

Hydroclimatological influences on recently increased droughts  
in China's largest freshwater lake

Yuanbo Liu<sup>\*</sup>, Guiping Wu

Nanjing Institute of Geography & Limnology

Chinese Academy of Sciences

73# East Beijing Road, Nanjing 210008, China

Email: ybliu@niglas.ac.cn, yb218@yahoo.com

## **Abstract**

Lake droughts are the consequences of climatic, hydrologic and anthropogenic influences. Quantification of the droughts and clarification of contributions from the individual influences are essential for understanding drought features and their causation structure, which is highly valuable for policymakers to make effective adaption, especially under the changing climate situations. This study examines Poyang Lake, the China's largest freshwater lake, which has been undergoing drastic hydrological alternation in recent decade. Standardized lake stage is used to identify and quantify the lake droughts, and hydroclimatic contributions are determined with water budget analysis, in which absolute deficiency is defined in reference to normal hydrologic condition. Our analyses demonstrate that in the recent decade the lake droughts worsened in terms of duration, frequency, intensity and severity. Hydroclimatic contributions to each individual drought varied from one to another and the overall contribution to the decadal lake droughts came from decreased inflow (46%), increased outflow (28%), and reduced precipitation (17%) and increased evapotranspiration (9%) at the lake region. In the decreased inflow, 71% resulted from reduced precipitation and 29% from increased evapotranspiration over the Poyang Lake Basin. The increased outflow was attributable to the weakened blocking effects of the Yangtze River, in which the Three Gorges Dam (TGD) established upstream contributed less to the droughts. The TGD impoundments were not responsible for the increased drought events, but they may have intensified the droughts and changed the frequency of classified droughts. However, the TGD contribution was limited in

45 comparison with the hydroclimatic influences. Hence, the recently increased droughts  
were the hydroclimatic consequences, with less important contribution from  
anthropogenic influences. The findings provide an example of intensified lake  
droughts, and offer an insightful view into lake droughts under the hydroclimatic and  
anthropogenic influences. It should be valuable for improving our understanding of  
50 lake droughts, and for promoting effective climate adaptation and water resources  
management practices.

**Keywords:** droughts, climate change, hydroclimatology, freshwater lake, water  
resources management

## 55 1. Introduction

A drought is a temporary lack of water caused by abnormal climate or  
environmental influences, among other factors (*Kallis, 2008; Mishra and Singh, 2010;*  
*and references therein*). There are meteorological droughts (abnormal precipitation  
deficits), hydrological droughts (abnormal streamflow, groundwater, or lake deficits),  
60 agricultural droughts (abnormal soil moisture deficits), ecological droughts (abnormal  
water deficits causing stress on ecosystems), and socio-economic droughts (abnormal  
failures of water supply to meet economic and social demands) (*Tallaksen and van*  
*Lanen, 2004; Kallis, 2008; Mishra and Singh, 2010*). The drought phenomena may  
have different temporal features and causation structure (*Kallis, 2008; Mishra and*  
65 *Singh, 2010*). It is anticipated that droughts would likely increase owing to global  
climate change (*Kallis, 2008; Mishra and Singh, 2010*).

Hydrological droughts occur when land water decreases significantly below its normal conditions, represented by low water levels in streams, lakes, reservoirs and groundwater as well (*Nalbantis and Tsakiris, 2009; Keskin and Sorman, 2010*).

70 Streamflow droughts may occur with basin-scale precipitation deficiency and/or excessive evapotranspiration (*Zelenhasic and Salvai, 1987; Tallaksen et al., 1997; Kingston et al., 2013*). In addition to local precipitation and evaporation, lake droughts involve other hydrological components, including inflows from streams surrounding the lake and outflows out of the lake. Hence, lake droughts can be more  
75 complicated than streamflow droughts in causation structure. Furthermore, both inflows and outflows may be affected by human activities, for example, groundwater pumping, reservoir construction, or land cover change (*Wilcox et al., 2010*). Therefore, lake droughts are the consequences of combined climatic, hydrologic and anthropogenic influences. In a disciplinary sense, in contrast to floods that have been  
80 given a great deal of attention in hydrology, droughts are not yet comprehensively understood (*Kallis, 2008; Mishra and Singh, 2011*). Quantification of lake droughts and clarification of contributions from individual influences are essential for understanding drought features and their causation structure, which is highly valuable for policymakers to make effective adaption, especially under the changing climate  
85 situations. Place-based drought analysis is a starting point towards integrated theories of drought (*Kallis, 2008*).

Poyang Lake is the China's largest freshwater lake, which has been undergoing drastic hydrological alterations in recent decade (*Jiao, 2009; Finlayson et al., 2010*;



*Hervé et al.*, 2011; *Liu et al.*, 2013; *Zhang et al.*, 2014). The lake is located at the south bank of the Yangtze River, which is a humid monsoon climatic region. Although the region historically experiences significant floods (*Shankman and Liang*, 2003; *Shankman et al.*, 2006), severe lake droughts have occurred frequently in the recent decade, resulting in tremendous hydrological, biological, ecological and economic consequences (*Feng et al.*, 2012; *Environment News Service*, 2012; *Wu and Liu*, 2014). Because the lake is the primary part of the well-known Poyang Lake Wetland and the lake region serves as an important food base for China, the frequently occurred lake droughts have also received increasing international attention (*Jiao*, 2009; *Finlayson et al.*, 2010; *Liu et al.*, 2011; *Environment News Service*, 2012; *The Ramsar Convention*, 2012; *Zhang et al.*, 2012, 2014).

Since lake droughts usually exhibit as an abnormal decline in lake stage or lake size, a number of studies documented the decline feature in Poyang Lake and its controlling factors (*Guo et al.*, 2012; *Zhang et al.*, 2012; *Liu et al.*, 2013; *Lai et al.*, 2014a; *Zhang et al.*, 2014). *Feng et al.* (2012) used 250-m satellite images and reported that the lake size had a decreasing trend between 2000 and 2010. *Liu et al.* (2013) revealed an abrupt decrease in the lake size in 2006, dominant in October and November. *Zhang et al.* (2014) demonstrated that the lake stage fell to the lowest during the 2000s compared to previous decades, in particular significantly lower in autumn recession periods. Since Poyang Lake receives inflows from its surrounding basin and discharges into the Yangtze River via a narrow outlet at the Hukou (Figure 1), the strong lake-river interaction makes it complex to separate relative impacts of

the inflow and outflow on the lake stage (*Hu et al.*, 2007; *Lai et al.*, 2014a). Zhang et al. (2014) employed a hydrodynamic model for Poyang Lake for the separation and declared that the lake decline in the 2000s was primarily ascribed to the weakened blocking effect of the Yangtze River. Compared to climate variability on the lake basin, modifications to the Yangtze River flows have had a much greater influence on the seasonal (September-October) dryness of the lake (*Zhang et al.*, 2014). The modification was largely attributable to the operation of the Three Gorges Dam (TGD), established upstream of the Yangtze River in 2003. Water impoundments of the TGD incurred water level drops with an average estimate of 2 m at the outlet of Poyang Lake in mid-September to November for 2003-2008 (*Guo et al.* 2012; *Zhang et al.* 2012). Alternatively, *Lai et al.* (2013) developed a hydrodynamic model for the middle Yangtze River region (CHAM-Yangtze), in which coupled both Poyang Lake and the Yangtze River to account for the lake-river interactions explicitly. They demonstrated that the lake stage was more sensitive to the alternation in lake inflow compared to the same discharge modification in the Yangtze River (*Lai et al.*, 2014a). The recent extremely low water levels in the Yangtze River resulted mainly from remarkable decline in inflows to the River, rather than solely from the TGD impoundments (*Lai et al.*, 2014b). Indeed, these studies highlighted the complexity of the multiple influences on Poyang Lake's decline in the complex basin-lake-river system.

