Examining the influence of river–lake interaction on the drought and water resources in the Poyang Lake basin

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\textbf{S U M M A R Y}

In recent years, the Poyang Lake basin is in a prolonged drought which has placed immense pressure on the water resources utilization. In this paper, we explore the spatial and temporal distributions of extreme droughts in the Poyang Lake basin by using the methods of SPI (Standardized Precipitation Index) and EOF (Empirical Orthogonal Function) for the period of 1956–2009, which are influenced by regional precipitation anomalies and river–lake interaction due to water impounding of the Three Gorges Dam (TGD). The results show that: (1) the Poyang Lake basin experienced six extreme droughts during the past 60 years, which lead to decreases in streamflow from five tributary rivers down to the Poyang Lake. The droughts in the 1960s and the 2000s were the most serious ones. However, there was an increasing trend of streamflow in the upper and middle Yangtze in the 1960s, and a decreasing trend appeared in the 2000s. The decline of streamflow in the upper Yangtze reaches has lowered the water level of lower Yangtze River which has caused more outflow from the Poyang Lake to the Yangtze River; (2) the operation of the Three Gorges Dam (TGD) has altered the seasonal pattern of flow regimes in the Poyang Lake and significantly reduced the water level in the lower Yangtze River during the TGD impounding period from late September to early November; and (3) the conjunction of extreme droughts in the Poyang Lake and the upper Yangtze reaches coincided with the impounding of the TGD is the main cause of the low water level in the Poyang Lake. Although the impact of the recent droughts in the Poyang Lake and upper Yangtze reaches has played a crucial role in the low water level of Poyang Lake, more attention should be paid to its sensitivity to the influence of the large dam–induced changes in the interaction between river and lake, particularly during impounding periods.

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1. Introduction

“Drought” as a natural hazard is mainly caused by large-scale climatic variability while water scarcity is more a result of human influence. Making the distinction between them is not trivial because they often occur simultaneously (Van Loon and Van Lanen, 2013). Evaluation of drought conditions in a particular area is the key step for planning water resources. Numerous drought indices have been developed to monitor droughts (Rossi et al., 2007), including the worldwide used indices of the Standardized Precipitation Index (SPI, e.g. Mckee et al., 1993; Zhang et al., 2012; Portela et al., 2015), the Normalised Flow Index (NFI, e.g. Gosling, 2014), the Reconnaissance Drought Index (RDI, e.g. Takiris and Vangelis, 2005; Rahmat et al., 2015), and the Palmer Drought Severity Index (PDSI, e.g. Palmer, 1965). These indices have been developed to evaluate the water supply deficit in relation to the time duration of precipitation shortage. However, the characteristics of drought in different climate zones may be different. A standardized index is often used to compare drought conditions in different areas. For example, the Standardized Precipitation Index (SPI) is one of the most powerful indices which can be
computed on different time scales (Bordi and Sutera, 2007). The SPI has been used in many studies (e.g., Hayes et al., 1999; Bordi et al., 2004; Chen et al., 2009; Zhang et al., 2011b) and it has proved to be a useful tool in the estimation of the intensity and duration of drought events (Bordi et al., 2004). SPI was also applied to examine the effects of large dam on hydrological droughts by comparing the drought index before and after the dam construction (Cancelliere et al., 1998; López-Moreno et al., 2009; Lorenzo-Lacruz et al., 2010).

Poyang Lake, China's largest freshwater lake, is located on the southern bank of the lower Yangtze River. The water level of the Poyang Lake depends on watershed runoff from the five tributary river basins and the water exchanges with the Yangtze River (Li et al., 2015a; Zhang et al., 2014). It varies greatly both in area and volume with seasonal and inter-annual changes. The lake level is elevated to the extent that all floodplains are inundated, thus forming a vast lake. In the drier season, lake level declines and lake water recedes into sublacustrine channels and the floodplains are exposed, resulting in the lake surface almost dwindling to a meandering line. At the moment, the Poyang Lake is effectively just a river channel (http://www.jxsl.gov.cn/).

