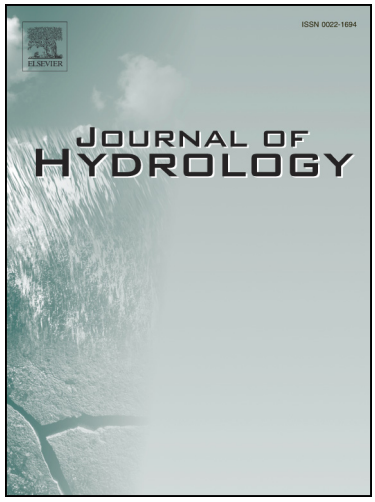
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# An investigation of enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts

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**Abstract**:

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 $11\times10^8$ $m^3$ 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. Modelling 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

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quality and aquatic ecosystem health, requiring considerable further research.

Keywords: Water level; Mann-Kendall test; Hydrodynamic model; Poyang Lake; Yangtze River; Lake-river interaction

## 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

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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 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).

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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.,

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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

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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 to 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

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155 the evapotranspiration fully accounted for this change.

156

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

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177 **2. Materials and Methods**

178

179 **2.1 Study Area**

180

181 Poyang Lake is located in the middle reach of the Yangtze River (N28°24′-29°46′,
182 E115°49′-116°46′), to which it is connected via a channel in the northern extremity of
183 the Lake (Fig. 1). The catchment of the Lake has an area of $16.2\times10^4$ $km^2$, and varies
184 in elevation from 2,200 m (above sea level) in mountainous regions to about 30 m in
185 alluvial plains downstream of the major watercourses and around the Lake. The
186 boundary of the catchment is almost identical to the administration boundary of
187 Jiangxi Province, which has a population of 45 million (in 2012). Land use in the
188 catchment consists of forest (46%), shrub land (25%), crop land (25%) and small
189 areas of pasture, urban centers and open water (Ye et al., 2011). The soils in the
190 catchment were classified by Ye et al. (2011) according to the Genetic Soil
191 Classification of China. Eight major soil types are identified as: red soil (43%), latosol
192 (23%), paddy soil (21%), yellow soil (7%), alluvial soil (3%), purplish soil (1.5%),
193 yellow-brown soil (1%) and limestone soil (0.5%). Physical properties of the soils
194 were obtained from a soil survey by Shi et al. (2004), with total porosity ranging from
195 0.41 to 0.52, field capacity from 0.32 to 0.36, and saturated hydraulic conductivity
196 varying from 0.14 to 0.97 m/d.

197

198 The Poyang Lake catchment has a subtropical, monsoon climate. Climate data,

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199 covering a 49-year observation period from the 1960s, are available from 14
200 meteorological stations in the catchment. Annual rainfall is 1654 mm, of which 55%
201 occurs in March to June. Temperatures are highly seasonal, with June-August average
202 of 27.3°C and December-February average of 7.1°C, and annual average of 17.6°C.
203 The annual potential evapotranspiration is 1049 mm/year, with the highest rates
204 occurring during May to September.
205
206 Poyang Lake receives inflows from five major rivers (Xiushui, Ganjiang, Fuhe,
207 Xinjiang and Raohe) within the catchment, and discharges to the Yangtze River at
208 Hukou (Fig. 1). Figure 2 shows the monthly average runoff depth for the five rivers,
209 and the monthly average Lake water level variation at Xingzi gauging station, which
210 is situated in the northern arm of the Lake at about 39 km from the Yangtze River.
211 Catchment runoff varies considerably throughout the year, with mean monthly runoff
212 varying between $0.34\times10^8$ and $16.4\times10^8$ $m^3/d$, based on average values for the period
213 1953 to 2010. Both stream flows and Lake water levels demonstrate a distinct
214 seasonal variation, with a time lag in the peak water level relative to the maximum
215 catchment runoff. The catchment runoff starts to increase in February and peaks in
216 June, while the Lake water level starts to rise in February and peaks in July, before
217 dropping some 8.8 m (on average) to minimum values during December and January.
218 Accordingly, the Lake area varies significantly. The historical maximum and
219 minimum are about 4553 $km^2$ and 244 $km^2$, respectively (Tan et al., 2013).
220

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221 **2.2 Hydrological data**

222

223 Observed daily stream flows at seven gauging stations are available for the period of
224 1950-2010 (Fig. 1 and Table 1). For sub-catchments of the Ganjiang, Fuhe and
225 Xinjiang Rivers, only one gauging station at each main stream was selected to
226 represent River discharge. For sub-catchments of the Xiushui and Raohe Rivers,
227 gauging stations at tributaries (Wanjiabu station for the Xiushui River, Hushan and
228 Dufengken stations for the Raohe River) were included to account for the runoff
229 contributions to the main stream (Table 1). River gauging stations are upstream of the
230 Lake's maximum inundated area, and hence Lake surface expansion does impact on
231 these recordings. The total drainage area of these gauging stations is 137,143 km2,
232 leaving an area of 25,082 $km^2$ (15.5% of the whole catchment area, including the
233 Lake surface) that is not gauged. Lake discharge is monitored at Hukou gauging
234 station, which has a drainage area of 162,225 $km^2$.