Definitely, drought differs from low water level and persistent dryness. Water level can be low in seasonal dry seasons, but it does not necessarily constitute a

drought (*Smakhtin*, 2001). Persistent dryness refers to water decrease in a long run, equivalent to decreasing trend or shrinkage, which is usually unrecoverable in a short time (*Zhang et al.*, 2012). Droughts are complex events that have a recurrent feature, and it may occur in any season lasting several months or longer (*Todd et al.*, 2013). Feng et al. (2012) used 250-m satellite images to delineate inundation area for quantifying the drought severity of Poyang Lake in 2011. Linear regression analysis showed that the drought was primarily due to low basin-scale precipitation, rather than mis-balanced discharge between the Lake and the Yangtze River with TGD impoundments. Very recently, Wu and Liu (2014) used satellite-delineated inundation area to quantify two lake droughts occurred in 2006 and 2011. Statistical comparison indicated that the 2006 drought was mainly attributable to abnormal decrease of water flow in the Yangtze River and the 2011 drought was due to combined influences of the Poyang Lake Basin and the Yangtze River. Although the studies specified two extreme drought events, neither of them offered a full explanation to the frequently occurred droughts in Poyang Lake.

In principle, drought identification, quantification or characterization with a consistent standard is a prerequisite for drought analysis. However, few studies have comprehensively quantified and addressed the Poyang Lake droughts in the 2000s. The current understanding of the Lake's decline in autumn cannot provide a complete explanation to the lake droughts spanning non-autumn seasons. It remains unknown to what extent the climatic, hydrologic and anthropogenic influences have contributed to the lake droughts, which is one of key issues identified for developing integrated,

interdisciplinary theories of droughts (*Kallis, 2008*). Especially for practice, clarification of the multiple influences on the recently increased droughts is essential to effective prevention of the droughts.

Complicated causality of lake droughts requires robust approach for determining the contributions from multiple influences. Analogous to standardized precipitation index, this study utilizes standardized lake index to quantify lake droughts (Section 2). With the principle of lake water balance, it proposes to define an absolute deficiency for each water component and determine their contributions to lake droughts (Section 2). The approach is applicable to basin-scale water balance, quantifying regional hydroclimatic influences on lake inflow, and subsequently on lake droughts (Section 2). Poyang Lake droughts are examined with the proposed approach, in combination with five-decade hydroclimatic data including latest satellite products (Section 3). The drought features in the 2000s and its mechanism are addressed subsequently (Section 4). Our findings should be valuable for improving our understanding of lake droughts under the changing climate situations and be useful for local water resources management and climate change adaptation.

## **2. Methodology**

Drought has a multi-faceted nature. Major attributes of a drought event involve initiation, termination, duration, severity, magnitude, and intensity, as well as spatial extent for the case of meteorological or agricultural droughts (*Yevjevich, 1967; Dracup et al., 1980; Wilhite and Glantz, 1985; McKee et al., 1993; Mishra and Singh, 2010; Spinoni et al., 2014*). Drought initiation time is the starting of the drought.

Termination time is the end when the drought no longer persists. Drought duration is the period between the initiation and the termination (*Yevjevich, 1967; Mishra and Singh, 2010*). Drought severity is the total, cumulative water deficient for the duration.

180 Drought magnitude is a derivative of drought severity, defined as the average water deficit in the drought period (*Dracup et al., 1980; Wilhite and Glantz, 1985*). Drought intensity usually refers to the largest departure from the normal conditions (*McKee et al., 1993; Spinoni et al., 2014*). For a given historical period, drought description also includes drought frequency, which refers to the number of drought events occurred  
185 (*Mishra and Singh, 2010; Spinoni et al., 2014*).

## 2.1 Quantification of Lake Droughts

For quantitative analysis, various indices have been proposed to characterize the complex features of droughts (*Dracup et al., 1980; Keyantash and Dracup, 2002; Mishra and Singh, 2010; 2011*). Among the numerous indices, standardized  
190 precipitation index (SPI) is commonly used (*McKee et al., 1993; Mishra and Singh, 2010*). It is a normalized dimensionless index, defined as the difference of precipitation from the mean divided by the standard deviation for a given period, in which a gamma distribution is generally fitted to the long-term precipitation records for each calendar month to account for seasonal differences (*McKee et al., 1993*). The  
195 SPI is simple but capable of quantifying drought features, and has been recently recommended by the World Meteorological Organization (WMO) to characterize meteorological droughts (*Hays et al., 2011*). Despite it was proposed to quantify precipitation deficiency, the SPI methodology has been applied in a similar manner to

other hydroclimatic variables, for example, streamflow discharge, soil moisture,  
 200 reservoir storage, and groundwater level (*McKee et al.*, 1993; *Sheffield et al.*, 2004;  
*Vicente-Serrano and López-Moreno*, 2005; *Mendicino et al.*, 2008; *Shukla and Wood*,  
 2008).

In the case of lake drought, it can be described with lake stage, lake area or water  
 storage. Because the time series data of lake area or water storage are generally  
 205 unavailable, lake stage is feasible for analysis. Analogue to SPI, standardized lake  
 index (SLI) is described as follows

$$SLI_{ij} = \frac{L_{ij} - \bar{L}_j}{\sigma_j}, \quad (1)$$

where  $L_{ij}$  is the monthly average lake stage (unit in m) of year  $i$  and month  $j$  ( $j = 1, 2, \dots, 12$ ), normalized with a gamma distribution (*McKee et al.*, 1993).  $\bar{L}_j$  is the  
 210 multi-year mean of monthly average stage for month  $j$ , and  $\sigma_j$  is one standard  
 deviation (S.D.) of monthly average stage for month  $j$ . Since SLI uses  $\bar{L}_j$  and  $\sigma_j$ ,  
 both of which are monthly dependent, it thus removes seasonal differences in lake  
 stage.

A drought event is discernible with SLI. While a negative SLI indicates the lake  
 215 stage is lower than the normal, not all the negatives can be classified into a drought  
 event. Only when SLI deviates away from the normal by more than one standard  
 deviation ( $SLI < -1$ ), an event can be established (*McKee et al.*, 1995). Furthermore, a  
 drought initializes when SLI becomes negative and terminates before SLI becomes  
 positive in SLI time series (*McKee et al.*, 1995). The initialization and the termination  
 220 time yield drought duration (unit in day, month or year). Once all the drought events

are identified, drought frequency can be determined for a given period.

In accordance with McKee et al. (1993)'s definition of SPI, SLI represents a departure of lake stage from its normal conditions. The departure corresponds to a probability of drought intensity, highly valuable to drought risk analysis. Namely, SLI=-1 denotes an occurrence probability of 15.9% (*Lloyd-Hughes and Saunders, 2002*). Furthermore, SLI can be either positive or negative. The positive (negative) value indicates lake stage higher (lower) than the normal condition for the period. The negative value quantifies the drought intensity. For an individual drought event, its lowest SLI value indicates the intensity of the event (*McKee et al., 1993; Spinoni et al., 2014*). Accordingly, a drought event can be classified into four categories with its lowest SLI: extreme drought ( $-\infty, -2.0$ ], severe drought ( $-2.0, -1.5$ ], moderate drought ( $-1.5, -1.0$ ] and mild drought ( $-1.0, 0.0$ ) (*Dracup et al., 1980; McKee et al., 1993*).

In addition, drought severity of a drought event is calculated as follows

$$\text{Severity} = \sum_{k=m}^{k=n} \text{SPI}_k, \quad (2)$$

where  $m$  denotes the initialization time of a drought and  $n$  represents the termination time (*Keyantash and Dracup, 2002; Mishra and Singh, 2010*). Drought magnitude is then calculated as (*Keyantash and Dracup, 2002*)

$$\text{Magnitude} = \text{Severity}/\text{duration}. \quad (3)$$

## 2.2 Contribution of Water Deficiency to Lake Droughts

A lake drought results directly from an abnormal change in lake water budget. Thus, water budget analysis is essential to clarify the drought causes. A general water balance for lake in a period can be described as follows

$$\Delta_L = P_L - E_L + G_L + I_L - O_L, \quad (4)$$

where  $\Delta_L$  is the lake water budget (mm or m<sup>3</sup>),  $P_L$  is the precipitation (mm or m<sup>3</sup>),

245  $E_L$  is the lake evaporation (mm or m<sup>3</sup>),  $G_L$  is the groundwater net inflow to the lake (mm or m<sup>3</sup>),  $I_L$  is the inflow (mm or m<sup>3</sup>) and  $O_L$  is the outflow (mm or m<sup>3</sup>).