The impact of climate variability and change on the Poyang Lake outflows, particularly on the floods, has been extensively studied (e.g., Jiang and Shi, 2003; Shankman et al., 2006; Guo et al., 2008; Zhang et al., 2011a; Zhao et al., 2010; Li et al., 2015b). Different conclusions have been drawn by previous studies which were undertaken at different time and used different methods and data. The river–lake interaction related to flood storage ability of the lake and TGD was investigated by Nakayama and Shankman. (2013a), and they pointed out that the TGD will increase flood risk during the early summer monsoon, in contrast to the original justifications for building the dam, due to complex river–lake–groundwater interactions. Hu et al. (2007) reported that basin effect (basin discharge generated by rainfall) has played a primary role influencing the water level of Poyang Lake and development of severe floods, while the Yangtze River played a complementary role of blocking outflows from the lake. Zhang et al. (2011a) also found that the occurrence of water intrusion from the Yangtze River to the Poyang Lake was heavily influenced by hydrological processes of the Poyang Lake basin. Guo et al. (2011) found that the Poyang Lake has the largest outflow to the Yangtze River and exerts a strong pressure on the mainstream during April–June, and the Yangtze River’s blocking and/or reversed flow to the Poyang Lake are the strongest during July–September.

Currently, the most severe droughts in the Poyang Lake basin have drawn people’s attention to the water resources shortage problem along the lower reaches of the Yangtze River. The lower reaches of the Yangtze River, covering eight provinces of both Central and Southern China, are usually considered to be an area with relatively abundant water resources. However, the continuous droughts in this region have changed this situation and the Poyang Lake is facing the danger of water shortage. The precipitation in this region during November 2010–May 2011 was the lowest in the past 60 years. The Poyang Lake shrank to its smallest area of 1326 km² in May 2011, reducing about two-thirds of its normal surface area of 3585 km². Meanwhile, the prolonged drought in the Yangtze River basin coincides with the water level rising of the Three Gorges Dam (TGD) from 135 to 175 m. Recently, low water levels in the drier season of the lower Yangtze River have started earlier and lasted longer, which aroused a debate over whether the TGD contributed to the decrease in water level of the Poyang Lake (Zhang et al., 2014). Some researchers suggested the TGD, along with the droughts, had caused the water level decline in the Poyang Lake in the drier season (Dai et al., 2008; Guo et al., 2011, 2012). Guo et al. (2011) reported that the influence of the TGD has resulted in less than 10% of the variation in the Yangtze River flow in most of the seasons. Dai et al. (2008) pointed out that 54% of the water flux was lost at Datong station during September 20–October 27, 2006, in comparison with the same period in 2005. It can be estimated that the impounding of TGD and the extreme drought in 2006 contributed 9% and 45% of this loss, respectively. Meanwhile, Guo et al. (2012) suggested that the impacts of large dams in the Yangtze River should alter from the previous studies in the dam-river setting to a new dam-river–lake construction. Nevertheless, Lai et al. (2014) also suggested that the effects of the TGD on downstream rivers and lakes will be intensified in the foreseeable future when many ongoing and planned large-scale dams located in the upstream tributaries in the Yangtze River, with a combined water storage capacity far larger than the TGD, will be put into operation in the near future. On the other hand, the Government of Jiangxi province situated in Poyang Lake area has stirred up another controversy by pushing to build a dam at the outlet of the Poyang Lake to prevent water from flowing into the Yangtze River. So water shortage is becoming one of the most serious problems in the Poyang Lake.

Although there are some studies about the influences of drought and TGD impounding on the lower Yangtze River (e.g. Chen et al., 2001; Dai et al., 2008; Guo et al., 2011), question like, “How do the droughts in the Poyang Lake basin together with the associated streamflow of the upper Yangtze River affect the water resources of Poyang Lake?”, has not yet been analyzed thoroughly, which is of great scientific merit in understanding the causes of current water shortage in the Poyang Lake. The scientific problems to be investigated in this paper include: (1) Are there any regularity of the extreme droughts in the Poyang Lake basin and how do they affect the water resources? (2) To what extent does the low streamflow of the Yangtze River affect the water resources in the Poyang Lake? (3) Are there any differences in the interaction of the Yangtze River and the Poyang Lake before and after the impoundment of the TGD? In this study, we attempt to address these problems based on a thorough analysis of long-term hydrological and precipitation datasets across the Yangtze River basin. This study is of importance in further understanding the impacts of the droughts coincided with the dam-induced river–lake interaction on hydrological processes of the Poyang Lake.

