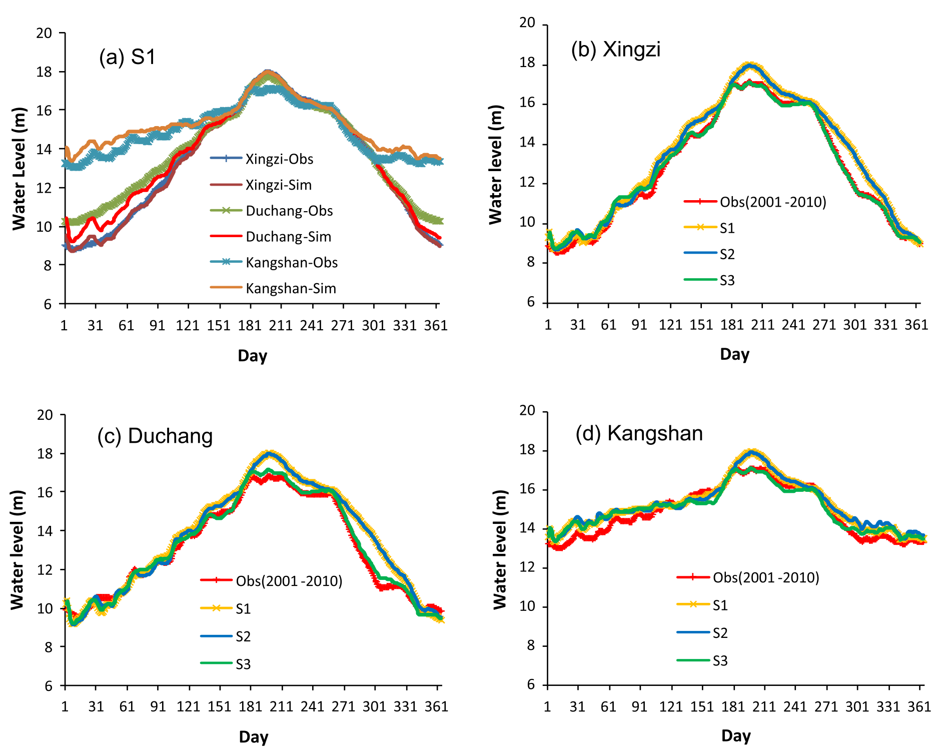

Fig. 7. Comparison of simulated (Sim) and observed (Obs) water levels for three scenarios (S1, S2, S3): (a) Comparison of Xingzi, Duchang and Kangshan stations for S1; (b) Comparison of S1, S2 and S3 at Xingzi station; (c) Comparison of S1, S2 and S3 at Duchang station; (d) Comparison of S1, S2 and S3 at Kangshan station.

250-m MODIS images for 2000–2010, and found that the inundation area varies significantly at the inter-annual scale. A total reduction of 302 km^2 in inundation area was found for the above period.

This work builds on previous studies by compiling extensive hydrological data and using these to quantify the severity of Poyang Lake drought for the decade of 2000s, in terms of the changes in Lake volume and area relative to previous decades. It is the first study to employ a physically-based hydrodynamic model to quantify the relative significance of various attributes of the Lake catchment and Yangtze River connection to the Lake hydrology. It was found that the Yangtze River drainage effects had a much greater influence on the seasonal (September–October) dryness of the Lake, compared to the local catchment. Ye et al. (2013) suggest that, although human activities in the catchment may reduce catchment discharge, climate variables are the dominant factors affecting intra-annual variations in catchment discharge. Model simulations in Ye et al. (2011) indicate that under future climate conditions, monthly catchment discharge will change, i.e. more catchment discharge in wet seasons and less discharge in dry seasons, resulting in a possible increase in the frequency and severity of flooding and droughts in the Lake. Considering the outcomes of this study, the seasonal dryness of the Lake may be further worsened in the future with more dams to be constructed in the upper reach of the Yangtze River.

Uncertainties still exist with regard to the simulation of Poyang Lake and its catchment. For example, the calculation of runoff from ungauged regions of the catchment is only approximate. Additional hydrological measurements and modeling are needed to simulate the rainfall–runoff processes across the entire Lake catchment, paying particular attention to wetland hydrology and groundwater dynamics. An improved water budget analysis may be achieved by accounting for components of the catchment's water balance that are presently not well constrained, such as the ungauged areas of the catchment, the areas of intermittent inundation, and the system of aquifers underling the Poyang Lake catchment. Further modeling would be enhanced by coupling catchment simulation models with the existing hydrodynamic model. At this stage, data are inadequate to support such a modeling strategy, and hence, further field investigations are warranted as the first priority.