235

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

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243

244 **2.3 Mann–Kendall Test**

245

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

252 $$d_k = \sum_{i=1}^{k} n_i \qquad (2 \le k \le n) \tag{1}$$

253

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

256 $$E(d_k) = k(k-1)/4 \tag{2}$$

257 $$\mathrm{var}(d_k) = k(k-1)(2k+5)/72 \tag{3}$$

258

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

261 $$UF(d_k) = \frac{[d_k - E(d_k)]}{\sqrt{\mathrm{var}(d_k)}} \qquad (k = 1,2,3\cdots,n) \tag{4}$$

262

263 Where $UF(d_k)$ is the forward sequence, and the backward sequence $UB(d_k)$ is

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264 calculated using the same equation but with a reversed series of data. The null
265 hypothesis is rejected when any of the points in $UF_k$ exceeds the confidence interval
266 ±1.96. An increasing or decreasing trend is indicated at the 5% significance level.
267 Because the presence of serial correlation can influence the identification of trends
268 (Yue et al., 2003; Khaliq et al., 2009), it is necessary to do autocorrelation (serial
269 correlation) analysis before the trend test.
270
271 The test statistics used here also enable the detection of the approximate time of trend
272 occurrence by locating the intersection of the forward and backward curves of the test
273 statistic. An intersection point of $UF(d_k)$ and $UB(d_k)$ located within the confidence
274 interval indicates the beginning of a step-change point (Zhang et al., 2011).
275
276 **2.4 Simulation Model**
277
278 The distinct seasonal variation in Lake water levels results in not only considerable
279 expansion and retraction of the Lake surface, but also complex flow patterns. In
280 January and February, a stage difference of up to 6 m may develop in the Lake from
281 upstream in the south (e.g. Kangshan station) to downstream in the north (e.g. Xingzi
282 station), producing conditions in which hydrodynamic processes need to be
283 considered in modelling Lake behavior. In response to this, Li et al. (2014) recently
284 constructed a physically-based mathematical model for the Lake using the MIKE 21
285 code (DHI, 2007). The model covers an area of 3124 $km^2$, which was determined by

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286 examining the historic Lake surface under high water levels. The model utilizes a
287 Digital Elevation Model (DEM) of the study area that was generated using data
288 provided by Jiangxi Hydrological Bureau, surveyed in 1998 and updated with new
289 data obtained in 2000.
290
291 Given the extensive area (about 3000 km2) of periodic inundation, a proportion of the
292 catchment (2%) fluctuates between regions of surface runoff and Lake storage. For
293 this periodically inundated area, an option in MIKE 21 was used to account for
294 incidental rainfall at all model elements, whereas evaporation applied only to the
295 permanently wet elements. For dry elements, it was assumed that all rainfall was
296 transformed to surface runoff (Li et al., 2014). Daily catchment inflows from the five
297 main rivers were specified as upstream boundary conditions in the Lake model.
298 Runoff from the ungauged catchment area was calculated using a simple linear
299 extrapolation of the gauged runoff, and was added to the gauged inflows (see Section
300 3.3 for more detail). The connection of the Lake to the Yangtze River was simulated
301 by specifying the downstream boundary water levels as those observed at Hukou. The
302 model used a variable spatial discretisation of 70 to 1500 m, resulting in a total of
303 20,450 triangular elements. The time step was set to 5 s to limit the
304 Courant-Friedrich-Levy number (DHI 2007) for a stable solution. Outputs from the
305 model included nodal water levels and velocities, and the outflows at Hukou.
306
307 Li et al. (2014) calibrated and validated the model against observed water levels for

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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 0.80-0.98, suggesting a satisfactory accuracy (Li et al., 2014). The modelled 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

Figure 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 1980's and 1990's, and were significantly lower during 2001-2010. Figure 5 highlights variability in seasonal water-level variations across different decades, based on decadal averages of the daily

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water levels at Xingzi station, with comparison to the long-term condition. The water levels in July–August during the 1990's, and in October–November during the 2000's deviated considerably from the reference period. The high mid-year water levels for the 1990's 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 2000's 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 2000's. 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.

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352 The M-K test indicates a decreasing trend in catchment inflows before 1993 ($UF$<0),
353 while an increasing trend occurs thereafter.
354
355 The annual variations in outflow show largely similar trends to those of the catchment
356 inflows, both of which have clearly decreased during the last decade (Fig. 6b).
357 However, the difference between annual outflows and inflows is distinctly different
358 (Fig.6c), showing an increasing monotonic trend during the study period that is
359 significant after 1999, when $UF$ exceeds the critical value of 1.96.
360
361 Quantitative analyses were performed by considering the Lake's water balance, which
362 can be expressed as:
363 $$Q = R_1 + R_2 + R_G + \Delta V \quad (5)$$
364
365 Where, $Q$ is the outflow at Hukou, $R_1$ is the gauged runoff (Fig. 1 and Table 1), $R_2$ is
366 the ungauged runoff, $R_G$ is groundwater net inflow to the Lake, and $\Delta V$ is the change
367 in Lake volume (positive for volume reductions). In equation (5), observation data are
368 available for only $Q$ and $R_1$. According to Feng et al. (2011), $R_G$ is only 1.3% of the
369 total water balance, and hence is neglected in the current analysis. We combine $R_2$ and
370 $\Delta V$ and refer to this as the unknown water balance component $R_X$.
371
372 Long-term (1953-2010) averages of $Q$ and $R_1$ are $1489\times10^8$ $m^3$/year and $1228\times10^8$
373 $m^3$/year, respectively, with the difference of $261\times10^8$ $m^3$/year (21.3% of the inflow)