2. Data and methodology

2.1. Study area and data

Poyang Lake basin, located in Jiangxi province, has an area of 162,200 km², occupying 9% of the Yangtze River basin. The water balance at the Poyang Lake is mainly dominated by five main tributary rivers: Ganjiang River, Fuhe River, Xinjiang River, Raohe River and Xiushui River, and several smaller rivers (as shown in Fig. 1). In addition, inflow from the Yangtze River to the Poyang Lake also plays an important supplementary role in maintaining the water resources stability of the Poyang Lake (Hu et al., 2007). Thus, the inflow of the Poyang Lake should include two parts: the inflow from the five tributary rivers and inflow from the Yangtze River. The Hukou station is the junction of the Poyang Lake basin with the Yangtze River, and streamflow from this station is regarded as the outflow of the Poyang Lake. The highest recorded lake level at Hukou hydrological station is 22.59 m. The corresponding lake area is approximately 4500 km² with the lake volume reaching 34 billion m³. The lowest lake level at the same station is 5.90 m, and its corresponding lake area and lake volume are 146 km² and 450 million m³, or rather, 1/32 and 1/76 of the largest area and volume, respectively.

Daily mean streamflow and water level data from 16 hydrological stations during the period of 1956–2009 and 215 daily
precipitation stations (of which 83 stations are located in the Poyang Lake basin) from 1957 to 2009 in the Yangtze River basin are used in this study. A few missing precipitation data are interpolated by the average value of its adjacent stations. The sum of the five tributary rivers in the Poyang Lake River basin was chosen as the inflow to the Poyang Lake. The key hydrological stations of Cuntan, Yichang, Hankou, Jiujiang and Datong in the main Yangtze River were selected to analyze the streamflow variabilities of the Yangtze River, and the Hukou station was selected to analyze the water exchange between the Poyang Lake and the Yangtze River (Referring to Fig. 1 and Table 1 for the location and basic data of the Poyang Lake basin and the gauging stations).

2.2. Methodology

The SPI is a drought index based on the probability of an observed precipitation deficit occurring over a given prior time period (McKee et al., 1993). It is a useful tool for monitoring dry and wet periods on multiple time scales and for comparing climatic conditions of areas governed by different hydrological regimes. The assessment periods are considered to range from 1 to 36 months where the shorter time scales may represent agricultural drought and the longer time scales relate to hydrological drought. The SPI at a 24-month time scale is used in this work and it is usually considered as a hydrological drought index which can be used to monitor surface water resources, e.g., river
flows (Hayes et al., 1999). A clear and detailed description of the steps required to calculate the SPI is provided in Lloyd-Hughes and Saunders (2002). The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a standard normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997)(http://drought.mssl.ucl.ac.uk/spi.html). The gamma distribution was tested to be a good candidate probability distribution function for the precipitation amount in the Yangtze River (result not shown) and it is used for calculation of SPI in this paper. The drought is classified into four categories – mild, moderate, severe and extreme drought (Mckee et al., 1993; Chen et al., 2009). Standardized Runoff Index (SRI) is also adopted in this research to calculate the hydrologic droughts (Gosling, 2014).

To compare the drought characteristics between different drought periods in the Poyang Lake, the drought duration (D) and drought magnitude (M) are adopted in this study. The drought duration (D) can be defined as the cumulative months when a continuous drought occurs (SPI $(i)\leq -1.0$ is used at the beginning and ending of a drought and SPI $(i)\leq -2.0$ is regarded as an extreme drought event). The drought magnitude (M) is defined as:

$$M = \sum_{i=1}^{D} SPI(i)$$

where SPI$(i)$ is the SPI value, and $i$ is the sequential month of a time series of a drought (Chen et al., 2009).

To examine more details on temporal variability of hydrological time series, cumulative curve analysis is performed. The cumulative curve method was first used by Hurst (1951) to determine the storage capacity of reservoirs on the Nile River. The cumulative departure is used in this paper to detect the streamflow and water level variability in different regions for a long time.

The Empirical Orthogonal Function (EOF) method is used to analyze the main drought features of spatial and temporal variability in the Poyang Lake basin. The EOF analysis is a statistical technique that linearly transforms an original set of variables into a substantially small set of uncorrelated variables representing most of the information of the original set of variables (North, 1984; von Storch, 1995,1999). Basically, the goal of EOF analysis is to reduce the dimensionality of the original data set (Jolliffe, 2002; Wilks, 2006; Hannachi et al., 2007).

### Table 1
Characteristics of the hydrologic records of stations at the Poyang Lake River basin and the main stream of Yangtze River basin.