5. Conclusions

This study demonstrates that Poyang Lake water levels were generally lower in the last decade than the long-term average condition, in agreement with previous studies. In particular, Lake water levels were significantly lower during autumn recession periods. The average Lake size and volume reduced during 2001–2010 by 154 km^2 and 11×10^8 m^3, respectively, compared to the preceding period (1970–2000). Model simulations explored the drainage effect and revealed that, compared to climate variability impacts on the catchment, modifications to Yangtze River flows (e.g. from TGD) have had a much greater influence on the seasonal (September–October) dryness of the Lake. Yangtze River effects on the Lake are attenuated with distance from the River, but nonetheless propagate to the Lake's upstream limit.

This paper addresses knowledge gaps from previous studies by assessing the magnitude and longitudinal propagation of the drainage effect of the River on the Lake storage behavior, and the relative contribution of the Lake catchment to periods of enhanced dryness. The results quantify the dryness of the Lake for the last decade in terms of reductions in the Lake volume and surface area. Outcomes of this work are expected to assist in resolving debates regarding the severity of Lake droughts during the last decade and the unusual seasonal dryness.

It is anticipated that more dams will be built in the upper reach of the Yangtze River in the future. The operation of these dams in combination with the TGD will likely lower the River stage further during particular times of the year (e.g. September–October), which is expected to worsen the autumn dryness of the Lake. Consideration should be given to the regulation of Yangtze River flow, given that management within the local catchment will probably have only a minor influence on the drying effect. Alternatively, the proposal of a control structure at the Lake outlet to manage dry season discharge could be an effective way to balance the operation of reservoirs in the upper Yangtze River and the water shortage of Poyang Lake, albeit it may change the hydrological and hydrodynamic processes of the Lake, and subsequently affect the water quality, wetland vegetation and the migration of aquatic species. The control of Lake–River interaction may also impact the flow regimes of the Yangtze River. These aspects require substantial further research to protect against further degradation of Poyang Lake.

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References

Bond, N.R., Lake, P.S., Arthington, A.H., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600, 3–16.
Burn, D.H., Hag Elnur, M.A., 2002. Detection of hydrologic trends and variability. J. Hydrol. 255, 107–122.
Carpenter, S.R., Fisher, S.G., Grimm, N.B., Kitchell, J.F., 1992. Global change and freshwater ecosystems. Annu. Rev. Ecol. Syst. 23, 119–139.
Carter, V., 1986. An overview of the hydrologic concerns related to wetlands in the United States. Can. J. Bot. 64 (2), 364–374.
Casanova, M.T., Brock, M.A., 2000. How do depth, duration and frequency of flooding influence the establishment of wetland plant communities? Plant Ecol. 147, 237–250.
Chen, H., Guo, S.L., Xu, C.Y., Singh, V.P., 2007. Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. J. Hydrol. 344, 171–184.
Danish Hydraulic Institute (DHI), 2007. MIKE 21 flow model: hydrodynamic module user guide. Danish Hydraulic Institute Water and Environment, Hørsholm, Denmark, 90 pp. <http://www.mikebydhi.com/Products/CoastAndSea/MIKE21/Hydrodynamics.aspx>.
Feng, L., Hu, C., Chen, X., Li, R., 2011. Satellite observations make it possible to estimate Poyang Lake's water budget. Environ. Res. Lett. 6, 044023, 7pp.
Feng, L., Hu, C., Chen, X., Cai, X., Tian, L., Gan, W., 2012. 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., Zhao, X., 2013. Dramatic inundation changes of China's two largest freshwater lakes linked to the Three Gorges Dam. Environ. Sci. Technol. 47, 9628–9634.
Gao, B., Yang, D., Yang, H., 2013. Impact of the Three Gorges Dam on flow regime in the middle and lower Yangtze River. Quatern. Int. 304, 43–50.
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.
Humphries, P., Baldwin, D.S., 2003. Drought and aquatic ecosystems: an introduction. Freshw. Biol. 48, 1141–1146.
Jiangxi Water Conservancy Planning and Designing Institute (JWCPDI), 2011. Technical Report of Assessment on Irrigation and Water Supply of Poyang Lake Hydraulic Engineering (in Chinese, unpublished).
Kahya, E., Partal, T., 2007. Is seasonal precipitation decreasing or increasing in Turkey? Online J. Earth Sci. 1 (1), 43–46.
Khaliq, M.N., Ouarda, T.B.M.J., Gachon, P., Sushama, L., St-Hilaire, A., 2009. Identification of hydrological trends in the presence of serial and cross correlations: a review of selected methods and their application to annual flow regimes of Canadian rivers. J. Hydrol. 368, 117–130.
Lai, X., Jiang, J., Yang, G., Lu, X.X., 2014. Should the Three Gorges Dam be blamed for the extremely low water levels in the middle-lower Yangtze River? Hydrol. Process. 28, 150–160.