Once the water budget appears abnormal, it suffers from the anomalies of some or all the water components, namely, low precipitation, high evapotranspiration, low inflow and/or high outflow. At the monthly scale, for a water component  $X$ , being  $\Delta_L$ ,

250  $P_L$ ,  $E_L$ ,  $G_L$ ,  $I_L$  or  $O_L$ , its anomaly is described as follows

$$X_{a,ij} = X_{ij} - \bar{X}_j, \quad (5)$$

where  $X_{a,ij}$  denotes the anomaly ( $a$ ) of the water component (mm or m<sup>3</sup>) for year  $i$  and month  $j$ .  $\bar{X}_j$  is the multi-year mean of  $X_{ij}$ . Notably, Eq. (5) defines an absolute water deficiency from its normal amount, different from Eq. (1) that defines a relative deficiency for drought identification. The equation offers a baseline to quantify

255 contributions from individual water components to a drought.

During a drought event, the anomaly of lake water storage ( $S$ ) at month  $j$  ( $m < j \leq n$ ) results from the consecutive anomalies of the lake water budget, which can be described as

$$260 \quad S_{a,j} = \sum_{k=m}^{k=j} \Delta_{a,k}. \quad (6a)$$

The individual contribution from each water component to the water deficiency of the lake water storage at month  $j$  is quantifiable with a ratio defined as follows



$$C_{X_j} = \frac{\sum_{k=m}^{k=j} X_{a,k}}{\sum_{k=m}^{k=j} \Delta_{a,k}}, \quad (7a)$$

where  $C_{X_j}$  denotes the contribution, the numerator is the sum of the monthly

265 anomalies of the water component from month  $m$  to  $j$ .  $\sum_{k=m}^{k=j} \Delta_{a,k}$  is generally negative,

but  $\sum_{k=m}^{k=j} X_{a,k}$  may vary with hydroclimatic conditions. For example, precipitation

deficiency leads to a negative  $\sum_{k=m}^{k=j} X_{a,k}$  value and produces a positive  $C_{X_j}$ . Low

evapotranspiration lessens water deficiency and generates a negative  $C_{X_j}$ . Therefore,

$C_{X_j}$  can be either positive or negative. Notably, Eq.(7a) requires all the involved water

270 components be independent from each other, which is the general case for  $P_L$ ,  $E_L$ ,  $G_L$

and  $I_L$ , but not for  $O_L$ .  $O_L$  is the output water, largely dependent on the sum of

$(P_L - E_L + G_L + I_L)$ . To eliminate the dependence in quantifying the individual

contributions with the equation,  $\bar{O}_k$  is replaced with  $(P_{L_k} - E_{L_k} + G_{L_k} + I_{L_k})$  for

$O_{a,k} = O_k - \bar{O}_k$  which is included in Eq.(7a). This is also applicable for Eq.(7b)

275 described subsequently.

For an entire drought event, in accordance with the concept of drought severity

(Eq.(2)), the total water deficiency of lake water storage from the initialization time ( $j$

$= m$ ) to the termination ( $j = n$ ) can be described as follows

$$\sum_{k=m}^{k=n} S_{a,k} = \sum_{j=m}^{j=n} \sum_{k=m}^{k=j} \Delta_{a,jk} . \quad (6b)$$

280 Then, the individual contribution from each water component to the total water

deficiency for a drought event can be described as

$$C_X = \frac{\sum_{j=m}^{j=n} \sum_{k=m}^{k=j} X_{a,jk}}{\sum_{j=m}^{j=n} \sum_{k=m}^{k=j} \Delta_{a,jk}}. \quad (7b)$$

In many cases, quantification of individual hydro-climatic contributions to droughts is of high concern in decadal or longer time scales, for example, in climate change related studies (*Todd et al., 2013; Joetzjer et al., 2013; Van Lanen et al., 2013*). In this case, their individual contributions can be determined from Eq. (7b), given the total integrated hydrological components for the period.

### 2.3 Contribution of Basin-scale Hydroclimatic Influences on Lake Droughts

In addition to quantification of water deficiency in inputs and outputs to lake, it is natural to trace the causes of inflow deficiency for complete understanding of hydroclimatic influences on lake droughts. Lake inflow originates from precipitation in its surrounding basin. Given the water balance for the basin in a period, lake inflow is described as

$$I_L = P_B - E_B + \Delta_B, \quad (8)$$

where  $P_B$  is the precipitation (mm or  $m^3$ ),  $E_B$  is the evapotranspiration (mm or  $m^3$ ), and  $\Delta_B$  is the change of water storage (mm or  $m^3$ ), including soil moisture and groundwater in the basin.

In practice, there are often areas ungauged downstream from hydrological stations. In this case, the lake inflow includes two parts, one from gauged areas and another from ungauged areas. It has

$$I_U = P_U - E_U + \Delta_U, \quad (9a)$$

$$I_G = P_G - E_G + \Delta_G, \quad (9b)$$

where the subscript  $G$  represents the components for the gauged areas and the subscript  $U$  denotes that for the ungauged areas.

305 In combination with Eq. (4) and Eq. (9a), the lake water budget can be expressed as

$$\Delta_L = \underbrace{P_L - E_L + G_L}_{lake} + \underbrace{P_U - E_U + \Delta_U}_{ungauged\_area} + I_G - O_L. \quad (10a)$$

Or in parallel,

$$\Delta_L = \underbrace{P_R - E_R + \Delta_R}_{lake\_region} + I_G - O_L. \quad (10b)$$

310 where the subscript  $R$  represents the components for the lake region. It shows that the lake change involves water budgets in the lake and the ungauged areas, in addition to gauged inflow and outflow.

Further incorporated with Eq. (9b), the lake water budget can be expressed as

$$\Delta_L = \underbrace{P_L - E_L + G_L}_{lake} + \underbrace{P_U - E_U + \Delta_U}_{ungauged\_area} + \underbrace{P_G - E_G + \Delta_G}_{gauged\_area} - O_L. \quad (11a)$$

315 Or in parallel,

$$\Delta_L = \underbrace{P_R - E_R + \Delta_R}_{lake\_region} + \underbrace{P_B - E_B + \Delta_B}_{lake\_basin} - O_L. \quad (11b)$$

Clearly, the lake water change is a combined result of precipitation, evapotranspiration, soil moisture, groundwater, and outflow.

As done with Eq. (5), the water anomaly of each component in Eq. (10) and Eq. 320 (11) can be defined, respectively. As done with Eq. (6), their contributions to the abnormal change of the lake water can be determined for water balance at different spatial scales, namely, the lake, the lake region, and the basin. The multi-scale determination is useful to trace regional hydroclimatic influences on the lake

droughts.

### 3. Study Area and Data Processing

#### 3.1 Study Area and Data

Poyang Lake has a maximum area of 3,860 km<sup>2</sup> with an average depth of 8 m at the lake stage of 22 m (*Shankman et al.*, 2003). It varies remarkably from several thousand km<sup>2</sup> in summer to less than one thousand km<sup>2</sup> in winter (*Liu et al.*, 2013).