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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 ($1151\times10^8$ $m^3$/annum) 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.

Table 2 also reveals that the lowest decadal-average water level of 12.74 m, and corresponding Lake volume of $35\times10^8$ $m^3$ (using the Lake storage curve of Tan et al. (2013)), occurred during 2001-2010. This is a reduction of $11\times10^8$ $m^3$ (23.9%) compared to the average for 1971-2000, and a reduction of $14\times10^8$ $m^3$ (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.

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### 3.3 Hydrodynamic modeling assessment

Hydrodynamic modeling was undertaken to further explore the relative contributions of the catchment and the Yangtze River to 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 $\Delta V$ can be regarded as nearly zero, $R_2$ is $261\times10^8$ $m^3$/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,

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418 daily variations in Lake inflows are averages for the period 2001-2010. $R_2$ was
419 calculated using equation (5) for 2001-2010 ($\Delta V$ was estimated using the Lake storage
420 curve and the water levels at Xingzi). The downstream boundary condition in S2 is
421 the same as in S1. Lake inflows ($R_1$ and $R_2$) in S3 are the same as in S1, and the
422 downstream boundary condition represents average daily water levels at Hukou from
423 the observation period 2001-2010.
424
425 Model results for the S1 case were compared with water level observations (averages
426 from 1953-2010) at Xingzi, Duchang and Kangshan stations (Fig.7a), producing
427 Nash–Sutcliffe efficiencies of 0.998, 0.973 and 0.872, respectively. The model results
428 demonstrate a better agreement during high water levels than during low water levels.
429 The reason was that the complex Lake bathymetry and the interactions between
430 wetlands and the Lake storage may exert more influence on the prediction of low
431 water levels than high water levels (Li et al., 2014). Nevertheless, the model is
432 generally capable of capturing the rising and recession periods of water levels with
433 satisfactory agreement. It is also noted that the model's agreement with observations
434 reduces in the upstream direction, as expected given that the water level at Hukou is
435 assigned observed values. Model results for the three scenarios are also compared in
436 Fig. 7(b), 7(c) and 7(d). The model predictions for S3 are the closest to the observed
437 values for the respective periods of averaging, especially during Lake water level
438 recession. This indicates that the Lake water levels are more sensitive to the River
439 stage during the recession period, compared to the rising period. That is, the Yangtze

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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), 7(c) and 7(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) analysed 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 $41\times10^8$ $m^3$/year and $52\times10^8$ $m^3$/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 $57\times10^8$ $m^3$/year for Lake outflow during 2000-2009, in agreement with the findings of the current study.

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463 The dryness of Poyang Lake, in terms of reductions in Lake volume and Lake surface
464 area, was quantified for the 2000's. The Lake volume was found to be lower on
465 average by $14\times10^8$ $m^3$ for the period 2001-2010, compared to that for 1991-2000. The
466 reduction in Lake volume was the underlying cause of the high ratio of the difference
467 between the outflow to the inflow. Loss of water storage in the Lake also resulted in
468 shrinkage of the annual average surface area by 226 $km^2$, compared to that for
469 1991-2000. Liu et al. (2013) examined the change in Lake surface area using Landsat
470 images for the period 1973-2011, and found that the Lake area started to decrease
471 after 1998, dropping abruptly by some 311.6 $km^2$ in 2006, and remaining a reduced
472 extent since then. Feng et al. (2012) obtained the inundation area for Poyang Lake
473 using 250-m MODIS images for 2000-2010, and found that the inundation area varies
474 significantly at the inter-annual scale. A total reduction of 302 $km^2$ in inundation area
475 was found for the above period.