Li, J., 2009. Scientists line up against dam that would alter protected wetlands. Science 326, 508–509.
Li, F., Qin, X., Xie, Y., Chen, X., Hu, J., Liu, Y., Hou, Z., 2013. Physiological mechanisms for plant distribution pattern: responses to flooding and drought in three wetland plants from Dongting Lake, China. Limnology 14, 71–76.
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.
Liu, Y., Wu, G., Zhao, X., 2013. Recent declines in China's largest freshwater lake: trend or regime shift? Environ. Res. Lett. 8, 014010, 9pp.
Maltby, E., Ormerod, S., 2011. Freshwaters: Open waters, wetlands and floodplains. In: The UK National Ecosystem Assessment Technical Report, UK National Ecosystem Assessment. UNEP-WCMC, Cambridge, pp. 295–360 (Chapter 9).
Min, Q., Zhan, L., 2012. Characteristics of low-water level changes in Lake Poyang during 1952–2011. J. Lake Sci. 24 (5), 675–678 (in Chinese, with English abstract).
Mitsch, W.J., Gosselink, J.G., 2000. Wetland Hydrology. In: Wetlands. John Wiley & Sons Inc., pp. 107–153 (Chapter 5).
Shankman, D., Liang, Q., 2003. Landscape changes and increasing flood frequency in China's Poyang Lake region. Professional Geographer 55 (4), 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.
Shi, X.Z., Yu, D.S., Warner, E.D., Pan, X.Z., Petersen, G.W., Gong, Z.T., Weindorf, D.C., 2004. Soil database of 1:1,000,000 digital soil survey and reference system of the Chinese Genetic Soil Classification System. Soil Survey Horizons 45 (4), 129–136.
Tan G., Li, G., Yu, Z., Chen, J., 2013. Lake stage-area-storage relationship for Poyang Lake. In: Chinese Hydraulic Engineering Society (CHES), Proceedings of 2013 CHES Annual Conference, Guangzhou, China, 25–28 November 2013 (in Chinese).
Wang, Y., Jia, Y., Guan, L., Lu, C., Lei, G., Wen, L., Liu, G., 2013. Optimising hydrological conditions to sustain wintering waterbird populations in Poyang Lake National Natural Reserve: implications for dam operations. Freshw. Biol. 58 (11), 2366–2379.
Wantzen, K.M., Rothhaupt, K.-O., Mörtl, M., Cantonati, M., Tóth, L., Fischer, P., 2008. Ecological effects of water-level fluctuations in lakes: an urgent issue. Hydrobiologia 613, 1–4.
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., Zhang, Q., Liu, J., Li, X., Xu, C.-Y., 2013. Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. J. Hydrol. 494, 83–95.
Yin, H., Li, C., 2001. Human impact on floods and flood disasters on the Yangtze River. Geomorphology 41, 105–109.
Yu, L., He, L.-H., Zhang, Q., Chen, Y.-W., Wang, X.-L., 2011. Effects of the Three Gorges Project on the typical wetland vegetations of Poyang Lake. Geogr. Res. 30 (1), 134–144.
Yue, S., Pilon, P., Phinney, B., 2003. Canadian streamflow trend detection: impacts of serial and cross-correlation. Hydrol. Sci. J. 48 (1), 51–63.
Zedler, J.B., Kercher, S., 2005. Wetland resources: status, trends, ecosystem services, and restorability. Annu. Rev. Environ. Resour. 30, 39–74.
Zhang, Q., Li, L., Wang, Y.-G., Werner, A.D., Xin, P., Jiang, T., Barry, D.A., 2012. Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier? Geophys. Res. Lett. 39, L20402, 7pp.