There are five stations (Kangshan, Tangyin, Duchang, Xingzi, and Hukou) to measure lake stage across the lake from the south to the north (Figure 1d). It is located at the northern part of the Poyang Lake Basin, a sub-basin of the Yangtze River Basin of China (Figure 1a). The lake water flows out into the Yangtze River via the Hukou outlet. The lake water principally comes from five major river systems including Xiushui, Ganjiang, Fuhe, Raohe and Xinjiang. Seven hydrological control stations (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Dufengkeng, and Shizhenjie) are located downstream to measure the discharge of the five rivers (Figure 1b). The lake region (Figure 1c) downstream from the stations is ungauged, with an area of 23,089 km<sup>2</sup>, approximately six times of the maximum lake size. The Poyang Lake Basin has an area of 162,225 km<sup>2</sup> and belongs to a humid subtropical climate zone with an annual mean surface air temperature of 17.5°C and an annual precipitation of 1,635.9 mm for the years 1960-2010 (*Liu et al.*, 2012). Forestlands, agricultural fields, grasslands, bare-lands and water surfaces are the dominant land cover types (*Liu et al.*, 2012).

Daily lake stage data from five hydrological stations and daily discharge data

from seven control stations were obtained from the Hydrological Bureau of Poyang Lake. Lake stage data from Xingzi and Hukou were available for 1961-2010, but the data from other three stations were unavailable for 2009-2010. Daily discharge data for the Hukou outlet are available from the Hydrological Bureau of the Yangtze River Water Resources Commission. Daily precipitation data from 73 national weather stations within the Poyang Lake Basin are available from the National Meteorological Information Center of China for 1961-2010. Regional evapotranspiration data were extracted from the latest satellite products (MOD16) of the Moderate resolution Imaging Spectroradiometer (MODIS) (<http://www.ntsg.umd.edu/project/mod16>) (Mu *et al.*, 2011) for the lake region and the lake basin in 2000-2010. In addition, the lake stage at Hukou is available for the case without the TGD for 2006-2010, which is the output of the CHAM-Yangtze model (Lai *et al.*, 2013).

### 3.2 Drought Quantification

To identify lake droughts, SLI was calculated with Eq. (1) from monthly lake stage. Notably, it is approximate 110 km from the north to the south of Poyang Lake requiring a best representative of the lake conditions. Among five stations to measure the lake stage, the SLI values of Xingzi station had the highest correlation with that calculated from averaged lake stage of the five stations using all the available data for 1960-2008 ( $y=0.9953x$ ,  $R^2=0.9901$ ,  $p<0.0001$ ). Thus, the station was selected for drought quantification.

Drought initialization, termination, duration, intensity, severity, and frequency were subsequently determined from the SLI values of Xingzi, with the criteria

described in Section 2.1. Finally, all the lake droughts were identified and classified into extreme, severe, or moderate drought (*McKee et al.*, 1993).

370 In addition, for the case without the TGD impoundments, the lake stage at Xingzi was estimated from its highly correlated relationship with Hukou,  $y = 0.9594x + 0.8034$  (*Min and Zhan*, 2013), for 2006-2010. Consequently, the SLI values of Xingzi were re-calculated for the case without TGD. It serves as a reference to evaluate the TGD effect on the lake droughts.

### 375 **3.3 Water Budget Analysis**

To quantify hydroclimatic influences on lake droughts, water budget analysis was designed at multi-spatial scales, preferably at the lake, the lake region and the lake basin (Figure 1). At the lake scale, water components include precipitation, evaporation, groundwater net inflow, inflows from gauged and ungauaged areas, and  
380 outflow (Eq. (4)). It has several difficulties to perform water balance analysis with a high accuracy for the lake. First, evaporation data are unavailable for the lake in monthly time series. Second, the lake has a remarkable surface variation, which significantly regulates wetland evapotranspiration (*Zhao and Liu*, 2014). Third, there are many small rivers and brooks downstream from the hydrological control stations.

385 It is impractical to measure all of the surface runoff into Poyang Lake. Given the hydrological data, the Poyang Lake region is thus the minimum closure entity directly available for water budget analysis. For complete understanding of climatic, hydrologic and anthropogenic influences on lake droughts, water budget analysis should be performed for the lake basin, with a focus on the causes of inflow

390 deficiency. Besides, the boundary effect of the Yangtze River is taken into consideration to account for the anomaly of lake outflow.

Specification of normal hydrologic condition is a prerequisite for determining water deficiency. First, precipitation data were grouped for the Poyang lake region and the lake basin. Multi-year mean of monthly precipitation was obtained from the observation data for 1961-2010. Second, multi-year mean of monthly discharge was calculated from the data for inflows and outflow in the period. Third, since evapotranspiration data prior to 2000 was unavailable, the multi-year mean of annual evapotranspiration was calculated from the difference between annual precipitation and discharge, respectively for the lake region and the entire lake basin in 1961-2010.

400 The multi-year mean of monthly evapotranspiration was then obtained from the annual value distributed with a monthly weighting factor calculated from the MOD16 time series, with an assumption that the annual variability is relatively similar for 1961-2010.

Once the normal hydrologic condition was established, the water deficiency of a water component and its contribution to lake droughts were determined with Eq. (5) and Eq. (6). It was also applied to water budget for the lake region (Eq.(10b)) and the lake basin (Eq.(11b)), respectively. For the basin, a one-month lag was determined with correlation analysis between peak rainfall and peak discharge, and it was applied to account for the peak difference (*Senay et al.*, 2011; *Liu et al.*, 2013). In addition, there are three points addressed here. First,  $\Delta_R$  in Eq. (10b) for the lake region is only 1.3% of the total water balance and is neglected in the present study (*Wan and*

*Xu, 2010; Zhang et al., 2014*). Second,  $\Delta_G$  in Eq. (9b) for the gauged lake basin is generally unavailable. According to Feng and Liu (2014), it is roughly 5% of the total water balance and is neglected here. Third, the MOD16 datasets provide one-decade  
 415 monthly evapotranspiration, making it feasible to use the independent observations for water budget analysis in time series. While the datasets have been extensively evaluated and applied worldwide, namely Australia, Brazil, Asia, and the United States (*Loarie et al., 2011; Kim et al., 2012; Velpuri et al., 2013; Wang et al., 2014*), our recent assessment showed that it had an error of approximate 10% for the study  
 420 area (*Wu et al., 2013*). The error, together with the neglected  $\Delta_R$  and  $\Delta_G$ , may introduce uncertainties. Given that water anomaly (Eq. (5)) and relative contribution (Eq. (7b)) are used, the uncertainties would not be enlarged but minimized in water balance calculation and water budget analysis.

It should be emphasized that, for the sake of addressing water contribution at the  
 425 lake region and the lake basin, the water amounts (unit in  $\text{m}^3$ ) of all the water components were normalized to equivalent water height (unit in mm) of the whole basin (unit in  $\text{km}^2$ ). Besides, statistical approaches were adopted in the present analysis (*Lomax, 2001*), in which paired F-test (and T-test) were used to examine the variance (and mean) difference between the statistics for 1961-2000 and that for  
 430 2001-2010.

## **4. Results and discussion**

### **4.1 Poyang Lake Droughts in Recent Decade**

Figure 2(a) illustrates the SLI variation for Poyang Lake in the recent decade.



The negative values prevail over the positive, indicating the dry phase dominates the lake for the period. There occurred three extreme, two severe and four moderate droughts, according to the drought classification criteria (*McKee et al.*, 1993). Among the nine cases, three droughts started in spring, two in summer and four in autumn (Table 1). Drought duration varied from 2 to 13 months with a mean of 6.2 months and one standard deviation (S.D.) of 4.1 months, which demonstrated that the lake droughts could occur in any month. Drought intensity ranged from -1.03 to -3.03 with a mean of  $-1.79 \pm 0.70$ . The top three lowest SLI values were -3.03, -2.66 and -2.01, corresponding to possibilities of 0.12%, 0.39% and 2.22%, respectively, for each occurrence. Drought severity varied from -1.39 to -20.22 with a mean of  $-7.16 \pm 6.41$ . More specifically, in the category of ‘extreme drought’, the drought event that ranked first in both intensity and severity occurred from July 2006-July 2007, lasting 13 months. The 2006 drought was addressed in Feng et al. (2012) and Wu and Liu (2014) in terms of inundated area, whereas the present study quantified its probability of occurrence and revealed that the drought lasted longer than the previous reports. The second most severe drought event emerged in September 2009-January 2010, persisting 5 months. The third most severe drought took place from October 2007-August 2008, lasting 11 months. The two droughts in the ‘severe drought’ category spanned 6 and 10 months, respectively. The four droughts in the ‘moderate drought’ category lasted 2~4 months. It appears that a drought with a lower SLI is usually more severe and lasts for a longer time.