<table>
<thead>
<tr>
<th>River</th>
<th>Sub-basins</th>
<th>Station</th>
<th>Area ($10^4$ km$^2$)</th>
<th>Annual mean streamflow (m$^3$/s)</th>
<th>Annual mean water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poyang Lake</td>
<td>Xiushui R.</td>
<td>Qujin</td>
<td>9914</td>
<td>265</td>
<td>22.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wangjiabu</td>
<td>3548</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ganjiang R.</td>
<td>Waizhou</td>
<td>80,948</td>
<td>1986</td>
<td>18.43</td>
</tr>
<tr>
<td></td>
<td>Fuhe R.</td>
<td>Lijiaju</td>
<td>15,811</td>
<td>379</td>
<td>25.98</td>
</tr>
<tr>
<td></td>
<td>Xinjiang R.</td>
<td>Meigang</td>
<td>15,533</td>
<td>543</td>
<td>19.30</td>
</tr>
<tr>
<td></td>
<td>Bahe R.</td>
<td>Dufengkeng</td>
<td>5013</td>
<td>147</td>
<td>22.49</td>
</tr>
<tr>
<td>Lake Region</td>
<td></td>
<td>Xingzi</td>
<td>6374</td>
<td>220</td>
<td>20.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Duchang</td>
<td>13.43</td>
<td>13.43</td>
<td>13.84</td>
</tr>
<tr>
<td>Control station of Poyang Lake</td>
<td>Hukou</td>
<td></td>
<td>162,200</td>
<td>4593</td>
<td>12.77</td>
</tr>
<tr>
<td>Mainstream</td>
<td>Upper Yangtze</td>
<td>Cuntan</td>
<td>866,559</td>
<td>10,964</td>
<td>156.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yichang</td>
<td>1,010,000</td>
<td>13,752</td>
<td>42.99</td>
</tr>
<tr>
<td></td>
<td>Middle Yangtze</td>
<td>Hankou</td>
<td>1,488,036</td>
<td>22,163</td>
<td>18.97</td>
</tr>
<tr>
<td></td>
<td>Lower Yangtze</td>
<td>Jiujang</td>
<td>1,523,000</td>
<td>23,125</td>
<td>13.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Datong</td>
<td>1,705,383</td>
<td>27,876</td>
<td>8.58</td>
</tr>
</tbody>
</table>

### 3. Results

#### 3.1. The impacts of extreme droughts on the Poyang Lake’s water resources

The aspects of drought over the Poyang Lake basin during the last several decades have been evaluated by computing the SPI and SRI on a 24-month time scale using the observed monthly precipitation and runoff datasets. Fig. 2a shows the temporal...
distributions of the dryness and wetness of SPI in the Poyang Lake basin by using the EOF method. It is noted that the first principal component (PC1) explains more than 60% of the total variation of the SPI-24. The PC1 can present the long-term features of dryness and wetness in the Poyang Lake basin as a whole. The Ganjiang River basin is the biggest tributary river in the Poyang Lake basin with an area of 80,948 km$^2$, occupying 49.9% of the Poyang Lake basin. This is much greater than the second biggest tributary river, the Fuhe River basin, with an area of 15,811 km$^2$, occupying 9.8% of the Poyang Lake basin. So the SRI of Waizhou station at the control hydrological station of Ganjiang River basin might present the main hydrologic droughts of the Poyang Lake to a great extent.

![Fig. 2a](image1)

![Fig. 2b](image2)

![Fig. 2c](image3)

![Fig. 2d](image4)

![Fig. 2e](image5)

![Fig. 2f](image6)

**Fig. 3.** The amount of accumulated lake inflow and lake outflow anomalies compared to the reference period of 1956–2009 for six different extreme drought events in the Poyang Lake basin.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>D (month)</td>
<td>45</td>
<td>17</td>
<td>31</td>
<td>37</td>
<td>21</td>
</tr>
<tr>
<td>M (SPI value)</td>
<td>-172</td>
<td>-51</td>
<td>-105</td>
<td>-118</td>
<td>-60</td>
</tr>
<tr>
<td>M/D (SPI value)</td>
<td>-3.8</td>
<td>-3</td>
<td>-3.4</td>
<td>-3.2</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

Table 2: The drought characteristics for six extreme droughts in the Poyang Lake basin during the past 60 years (D, drought duration, unit: month; M, drought magnitude, unit: SPI value).
1960s and 2000s were the most severe ones, with the longest drought duration (D) records of 45 and 56 months, and the largest drought magnitude (M) of −172 and −189, respectively. The extreme droughts in the 2000s occurred during 2004/3–2005/11 and 2007/1–2009/11. As mentioned above the characteristics of droughts during the 2000s are similar to those of the 1960s in terms of the drought magnitude (M), drought duration (D) and drought intensity (M/D) (Table 2). However, there is an interval of one year between the two extreme droughts in the 2000s, while the extreme droughts occur consecutively in the 1960s.