476

477 This work builds on previous studies by compiling extensive hydrological data and
478 using these to quantify the severity of Poyang Lake drought for the decade of 2000's,
479 in terms of the changes in Lake volume and area relative to previous decades. It is the
480 first study to employ a physically-based hydrodynamic model to quantify the relative
481 significance of various attributes of the Lake catchment and Yangtze River connection
482 to the Lake hydrology. It was found that the Yangtze River drainage effects had a
483 much greater influence on the seasonal (September-October) dryness of the Lake,

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484 compared to the local catchment. Ye et al. (2013) suggest that, although human
485 activities in the catchment may reduce catchment discharge, climate variables are the
486 dominant factors affecting intra-annual variations in catchment discharge. Model
487 simulations in Ye et al. (2011) indicate that under future climate conditions, monthly
488 catchment discharge will change, i.e. more catchment discharge in wet seasons and
489 less discharge in dry seasons, resulting in a possible increase in the frequency and
490 severity of flooding and droughts in the Lake. Considering the outcomes of this study,
491 the seasonal dryness of the Lake may be further worsened in the future with more
492 dams to be constructed in the upper reach of the Yangtze River.
493
494 Uncertainties still exist with regard to the simulation of Poyang Lake and its
495 catchment. For example, the calculation of runoff from ungauged regions of the
496 catchment is only approximate. Additional hydrological measurements and modelling
497 are needed to simulate the rainfall-runoff processes across the entire Lake catchment,
498 paying particular attention to wetland hydrology and groundwater dynamics. An
499 improved water budget analysis may be achieved by accounting for components of
500 the catchment's water balance that are presently not well constrained, such as the
501 ungauged areas of the catchment, the areas of intermittent inundation, and the system
502 of aquifers underling the Poyang Lake catchment. Further modelling would be
503 enhanced by coupling catchment simulation models with the existing hydrodynamic
504 model. At this stage, data are inadequate to support such a modelling strategy, and
505 hence, further field investigations are warranted as the first priority.

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506

507 **5. Conclusions**

508

509 This study demonstrates that Poyang Lake water levels were generally lower in the
510 last decade than the long-term average condition, in agreement with previous studies.
511 In particular, Lake water levels were significantly lower during autumn recession
512 periods. The average Lake size and volume reduced during 2001-2010 by 154 $km^2$
513 and $11\times10^8$ $m^3$, respectively, compared to the preceding period (1970-2000). Model
514 simulations explored the drainage effect and revealed that, compared to climate
515 variability impacts on the catchment, modifications to Yangtze River flows (e.g. from
516 TGD) have had a much greater influence on the seasonal (September-October)
517 dryness of the Lake. Yangtze River effects on the Lake are attenuated with distance
518 from the River, but nonetheless propagate to the Lake's upstream limit.

519

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

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528 It is anticipated that more dams will be built in the upper reach of the Yangtze River in
529 the future. The operation of these dams in combination with the TGD will likely lower
530 the River stage further during particular times of the year (e.g. September-October),
531 which is expected to worsen the autumn dryness of the Lake. Consideration should be
532 given to the regulation of Yangtze River flow, given that management within the local
533 catchment will probably have only a minor influence on the drying effect.
534 Alternatively, the proposal of a control structure at the Lake outlet to manage dry
535 season discharge could be an effective way to balance the operation of reservoirs in
536 the upper Yangtze River and the water shortage of Poyang Lake, albeit it may change
537 the hydrological and hydrodynamic processes of the Lake, and subsequently affect the
538 water quality, wetland vegetation and the migration of aquatic species. The control of
539 Lake-River interaction may also impact the flow regimes of the Yangtze River. These
540 aspects require substantial further research to protect against further degradation of
541 Poyang Lake.
542
543 **Acknowledgements**
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548
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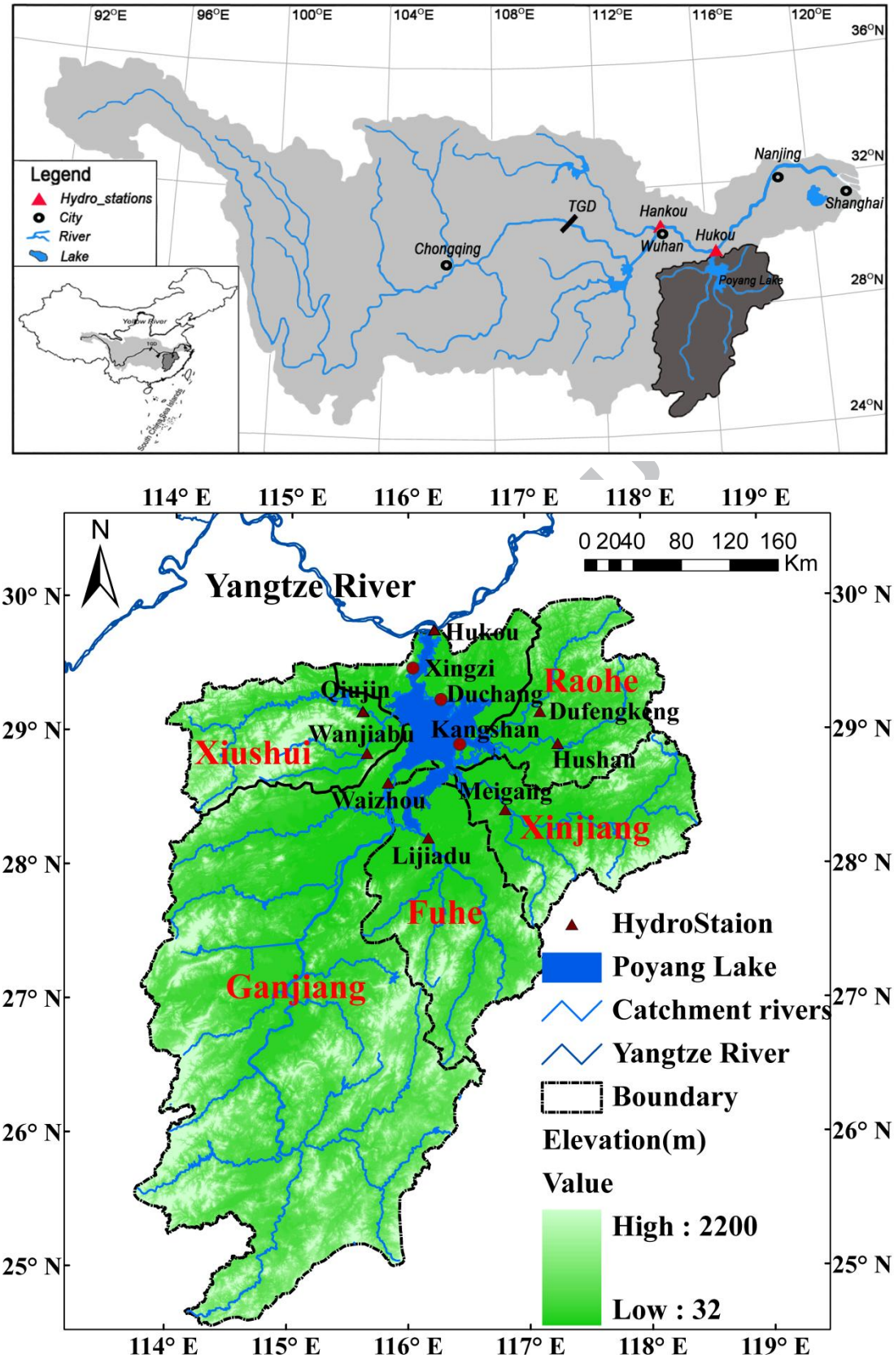