In comparison to the years 1961-2000, the lake droughts changed in terms of

duration, frequency, intensity and severity in the most recent decade (Figure 2(b)). On average, drought duration extended from 5.6 to 6.2 months. Drought frequency increased from 6.0 to 9.0 events per decade. Drought intensity intensified from -1.38 to -1.79, and drought severity increased from -5.02 to -7.16. In regard to the intensification, further analysis revealed that the moderate drought events increased. The severe droughts decreased, but the extreme droughts increased from 0.5 to 3.0 events per decade (Figure 2(c)). Overall, the lake droughts have worsened in terms of duration, frequency, intensity and severity over the last decade.

## 4.2 Hydroclimatic Change at Poyang Lake Region

Normal variation of water components is a baseline for quantitative analysis of drought occurrence as an abnormal change. Figure 3(a) shows the multi-year mean of monthly precipitation ( $P_R$ ) and evapotranspiration ( $E_R$ ) for the lake region, lake inflow ( $I$ ) from five major rivers and outflow ( $O$ ) into the Yangtze River. The monthly precipitation varied with a peak in June followed by a sharp decrease. Inflow had a similar seasonal pattern. Outflow had the maximum value in June and the minimum in January. The maximum evapotranspiration appeared in August and the minimum in December. From a perspective of water balance, the water budget was positive from January to June with a peak in June. It became negative from July to December, and the minimum value appeared in October. These results indicate a shift in water budget from a surplus phase in the first half of the year to a deficit phase in the second half of the year. The deficit phase is a part of the normal hydrologic condition, and thus it does not necessarily mean a drought occurrence. Furthermore, in annual water budget,

the equivalent water supply from the local precipitation was 312.0 mm, and that from inflow was 714.4 mm, more than two times of the local precipitation. The water loss from the local evapotranspiration was 118.3 mm, and that from outflow was 908.1 mm, approximate 7.7 times of the local evapotranspiration. It demonstrated that the inflow and outflow were much higher than the local precipitation and evapotranspiration. This finding implies the dominant role of hydrologic components over meteorological components in regulating Poyang Lake.

Lake droughts occur when abnormal change appears in the water budget. Table 2 lists the water components for the lake region during the periods of lake droughts. The water budgets ( $P_R - E_R + I - O$ ) were -67.1, -12.6 and -69.3 mm for three extreme lake droughts, -71.6 and 27.7 mm for two severe lake droughts, and 72.0, 5.4, 18.5, and -66.1 mm for four moderate lake droughts. In sum, the budget was negative (deficit) for five cases and positive (surplus) for four cases. Despite the positive water budgets, the large negative anomalies of  $P_R - E_R + I$  for the cases illustrated that the lake water income ( $P_R - E_R + I$ ) was exceptionally lower than normal. The low water income resulted from largely decreased inflow and precipitation, as well as increased evapotranspiration. The positive water budgets were attributed to the water surplus period in the first half of the year. In this sense, the definition of drought is a water anomaly referenced to a normal state of either water surplus or deficit phase. It indicated that a drought occurrence was more closely related to the water deficiency (negative anomaly) of water budget than the net water budget. For example, the net water budget did not show statistically significant relationships with drought intensity

or drought severity. On the contrary, the total water anomaly of a drought event showed a significant relationship with drought severity ( $x$ ) ( $y = 22.949x + 3.8772$ ,  $n = 9$ ,  $R^2 = 0.7513$ ,  $p < 0.01$ ) (Figure 3(b)). In general, the water budget analysis highlighted the importance of water deficiency in reference to a normal condition of either water surplus or deficit phase.

While a lake drought is generated from the anomaly of water budget, it is not clear to what extent each water component has contributed to the anomaly. Clarification of the contribution is helpful for understanding drought causes and will be useful for preventing droughts under the changing climate. Table 3 shows the ratios of the total water anomaly of a component to that of the water budget for each event (Eq. (6)). For the three extreme droughts, outflow and inflow played the most important role. For example, inflow was 210.7 mm lower, local precipitation was 100.9 mm lower and evapotranspiration was 44.8 mm higher than normal for the most severe drought (July 2006-July 2007). Outflow was 296.3 mm lower as a result of reduced inputs to the lake. For the second most severe drought (July 2007-August 2008), precipitation was 39.0 mm lower and evapotranspiration was 31.6 mm higher. Inflow was 141.9 mm lower, contributing to 23% of the anomaly. For the third most severe drought (September 2009-January 2010), precipitation was 12.0 mm lower and evapotranspiration was 11.2 mm higher. The reduced inflow contributed to 25% of the anomaly and the increased outflow contributed to 56% for the period. In addition to the positive contribution, a water component may contribute negatively. For example, there are two negative cases of outflow occurring mainly in a water surplus period

(Table 3). The negative contribution implies less outflow in reference to water income ( $\mathbf{P_R-E_R+I}$ ), which is consistent with the water budget ( $\mathbf{P_R-E_R+I-O}$ ). Clearly, hydroclimatic contributions to each individual drought varied from one to another, but the inflow appeared to be dominant. On average, for all the drought cases, 46% of the total water anomaly of the water budget came from the reduced inflow, 28% from increased outflow, 17% from decreased precipitation and 9% from increased evapotranspiration at the lake region. Since inflow reduction is the major contribution to the water anomaly in the lake region, it is vital to trace how precipitation and evapotranspiration have changed at the basin scale in the recent decade.

### 4.3 Hydroclimatic Change at Poyang Lake Basin

Likewise, prior to performing a water budget analysis, it is valuable to clarify the normal hydrologic condition. Generally, precipitation ( $\mathbf{P_B}$ ) and evapotranspiration ( $\mathbf{E_B}$ ) had similar seasonal patterns in the basin as its counterpart in the lake region (Figure 4(a)). Monthly precipitation varied seasonably with a peak in June, followed by peaks in May and April. Major precipitation appeared in the first half of the year. Monthly evapotranspiration was generally less than precipitation and its top three highest values appeared from June-August. Monthly outflow was approximately half of precipitation with a similar seasonal pattern. Consequently, the monthly water budget was positive (surplus) from December-June and negative (deficit) from July-November. The highest water surpluses appeared in March, April and May, and the lowest water deficits in July, August and September. On an annual scale, outflow occupies approximately 55% of precipitation, 10% higher than evapotranspiration,

which is one of the climate features of this humid subtropical region.

545 Concerning water budget for a drought event, it was -252.2, -79.4 and -95.8 mm  
for the three extreme droughts, -251.9 and 152.0 mm for the two severe droughts, and  
136.3, 21.3, -9.5 and -65.1 mm for the moderate droughts (Table 2). For six negative  
cases, the water budget featured less precipitation (negative anomaly) and more  
evapotranspiration (positive anomaly). For three positive cases,  $P_B - E_B$  had large  
550 negative anomalies over 100 mm, but the water budgets became positive due to the  
largely reduced outflow. For the three extreme droughts,  $P_B - E_B$  was much lower than  
the normal, suggesting that meteorological droughts have made significant effects on  
the drought formation. For all the cases, the water anomalies of  $P_B$  and  $P_B - E_B$  had  
positive relationships with drought severity, which was consistent with the water  
555 budget for the lake region. Nevertheless, the basin-scale precipitation is the most  
important water source to the lake, as confirmed by a correlation between  $P_B - E_B$  ( $x$ )  
and  $I$  ( $y$ ) ( $y=0.9958x$ ,  $R^2=0.8667$ ,  $n=10$ ,  $p<0.005$ ) (Figure 4(b)). The  $P_B - E_B$ -to- $I$   
difference was -28.3 mm, approximately 10% of  $I$ , in agreement with our previous  
study (*Wu et al.*, 2013). The high correlation and relatively small difference also  
560 confirmed the suitability of the satellite evapotranspiration data for the study area.