The annual and seasonal mean inflow (the sum of the streamflow from the five tributary river basins) agrees well with the outflow (Hukou station) in the Poyang Lake basin. To reveal the difference between the inflow and outflow of the Poyang Lake during different drought periods, the accumulated inflow and outflow departures compared with the average over 1956–2009 were further analyzed (Fig. 3). It shows a decline of lake inflow and lake outflow during the six extreme drought events. The amount of accumulated decrease in the inflow of Poyang Lake is over 3 billion m$^3$ for both major droughts in the 1960s and 2000s (Fig. 3a and f). However, there are distinct dissimilarities between them. Although the amount of accumulated lake inflow anomalies in the droughts of the 2000s is somewhat similar to that of the 1960s, the amount of accumulated lake outflow anomalies in the 1960s are larger than that of the 2000s, which indicates the water remaining in the Poyang Lake during the droughts of the 2000s is less than that of the 1960s. Similar results can be found in Table 3. The much lower water level at Hukou station in October during the droughts of the 2000s led to a significant increase of the Poyang Lake outflow compared with that of the 1960s.

3.2. The impacts of Yangtze river–lake interaction on the Poyang Lake's water resources

Fig. 4 shows the percentage of monthly mean streamflow in the upper Yangtze (Yichang station), middle Yangtze (Hankou station) and Poyang Lake basin (Hukou station) to the whole Yangtze basin (Datong station). The amount of annual mean streamflow in the upper and middle Yangtze and Poyang Lake basin are 46.1%, 79.5% and 15.6% of the whole Yangtze basin, respectively, for 1957–2009. Fig. 4a indicated that the seasonal percentage of the streamflow in the upper and middle Yangtze to the whole Yangtze basin varies greatly and the higher proportion appears in July, August and September while the lower proportion occurs in February, March and April. However, the percentages of the streamflow in the Poyang Lake to the whole Yangtze basin are opposite, the higher proportion appears in spring (MAM) and lower proportion can be found in August, September and October. Fig. 4b shows the correlations between the streamflow at Yichang, Hankou and Datong stations and water level at Hukou station. Higher correlations can also be found between the streamflow in the upper Yangtze and the water level at Hukou station in summer (JJA) and autumn (SON). The correlations between the streamflow in the upper-middle Yangtze (Yichang and Hankou in Fig. 4b) and the water level at Hukou station are the highest with less seasonal variations. Similar results can be obtained for the correlation...
between the streamflow at Yichang, Hankou and Datong stations and water level at Duchang station (Fig. 4c).

The composite analysis of higher water level, middle water level and lower water level at Jiujiang station, which is very close to that of Hukou station (32 km upstream), was made to uncover the impacts of the Yangtze River on the Poyang Lake’s water resources. The highest water level at Jiujiang station appears in July and August, where the water level \( L \geq 18 \text{ m} \) in August was regarded as the highest water level year, \( L \leq 16.5 \text{ m} \) was the lowest water level year, and a level of \( 16.5 < L < 18 \text{ m} \) was a middle water level year. Statistical results during the period of 1957–2009 indicate that there are 16, 20 and 17 of the highest, middle and lowest water level years, respectively. For the higher water level years, the average water level at Jiujiang station in July and August is over 19 m and then falls slowly to a minimum water level of 9 m in January. For the lower water level years, the average water level is reduced to approximately 17 and 15 m in July and August, respectively. The averaged water level for the middle water level years is between the higher water level and lower water level from July to December (Fig. 5a). For the higher water level years at Jiujiang station, the composite monthly averaged water level at Hukou and Xingzi stations (Xingzi station is quite close to the Hukou station in the Poyang Lake) from July to December is also higher than that of lower water level years (Fig. 5b and c). Furthermore, the changing pattern of water level at Hukou and Xingzi stations are very close to that of Jiujiang station. However, there is a little difference between the composite higher water level years and lower water level years at Duchang station located in the central area of Poyang Lake, which indicates that the influences of the Yangtze River on the Poyang Lake’s water level reduce gradually with distance away from the Yangtze River (Fig. 5d).