Figure 1. The Poyang Lake catchment and its location in the Yangtze River. Hukou is the gauging station located at the junction of the Yangtze River and Poyang Lake's

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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.

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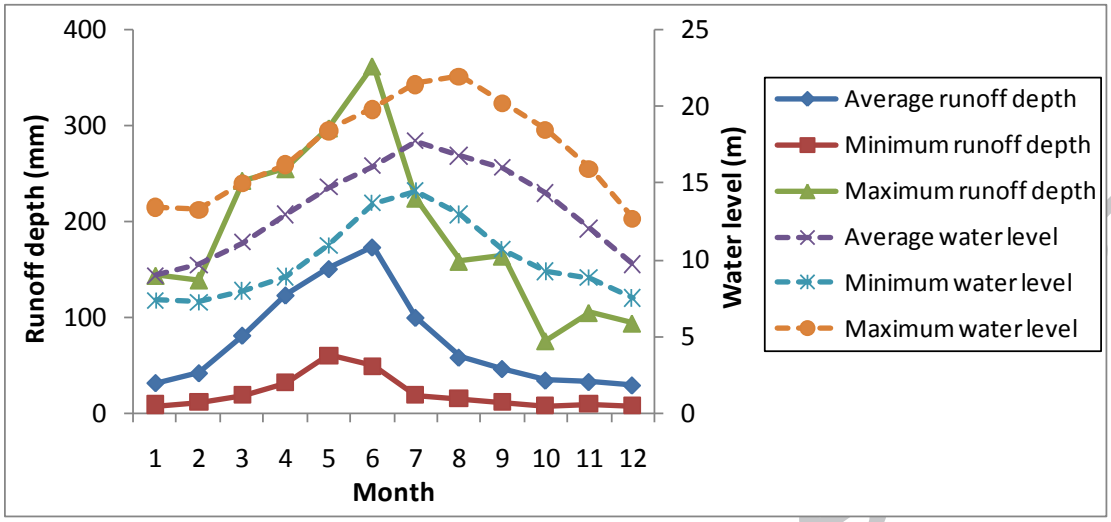



Figure 2. Seasonal variations in catchment runoff depth and Lake water level. The runoff is the sum of gauged flows from the five main rivers in the catchment. Lake water levels are for Xingzi station. Runoff depths and water levels were calculated using 1953-2010 observations.

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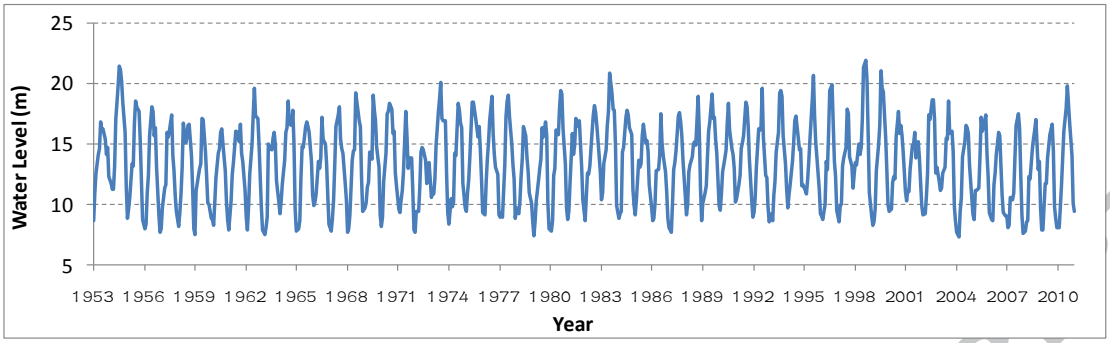



Figure 3. Variation of monthly average water level at Xingzi for 1953-2010.