While the inflow reduction generated from combined hydroclimatic change,  
precipitation and evapotranspiration may have made different contributions to the lake  
droughts. For example, precipitation was 248.0 mm lower and evapotranspiration was  
72.5 mm higher than the normal, and they produced inflow 152.8 mm lower from  
565 October 2007-August 2008. The decreased precipitation contributed 83% and the

increased evapotranspiration contributed 17% to the inflow deficiency, respectively.

In contrast, precipitation was 23.3 mm lower and evapotranspiration was 55.1 mm higher, and they generated inflow that was 21.1 mm lower than normal from June-November 2001. The corresponding contribution was 39% for precipitation and 61% for evapotranspiration to the inflow deficiency. For all nine-drought cases, 71% of reduced inflow came from decreased precipitation and 29% came from increased evapotranspiration as a whole (Table 3). These results demonstrated the dominant role of precipitation in reducing the inflow to Poyang Lake, despite it might vary with different drought cases.

#### 4.4 Mechanisms Accounting for Recent Lake Droughts

The above sections detail the lake droughts as abnormal phenomena and the hydroclimatic contribution to individual drought events. Yet, it remains unclear why the droughts strengthened in the recent decade, and whether the droughts resulted from a long-term change of hydroclimatic influences or a seasonal combination of these influences.

Figure 5(a) shows the accumulated anomalies of water budget from 2001-2010. At the lake region, the water budget ( $P_R - E_R + I - O$ ) declined from mid-2002 to a low value in September 2009, and then increased yet remained in a negative phase. Obviously, the decrease in the water budget is a hydroclimatic setting for the recent drought increase. The water deficits involve local precipitation and evapotranspiration, lake inflow and outflow, but each of these components has different courses. The accumulated  $P_R$  showed a decreasing trend after mid-2003. The accumulated  $E_R$

increased gradually but steadily, which was consistent with the rapid increase of surface temperature in the Poyang Lake Basin since 1998 (*Liu et al.*, 2012). The  $E_R$  exceeded the  $P_R$  after April 2010, exhibiting an increasing effect on the water budget. Comparatively, the accumulated  $I$  or  $O$  had a relatively large variation, consistent with their dominance over  $P_R$  and  $E_R$  at seasonal scale. They displayed similar behaviors with a peak in spring 2003, and then declined by the end of 2009. In the entire period, precipitation decreased by 5%, evapotranspiration increased by 19%, inflow declined by 5% and outflow declined by 4%, accounting for the negative water budget in the lake region.

Figure 5(b) displays seasonal variation of the water budget during 2001-2010. In comparison to 1961-2000, the water surplus reduced for the first half of the year, and the water deficit increased for the second half of the year except for August and November. The large reduced surplus includes March and June, and the enhanced deficit includes July and September. The reduced surplus and the enhanced deficit would increase the possibility of drought occurrence and intensify the drought intensity. In the enlarged water deficit, the  $P_R - E_R$  and the  $I - O$  contributed to 43% and 57%, respectively. In the  $I - O$  deficit, inflow decreased but outflow increased. Usually, the outflow decreases with reduced inflow and  $P_R - E_R$ . Since the Yangtze River serves as a boundary condition of Poyang Lake, the increased outflow is generally a result of weakened blocking effects of the lake-River interactions (*Guo et al.*, 2012; *Zhang et al.*, 2012; *Lai et al.*, 2014).

The weakened effects involve climate change in the upper reaches of the Yangtze



610 River, and water impoundments of the TGD (*Guo et al.* 2012). Routinely, the TGD  
impoundment begins in mid-September and spans one to two months. Among all the  
drought events, none occurred during exactly the same time span. Accordingly, the  
TGD impoundments should not be responsible for the increased drought events.  
However, the impoundments lowered the lake stage at the Hukou outlet by 1~2 meters  
615 for September-October (*Guo et al.* 2012; *Zhang et al.*, 2012, 2014). Our analysis  
indicated that the impoundments led to a change in SLI from -2.70 to -3.03 for the  
extreme drought in July 2006-July 2007, and from -1.81 to -2.66 for the extreme  
drought in September 2009-Januray 2010. The change has two implications. First, the  
droughts were intensified with the TGD impoundments. Second, a severe drought  
620  $(-2.0 < \text{SLI} \leq -1.5)$  was intensified to an extreme drought  $(-\infty < \text{SLI} \leq -2.0)$ , which changed  
the frequency of classified droughts. This is a reasonable explanation for the decrease  
in the number of severe droughts but increase in extreme droughts (Figure 2(c)).  
Furthermore, according to the latest lake storage curve described in Tan et al. (2013),  
the lowered lake stages would result in a water loss of  $7.1 \times 10^8 \text{ m}^3$  and  $24.1 \times 10^8 \text{ m}^3$   
625 for each event, respectively. The losses occupied 1.5% and 19.1% of the total  
anomalies of outflow, corresponding to 0.2% and 9.9% of the contribution to each  
drought event. In comparison with the hydroclimatic influences, the TGD  
contributions were rather limited.

In general, the recently increased droughts were principally attributed to  
630 decreased inflow, increased outflow, and reduced local precipitation and increased  
evapotranspiration at the lake region. The findings lay in several strengths or novelties

in the present study. First, use of satellite-retrieved evapotranspiration data makes it possible to analyze drought causes from a perspective of water budget with independent measures of major water components. Given measurement errors are  
635 quality controlled, the independent observations are more faithful than model simulation that is susceptible to model uncertainty and empirical parameterization. Indeed, the MOD16 products demonstrated its effectiveness in water balance calculation and subsequent water budget analysis. Second, in addition to drought quantification, absolute deficiency was defined for water component and water budget  
640 in reference to normal hydrologic state. Individual hydroclimatic contributions were isolated from the total anomalies of water budget, and the drought causation structure was subsequently distinguished. The quantification approach is straightforward and applicable to separate hydroclimatic influences to droughts, a key issue identified for developing integrated theories of droughts (*Kallis, 2008*). Third, it is the first time to  
645 quantify all the drought events and their causation structure in Poyang Lake. Most existing studies did not explicitly quantify the droughts but focused on low water levels mainly in autumn seasons. A few studies addressed 1-2 extreme droughts with statistical regression analysis (*Feng et al., 2012; Wu and Liu, 2014*), yet lack of systematic water balance analysis of the droughts and their decadal features. The  
650 present study completed drought quantification, water budget analysis, isolation of hydroclimatic contributions, and clarification of causation structure for the recently increased droughts in Poyang Lake. The complete assessments demonstrated that the droughts were the hydroclimatic consequences, with less important contribution from

the TGD influences. Yet, it should be noted that the present study did not address  
655 some potential influences, for example, land cover/use change, agricultural water use,  
soil moisture variation and vegetation dynamics. These factors can significantly affect  
the hydrological processes at seasonal and annual scales, and subsequently affect lake  
stage and droughts, which should be taken into consideration in future study.

## 5. Conclusions

660 This paper used standardized lake stage to identify and quantify droughts  
illustrated with the case in Poyang Lake for all seasons. From a perspective of water  
budget, it defined an absolute deficiency for water component and water budget in  
reference to normal hydrologic condition to determine hydroclimatic contributions to  
lake droughts. Given five-decade hydroclimatic observation data and the latest  
665 satellite products, water budget analysis was operational and performed in the study  
area.

Our analyses demonstrated that the lake droughts had strengthened in the recent  
decade, in terms of duration, frequency, intensity and severity. The overall  
contribution to the lake droughts came from decreased inflow (46%), increased  
670 outflow (28%), and reduced precipitation (17%) and increased evapotranspiration (9%)  
at the lake region. In the decreased inflow, 71% resulted from basin-scale  
precipitation and 29% from basin-scale evapotranspiration. The recently increased  
droughts were principally ascribed to hydroclimatic change, specified with decreased  
precipitation, increased evapotranspiration and reduced inflow. The TGD  
675 impoundments were not responsible for the increased drought events, but they did

intensify the droughts and change the frequency of classified droughts. However, the TGD contribution was limited, compared with the hydroclimatic influences.