**Fig. 6** shows the accumulated streamflow anomalies in the Poyang Lake basin and the upper and middle Yangtze River basin at Cuntan, Yichang and Hankou stations, respectively. The trends of streamflow in the upper and middle Yangtze reaches show a similar tendency: streamflow anomalies increase in the 1960s, 1980s and at the turn of the 21th century, and decrease in the 1970s, the early and middle of 1990s and the latter half of the 2000s. However, the inflow and outflow of the Poyang Lake basin are opposite to the upper Yangtze reaches in the 1960s. During the droughts of the 1960s, the inflow and outflow of the Poyang Lake decreased sharply; however, there was a marked increase in the streamflow in the upper and middle Yangtze reaches. As for the
droughts in the 2000s, the situation was completely different from that in the 1960s. The streamflow decreased obviously in the Poyang Lake and also decreased in the upper and middle Yangtze reaches. Similar results can also be found in comparison between the extreme droughts and pluvials in the Poyang Lake and in the upper and lower Yangtze reaches by using the methods of SPI and SRI (Fig. 2).

The accumulated precipitation anomalies during the droughts of the 1960s and 2000s might partly explain the difference between them (Fig. 7). Greater negative precipitation anomalies can be found both of them in the Poyang Lake basin, while in the upper and middle Yangtze, positive precipitation anomalies can be found in the 1960s and negative precipitation anomalies appear in the 2000s.

The inconsistent variation of streamflow in the Poyang Lake basin to the upper Yangtze reaches during the droughts of the 1960s increased the blocking and/or reversing flow from the Yangtze River to the Poyang Lake. During the droughts of the 1960s, the blocking and/or reversing flow lasted 181 days with the amount of water intrusion from Yangtze River to the Poyang Lake was 24.9 billion m³, and the largest monthly amount of water intrusion was detected in September 1964 with a value of over 7.1 billion m³. For the droughts of the 2000s, the blocking and/or reversing flow was only 69 days with the amount of 7.8 billion m³ water intrusion from the Yangtze River to the Poyang Lake in the years of 2007 and 2008, and almost no water intrusion from the Yangtze River to the Poyang Lake in 2009.

3.3. The impacts of TGD on the Poyang Lake’s water resources

The operation of the TGD has changed the seasonal variations of the Poyang Lake and the Yangtze River forcing. The strongest influence of the TGD on the lower Yangtze reaches occurs mainly from September to October when the TGD impounds each year. The TGD influence can be seen from the following evidence: (1) the impounding of water by the Three Gorges Projects (TGP) lasted from September 20 to October 28, 2006, which raised the water level in the front of the dam from 135 to 156 m over this period. The total impounded water in the TGD was around $1.08 \times 10^{10}$ m³ in October during the years of 2006, 2007, 2008 and 2009, respectively; and the total impounded water by TGD in October 2008 and 2009 might contribute around 20% and 31%, respectively, of the streamflow at Jiujiang station (Table 4). The impounding of the TGD caused over 3 billion m³ water flow from the Poyang Lake to the Yangtze River in October 2008 which is more than that of 1958 and 1991; (2) Cumulative probabilities of streamflow and water levels for the Poyang Lake and lower Yangtze River in October during the pre-TGD (1957–2002) and the post-TGD (2003–2009) periods demonstrate impacts of the TGD on the Poyang Lake outflow (Fig. 8).

Table 4  
Reservoir inflow and outflow of the Three Gorges Dam (TGD) in October during the period of 2006–2009 ($\Delta Q$, TGD outflow minus TGD inflow, $Q_J$ is the streamflow at Jiujiang station, $\Delta Q/Q_J$ means the impoundment of TGD account for the streamflow loss in the lower Yangtze. The reservoir inflow and outflow of the TGD data comes from: China Three Gorges Corporation, http://www.ctgpc.com.cn/).

<table>
<thead>
<tr>
<th>Year</th>
<th>Reservoir streamflow (10^8 m³)</th>
<th>Percentage $\Delta Q/Q_J$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>350</td>
<td>283</td>
</tr>
<tr>
<td>2007</td>
<td>358</td>
<td>308</td>
</tr>
<tr>
<td>2008</td>
<td>398</td>
<td>300</td>
</tr>
<tr>
<td>2009</td>
<td>330</td>
<td>222</td>
</tr>
</tbody>
</table>
for the extreme drought years ($P < 20\%$ in Fig. 8b). Moreover, the backward flow from the Yangtze River to the Poyang Lake (negative value in Fig. 8b) was found during the pre-TGD period but it disappeared for the post-TGD period. The cumulative probabilities of the water levels at the Poyang Lake (Xingzi station), outlet of the Poyang Lake (Hukou station) and the lower Yangtze (Jiujiang and Datong stations) were compared to illustrate the differences in water level between the pre-TGD and post-TGD periods. The data in Table 5 show the observed streamflow and water level of the Poyang Lake, and the simulated water level at Hukou station in October for the selected drought years. The selected years before and after TGP were with similar lake inflow and streamflow of middle and lower Yangtze River, and similar water level at Hukou, Jiujiang and Datong stations in October. The table includes observed water level, simulated water level using the observed streamflow at Datong station (Scenario-1), and the same as Scenario-1 but using the streamflow of Datong plus the impoundment of TGD (Scenario-2), along with the difference ($\Delta H$) between Scenario-2 and Scenario-1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Streamflow ($10^8$ m$^3$)</th>
<th>Water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lake inflow</td>
<td>Hukou</td>
</tr>
<tr>
<td>2007</td>
<td>27</td>
<td>166</td>
</tr>
<tr>
<td>1960</td>
<td>24</td>
<td>77</td>
</tr>
<tr>
<td>2008</td>
<td>38</td>
<td>120</td>
</tr>
<tr>
<td>2001</td>
<td>33</td>
<td>80</td>
</tr>
<tr>
<td>2009</td>
<td>22</td>
<td>46</td>
</tr>
<tr>
<td>1978</td>
<td>16</td>
<td>27</td>
</tr>
</tbody>
</table>