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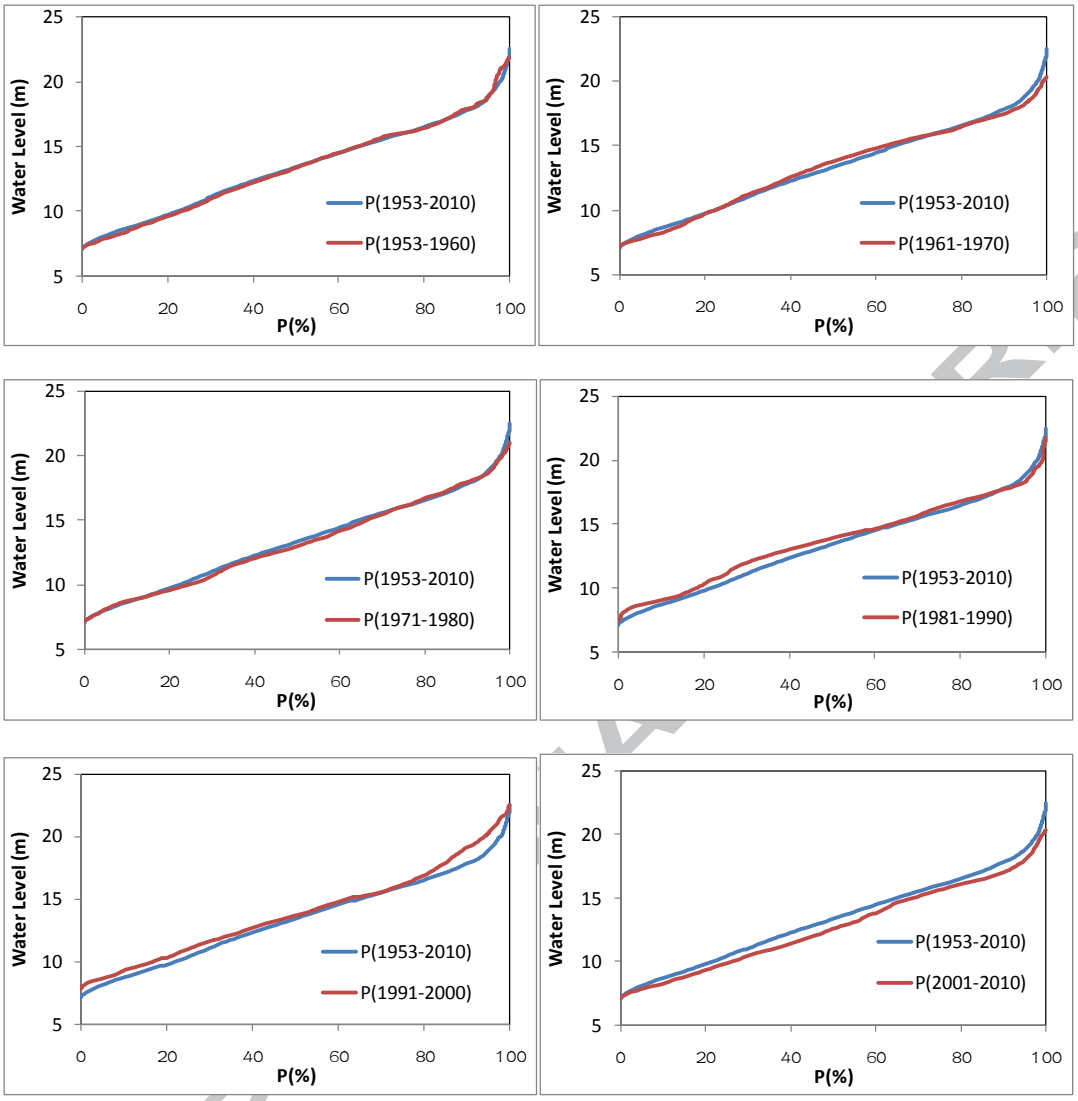



Figure 4. Cumulative probabilities of water levels at Xingzi for different decades, compared to the reference period of 1953-2010.