Overall, the findings provide an example of intensified lake droughts, and offer an insightful analysis of the droughts in the changing climate and anthropogenic  
680 influences. It should be valuable for improving our understanding of droughts, thus benefiting to develop integrated theories on the subject. This study is also useful for the effective promotion of water resource management and climate change adaptation.

### **Acknowledgments**

This work is supported by the 973 Program of National Basic Research Program of  
685 China (2012CB417003), a Key Program of Nanjing Institute of Geography and Limnology of the Chinese Academy of Sciences (CAS) (NIGLAS2012135001), and a CAS 100–Talents Project. We thank Prof. David Shankman for his constructive comments on an earlier version of the manuscript, Ms. R. Guo for data pre-processing, and Prof. Y. Chen for providing hydrological data. Prof. Peter Molnar and the  
690 anonymous reviewers are acknowledged for their constructive comments that have significantly improved the manuscript.

### **References**

- Dracup, J., Lee, K., Paulson Jr., E., 1980. On the definition of droughts. *Water Resour. Res.* 16(2), 297–302, doi: 10.1029/WR016i002p00297
- 695 Environment News Service, 2012. China's Largest Freshwater Lake Shrinks in Record Drought (available from <http://www.ens-newswire.com/ens/jan2012/2012-01-05-01.html>, accessed 8 August 2012).

- Feng, L., Hu, C., Chen, X., 2012. Satellites capture the drought severity around China's largest freshwater lake. *IEEE JSTAR*. 5, 1266–1271
- 700 Feng, H., and Liu, Y., 2014. Trajectory based detection of forest-change impacts on surface soil moisture at a basin scale [Poyang Lake Basin, China]. *Journal of Hydrology* 514, 337–346.
- Finlayson, M., Harris, J., McCartney, M., Lew, Y., Zhang C., 2010. Report on Ramsar visit to Poyang Lake Ramsar site, P. R. China (available from:  
705 [www.ramsar.org/pdf/Poyang lake report v8.pdf](http://www.ramsar.org/pdf/Poyang%20lake%20report%20v8.pdf), accessed 16 January 2013).
- Guo, H., Hu, Q., Zhang, Q., Feng, S., 2012. Impacts of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003-2008. *J. Hydrol.* 416-417, 19–27, doi: 10.1016/j.jhydrol.2011.11.027.
- Hays, M., Svoboda, M., Wall, N., Widhalm, M., 2011. The Lincoln declaration on  
710 drought indices: universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*. 92, 485–488.
- Hervé, Y., Claire, H., Lai, X., Stéphane, A., Li, J., Sylviane, D., Muriel, B-N., Chen, X., Huang, S., Burnham, J., Jean-François, C., Tiphane, M., Li, J., Rmié, A., Carlos, U., 2011. Nine years of water resources monitoring over the middle  
715 reaches of the Yangtze River, with ENVISAT, MODIS, Beijing-1 time series, altimetric data and field measurements. *Lake Reserv. Manage.* 16, 231–247, doi: 10.1111/j.1440-1770.2011.00481.x.
- 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,

720 90–100, doi: 10.1016/j.jhydrol.2007.09.005.

Jiao, L., 2009. Scientists line up against dam that would alter protected wetlands. Science 326, 508–509, doi: 10.1126/science.326\_508.

Joetzjer, E., Douville, H., Delire, C., Ciais, P., Decharme, B., Tyteca, S., 2013. Hydrologic benchmarking of meteorological drought indices at interannual to  
 725 climate change timescales : a case study over the Amazon and Mississippi river basins. Hydrol. Earth Syst. Sci., 17, 4885–4895.

Kallis, G., 2008. Droughts. Annu. Rev. Environ. Resour. 33, 85–118, doi : 10.1146/annurev.environ.33.081307.123117.

Keskin, F., Sorman, A. 2010. Assessment of the dry and wet period severity with  
 730 hydrometeorological index. Int. J. Water Resour. Environ. Engineer. 2, 29–139.

Keyantash, J., Dracup, J. A., 2002. The quantification of drought: an evaluation of drought indices. Bulletin of American Meteorological Society. 83, 1167–1180.

Kim, H. W., Hwang, K., Mu, Q., Lee, S. O., and Choi, M., 2012. Validation of MODIS 16 global terrestrial Evapotranspiration products in various climates and  
 735 land cover types in Asia. KSCE Journal of Civil Engineering, 16, 229–238.

Kingston, D., Fleig, A., Tallaksen, L., Hannah, D., 2013. Ocean–atmosphere forcing of summer streamflow drought in Great Britain. J. Hydrometeor. 14, 331–344, doi: 10.1175/JHM-D-11-0100.1.

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

- Lai, X., Huang, Q., Zhang, Y., Jiang, J., 2014a. Impact of lake inflow and the Yangtze River flow alternations on water levels in Poyang Lake, China. *Lake and Reservoir Management*. 30, 321–330.
- 745 Lai, X., Jiang, J., Yang, G., Lu, X., 2014b. Should the Three Gorges Dam be blamed for the extremely low water levels in the middle–lower Yangtze River? *Hydrol Process*. 28,150–160.
- Liu, Y., Song, P., Peng, J., Fu, Q., Dou, C., 2011. Recent increased frequency of drought events in Poyang Lake Basin, China: climate change or anthropogenic effects? *Hydro-climatology: Variability and Change (IAHS Publ.)*, 344, 99–104.
- 750 Liu, Y., Wu, G., Zhao, X., 2013. Recent declines of the China’s largest freshwater lake: trend or regime shift? *Environ. Res. Lett.* 8(1), 014010, 9pp. doi: 10.1088/1748-9326/8/1/014010.
- Liu, Y., Zhang, Q., Liu, J., Li, H., 2012. Climatic, Hydrologic and Environmental Change in Poyang Lake Basin. Science Press, Beijing. pp.262 (in Chinese).
- 755 Lloyd-Hughes, B., Saunders, M., 2002. A drought climatology for Europe. *Int. J. Climato.*, 22, 1571–1592, doi: 10.1002/joc.846.
- Loarie, S. R., Lobell, D. B., Asner, G. P., Mu, Q. and Field, C. B., 2011. Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Climate Change*. 1, 105–9.
- 760 Lomax, R. G., 2001. An Introduction to Statistical Concepts for Education and Behavioral Sciences. Lawrence Erlbaum Associates, Inc. Mahwah. pp.519.
- McKee, T. B., Doesken, N. J., Kliest, J., 1993. The relationship of drought frequency

- and duration to time scales. Proceedings of the 8th Conference of Applied  
765 Climatology, 17–22 January, Anaheim, CA. American Meteorological Society,  
Boston, MA. 179–184.
- McKee, T. B., Doesken, N. J., Kliest, J., 1995. Drought monitoring with multiple time  
scales. Ninth Conference on Applied Climatology, 15-20 January 1995, Dallas,  
TX. American Meteorological Society, Boston, MA. 233–236.
- 770 Mendicino, G., Senatore, A., and Versace, P., 2008. A groundwater resource index  
(GRI) from drought monitoring and forecasting in a Mediterranean climate. *J.*  
*Hydrol.*, 357, 282–302.
- Min, Q., and Zhan, L., 2013. Analysis of lake stage relationships between different  
locations in Poyang Lake. *The Yangtze River*, 44, 5–10 (in Chinese).
- 775 Mishra, A., Singh, V., 2010. Review of drought concepts. *J. Hydrol.* 391, 202–216,  
doi: 10.1016/j.jhydrol.2010.07.012.
- Mishra, A., Singh, V., 2011. Drought modeling – A review. *J. Hydrol.* 403, 157–175,  
doi: 10.1016/j.jhydrol.2011.03.049.
- Mu, Q., Zhao, M., Running, S. W., 2011. Improvements to a MODIS global terrestrial  
780 evapotranspiration algorithm. *Remote Sens. Environ.* 115, 1781–1800, doi:  
10.1016/j.rse.2011.02.019
- Nalbantis, I., Tsakiris, G. 2009. Assessment of hydrological drought revisited. *Water*  
*Resour. Manage.* 23, 881–897, doi: 10.1007/s11269-008-9305-1
- The Ramsar Convention, 2012. The List of Wetlands of International Importance, 25  
785 April 2012. (available from <http://www.ramsar.org/pdf/sitelist.pdf>, accessed on 8



August 2012).