Fig. 8. Cumulative probabilities of streamflow and water levels for pre-TGD (1957–2002) and post-TGD (2003–2009) period in the Poyang Lake and lower Yangtze River.
Datong stations) during the post-TGD period (Fig. 8c–f) are always lower than those of the pre-TGD period; (3) the lake inflow and water level for the six drought years with similar streamflow of middle and lower Yangtze River, and similar water level at Hukou, Jiujiang and Datong stations in October represent different behaviors before and after the TGP impounding (e.g. 2007 vs. 1960, 2008 vs. 2001, 2009 vs. 1978 in Table 5). Although the amount of lake inflow in October for the post-TGD years was larger than that of the pre-TGD period, the lake level (Obs. at Hukou station in Table 5) for the post-TGP period was lower than that of the pre-TGP period due to the increased Poyang Lake outflow.

The influence of the TGD impounding on the water level of the Poyang Lake is further estimated by correlation analysis. As shown in Fig. 9, a good relationship between water level at Hukou station and streamflow at Datong station can be found during the past several decades. Therefore, the correlation between them during the recession period (from 1st August to 31st December) is adopted to reveal the impacts of the TGD impounding on the water level of Poyang Lake (Fig. 9). Fig. 10 shows the observed and simulated water levels at the outlet of Poyang Lake (Hukou station) during the recession period of 2004–2009 (Scenario-1, the water level at Hukou station with the impounding of TGD; Scenario-2, the water level at Hukou station without the impounding of TGD).
the recession period of 2004–2009 for the two scenarios with and without the TGD impounding. For Scenario-1, the water level at Hukou station with the impounding of TGD was simulated by the observed streamflow at Datong station using the relationship between the streamflow at Datong station and water level at Hukou station. For Scenario-2, the water level at Hukou station without the impounding of TGD was simulated by the reconstructed streamflow at Datong station using the same relationship. Because the distance between Datong station and TGD is approximately 1,129 km, it takes 12 days for the water flowing from TGD to Datong station (http://www.cjw.com.cn/). The reconstructed streamflow at Datong station was estimated as the total of the impounding of TGD (TGD inflow minus TGD outflow) and the streamflow of Datong with a lag of 12 days.

The reliability of the simulated results by the correlation analysis was tested by comparison of the simulated and observed water levels at Hukou station. The simulated water levels agree well with the observed water levels at Hukou for the years of 2004–2009 (Scenario-1 vs. observation in Fig. 10). The simulated water levels were quietly close to the observed water levels in October for the selected drought years before and after the TGP operation periods (Scenario-1 vs. observation in Table 5). Therefore, the correlation analysis is reliable to estimate the influence of the impounding of the TGD on the water level of the Poyang Lake. Fig. 10 shows that the simulated water levels in Scenario-2 without the impounding of TGD are higher than those of the Scenario-1 with the impounding of TGD during the period of 2006–2008. The difference of the simulated water levels between Scenarios-1 and Scenarios-2 at the outlet of Poyang Lake (Hukou station in Table 5) indicates that the water level in October declined from 0.5 m in 2007 and 2008 to 1.5 m in 2009 due to the impounding of TGD.