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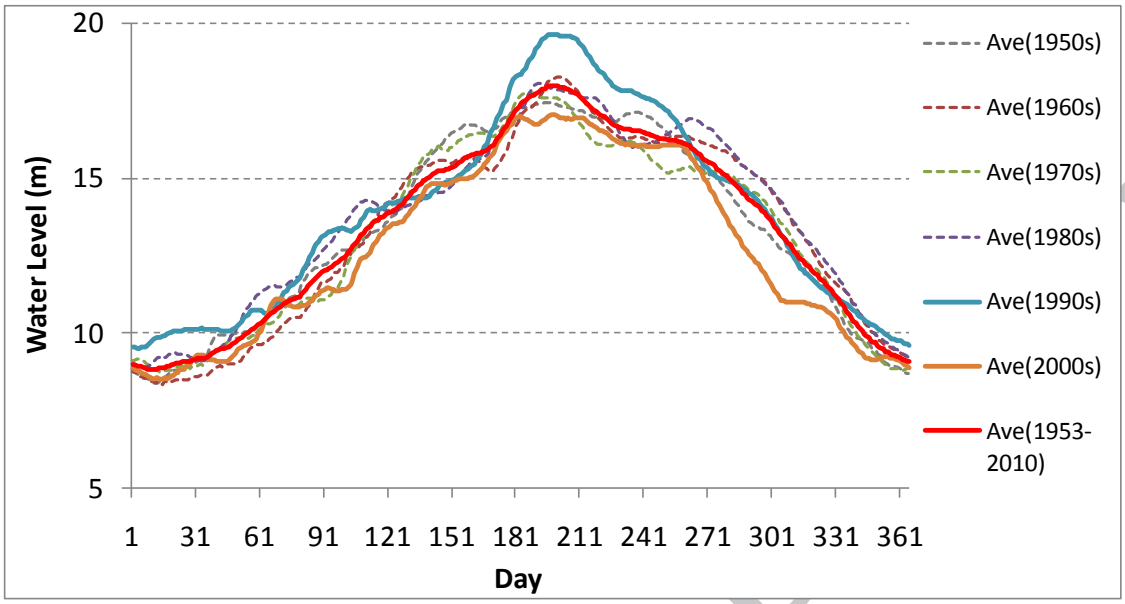
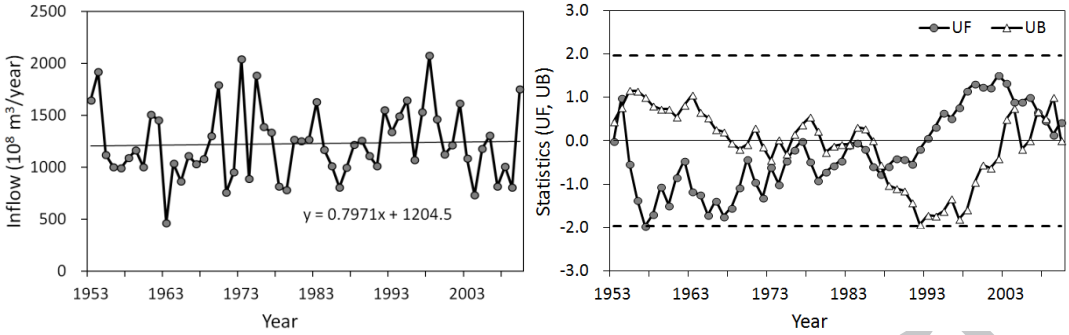



Figure 5. Decadal averages of seasonal variations in water levels at Xingzi station.

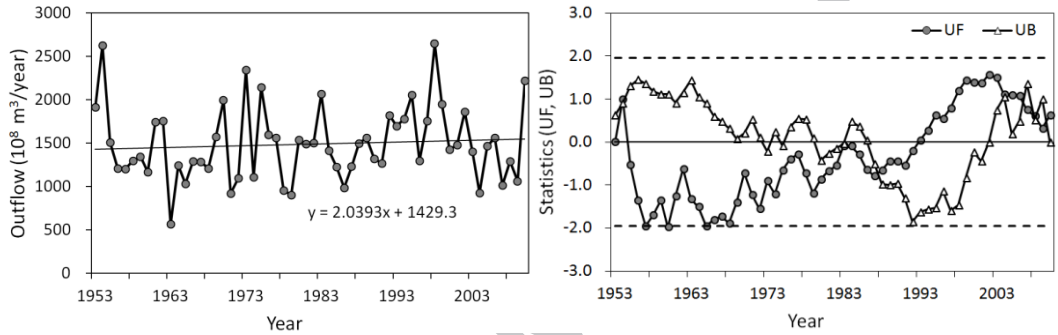
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(a) Gauged inflow