4. Discussions and conclusions

Severe water shortages of Poyang Lake have aroused wide concern recently and raised the possibility of the TGD being responsible for the low water level at the Poyang Lake. Despite various studies revealing the considerable effects on the water level of Poyang Lake (Dai et al., 2008; Guo et al., 2011; Lai et al., 2014), the TGD’s impact needs to be further assessed combined with the extreme droughts in the Poyang Lake basin and the upper Yangtze reaches. It remains unknown whether the shortage of water in the Poyang Lake is a trend or a regime shift, and how the TGD operation contributes it, which is of high importance for policymakers as it may lead to different decisions.

This work quantifies the extreme drought events and the TGD’s contributions to recent low water levels at the Poyang Lake by using a five-decade record of the streamflow and precipitation data in the Yangtze River basin. Continuous low water levels at the Poyang Lake in recent years are relevant to the conjunction of extreme droughts in the Poyang Lake basin and the upper Yangtze River basin. Comparison between the droughts of the Poyang Lake in the 1960s and 2000s explains how the extreme droughts affect the water resource in the Poyang Lake. Both of the droughts in the 1960s and 2000s in the Poyang Lake basin have caused an obvious decrease of streamflow from five tributary river basins to the Poyang Lake. However, the streamflow in the upper Yangtze reaches sharply decreased during the droughts of the 2000s while it increased obviously in the droughts of the 1960s compared to the period of 1957–2009. The decline of streamflow in the upper Yangtze reaches has lowered the water level in the lower Yangtze River. As an overflow lake with the seasonal characteristic pattern of taking in and sending out water, the water level in the lower Yangtze River plays a major role in the lake outflow of the Poyang Lake during the recession period. Less water flows backward into the Poyang Lake from the Yangtze River during the drought of the 2000s compared to that of the 1960s. As a result, the outflow from Poyang Lake to the Yangtze River increases greatly in the droughts of the 2000s with the amount of 195 billion m^3 compared to that of the 1960s (138 billion m^3). These results agree well with the research of Lai et al. (2014) who pointed out that the recent extremely low water levels at lower Yangtze River were mainly because of the remarkable decline in streamflow from the middle and upper Yangtze reaches resulting from precipitation changes and possible human activities by using a newly developed hydrodynamic model. Guo et al. (2008) also pointed out that the interaction between the Poyang Lake and the Yangtze River strongly affects the Poyang Lake water resources and drought potentials in the lake basin.

The TGD’s operation has altered the seasonal pattern of flow regimes and significantly reduced the water level mainly in the drought period of October when the TGD is impounding each year (Guo et al., 2012; Lai et al., 2014). This study demonstrates that the lake outflow for the post-TGP period is higher than that of pre-TGP period for the corresponding drought years before and after TGP impounding (e.g. 2007 vs. 1960, 2008 vs. 2001, and 2009 vs. 1978) although the lake inflow from the five tributaries of the watershed for the post-TGP period is less than that of the pre-TGP period. It was proven by the cumulative probabilities that the lake outflow in October for the post-TGD period was significantly larger than that of the pre-TGD period for the extremely drought years. This larger outflow from the Poyang Lake during the post-TGP period results from the decline of water levels in the lower Yangtze reaches due to the TGD impounding. The TGD impounding induced water level declines in 0.5, 0.5 and 1.5 m at Hukou station in October in 2007, 2008 and 2009, respectively, according to correlation analysis in this study. This study shows that, although the operation of TGD has altered the seasonal pattern of flow regimes in the lower Yangtze reaches, the conjunction of extreme droughts in the Poyang Lake basin and lack of rain in the upper Yangtze River basin is the main cause of the low water level in the Poyang Lake. Some researches show that groundwater also affects this hydrologic change, in particular, in drought seasons and after construction of TGD (Dai et al., 2010; Nakayama and Shankman, 2013b).

With more and more big dams have been and are being built in China and other countries, dams have major impacts on river hydrology and produce a hydrologic regime differing significantly from the pre-impoundment natural flow regime. Interaction between large rivers and reservoirs as well as natural lakes directly connecting to the rivers is an issue of international significance. For example, Al-Faraj and Scholz (2014) found that the upstream dams and large-scale water withdrawal have made great impacts on seasonal river flow regimes for the downstream countries in West Asia. Peters and Buttle (2010) also pointed out that the strength of the relationships between the Lake Athabasca and Peace River, Canada has been significantly changed because the runoff from the Peace River headwaters has been stored in the man-made Williston Lake since 1968. The estimated average duration of obstruction was shortened more than two weeks and reverse flow volume was reduced largely under a regulated regime compared to the simulated natural flow. Therefore, the research methods of this paper might be applied for the above mentioned areas and other relevant areas. The results of this study also call for more attention on the conjunction of dam impounding and abnormal climate for a river regime.

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References