(b) Gauged outflow at Hukou




(c) Difference between outflow and inflow

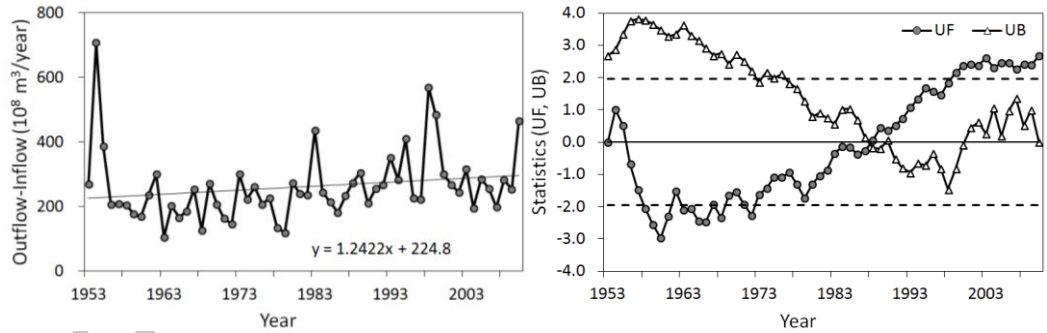



Figure 6. Variations of annual flow rates (left figures) and corresponded trend analyses using M-K testing (right figures): (a) gauged catchment inflow, (b) outflow at Hukou, and (c) difference between outflow and inflow. The *UF* and *UB* in the right figures are the calculated statistics of M-K testing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

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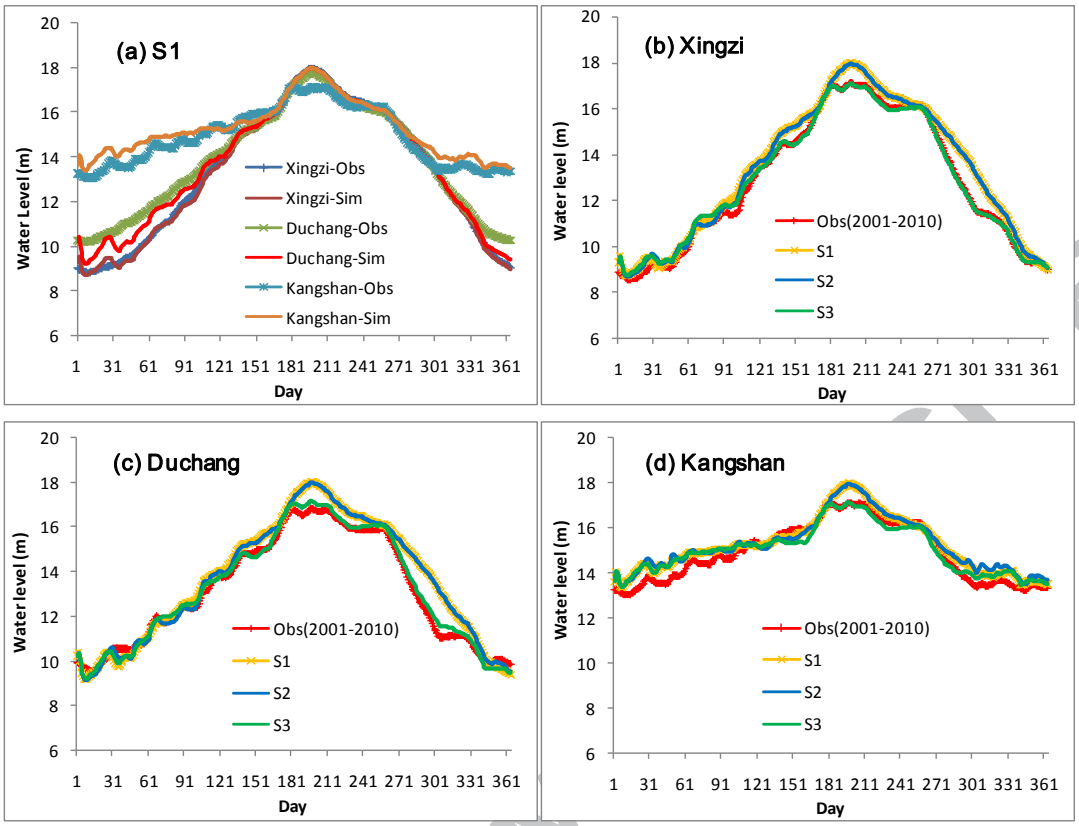



Figure 7. Comparison of simulated (Sim) and observed (Obs) water levels for three scenarios (S1, S2, S3): (a) Comparison of Xingzi, Duchang and Kangshan stations for S1; (b) Comparison of S1, S2 and S3 at Xingzi station; (c) Comparison of S1, S2 and S3 at Duchang station; (d) Comparison of S1, S2 and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

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

| 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[2] | Lake | (116.03°,29.45°) | - | - |
| Duchang[2] | Lake | (116.18°,29.27°) | - | - |
| Kangshan[2] | Lake | (116.42°,28.88°) | - | - |

659 [1]Data were obtained from the Hydrological Bureau of Jiangxi Province and the
660 Hydrological Bureau of the Yangtze River Water Resources Commission of the

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661 Ministry of Water Resources of China;

662 [2]Lake water level gauging station

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684 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 |

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687 Highlights
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689 - Interactions between lake, catchment and Yangtze River were investigated
690 - Yangtze River effect was the primary factor affecting recession period of Poyang
691 Lake
692 - Modifications to the River from the Three Gorges Dam caused seasonal dryness
693 of the Lake
694 - Hydraulic engineering between the Lake and River would resolve water supply
695 crisis

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