Senay, G. B., Leake, S., Nagler, P. L., Artan, G., Dickinson, J., Cordova, J. T., Glenn, E.

P., 2011. Estimating basin scale evapotranspiration (ET) by water balance and remote sensing methods. *Hydrol. Process.* 25, 4037–4049, doi:

10.1002/hyp.8379.

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, doi:

10.1002/joc.1307.

Shankman, D., Liang, Q., 2003. Landscape changes and increasing flood frequency in

China's Poyang Lake region. *The Professional Geographer* 55(4), 434–445, doi:

10.1111/0033-0124.5504003.

Sheffield, J., Goteti, G., Wen, F., and Wood, E. F., 2004. A simulated soil moisture based drought analysis for the United States. *J. Geophys. Res.*, 109, D24108.

Shukla, S., Wood, A. W., 2008. Use of a standardized runoff index for characterizing

hydrologic drought. *Geophys. Res. Lett.* 35, L02405, doi:

10.1029/2007GL032487.

Smakhtin, V.U., 2001. Low flow hydrology: a review. *J. Hydrol.*, 240, 147–186.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., Vogt, J., 2014. World drought

frequency, duration, and severity for 1951-2010. *Int. J. Climatol.*, 34, 2792–2804.

Tallaksen, L. M., Madsen, H., Clausen, B., 1997. On the definition and modelling of

streamflow drought duration and deficit volume. *Hydrol. Sci. J.*, 42, 15–33.

Tallaksen, L. M., van Lanen, Henny A. J., 2004. *Hydrological Droughts: Processes*

and Estimation Methods for Streamflow and Groundwater. Elsevier Science, Amsterdam, The Netherlands.

810 Tan, G., Guo, S., Wang, J., and Ly, S., 2013. Hydrologic Change and Water Resources in Poyang Eco-economic Zone. China Water & Power Press, Beijing, China.

Todd, B., Macdonald, N., Chiverrell, R., Caminade, C., Hooke, J., 2013. Severity, duration and frequency of drought in SE England from 1967 to 2011. *Climatic Change*, 121, 673–687.

815 Van Lanen, H., Wanders, N., Tallaksen, L., Van Loon, A., 2013. Hydrological drought across the world: impact of climate and physical catchment structure. *Hydrol. Earth Syst. Sci.*, 17, 1715–1732.

Velpuri, N. M., Senay, G. B., Singh, R. K., Bohms, S., Verdinb, J. P., 2013. A comprehensive evaluation of two MODIS evapotranspiration products over the  
820 conterminous United States: Using point and gridded FLUXNET and water balance ET. *Remote Sensing of Environment*, 139, 35–49.

Vicente-Serrano, S. M., and López-Moreno, J., 2005. Hydrological response to different time scales of climatological drought: an evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. *Hydrol. Earth Syst. Sci.*, 9, 523–533.  
825

Wan, X. and Xu, X., 2010. Analysis of supply and demand balance of water resources around Poyang Lake. *The Yangtze River*, 41, 43–7.

Wang, H., Guan, H., Gutiérrez-Jurado, H., Simmons, C., 2014. Examination of water budget using satellite products over Australia. *Journal of Hydrology*, 511,

830 546–554.

Wilhite, D. A., Glantz, M. H., 1985. Understanding the drought phenomenon: the role of definitions. *Water International*, 10, 111–120.

Wilcox, B. P., Huang, Y., Walker, J. W., 2010. Long-term trends in streamflow from semiarid rangelands: uncovering drivers of change. *Global Change Biology*, 14,  
835 1676–1689.

Wu G., Liu, Y., Zhao, X., 2013. Analysis of spatio-temporal variations of evapotranspiration in Poyang Lake Basin using MOD16 products. *Geophysical Research*, 32, 617–627 (in Chinese with English abstract).

Wu, G., Liu, Y., 2014. Satellite-based detection of water surface variation in China's  
840 largest freshwater lake in response to hydro-climatic drought. *International Journal of Remote Sensing*, 35, 4544–4558, doi:  
10.1080/01431161.2014.916444.

Yevjevich, V., 1967. An objective approach to definitions and investigations of continental hydrologic droughts. *Hydrology Paper No. 23*, Colorado State  
845 University, Fort Collins, CO, pp.18.

Zelenhasic, E., Salvai, A., 1987. A method of streamflow drought analysis. *Wat. Resour. Res.*, 23, 156–168.

Zhang, Q., Li, L., Wang, Y.-G., Werner, A., Xin, P. Jiang, T., Barry, D., 2012. Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier?  
850 *Geophysical Research Letters* 39, L20402, doi: 10.1029/2012GL053431.

Zhang, Q., Ye, X., Werner, A., Li, Y., Yao, J., Li, X., Xu, C., 2014. An investigation of

enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts. *J. Hydrol.* 517, 425–434.

Zhao, X., and Liu, Y., 2014. Lake fluctuation effectively regulates wetland evapotranspiration: A case study of the largest freshwater lake in China. *Water*, 6, 2482–2500.

### Figure Captions

**Figure 1.** Geographic location of Poyang Lake, China. The lake is principally fed by a five river systems of the Poyang Lake Basin. Lake water flows into the Yangtze River via a sole outlet at the Hukou. Jiujiang is located 25 km upstream of the Hukou on the Yangtze River. The Three Gorges Dam (TGD) is upstream of the river.

**Figure 2.** Poyang Lake droughts in 2001-2010. (a) Variation in the standardized lake stage index (SLI). (b) Drought duration, frequency, intensity and severity, and (c) Drought frequency for moderate, severe and extreme droughts, compared to 1961-2000.

**Figure 3.** (a) Multi-year mean of monthly precipitation ( $P_R$ ) and evapotranspiration ( $E_R$ ) for the Poyang Lake region, lake inflow ( $I$ ) from five major rivers of the Poyang Lake Basin, and outflow ( $O$ ) into the Yangtze River. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin. (b) The relationship between drought severity and total water anomaly of ( $P_R - E_R + I$ ) of each

event for nine cases of Poyang Lake droughts.

875

**Figure 4.** (a) Multi-year mean of monthly precipitation ( $P_B$ ) and evapotranspiration ( $E_B$ ) for the Poyang Lake Basin, and outflow ( $O$ ) into the Yangtze River. (b) The relationship between  $P_B - E_B$  and inflow for nine cases of Poyang Lake droughts. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.

880

**Figure 5.** (a) Accumulated anomaly of water components and ( b) water budget at the Poyang Lake region for 2001-2010 compared to 1961-2000. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.

**Table 1.** Drought events occurring during the 2001-2010 time period.

No.	period	duration (month)	intensity (possibility)	severity	drought classification
1	2001.06-2001.11	6	-1.64 (0.0505)	-4.33	severe
2	2003.11-2004.08	10	-1.96 (0.0250)	-10.23	severe
3	2005.04-2005.05	2	-1.03(0.1515)	-1.39	moderate
4	2006.07-2007.07	13	-3.03 (0.0012)	-20.22	extreme
5	2007.10-2008.08	11	-2.01 (0.0222)	-13.21	extreme
6	2009.01-2009.02	2	-1.39 (0.0823)	-2.47	moderate
7	2009.04-2009.07	4	-1.14 (0.1271)	-3.11	moderate
8	2009.09-2010.01	5	-2.66 (0.0039)	-7.90	extreme
9	2010.10-2010.12	3	-1.21 (0.1131)	-1.56	moderate
overall		7.3±3.8	-1.79±0.70	-7.16±6.41	

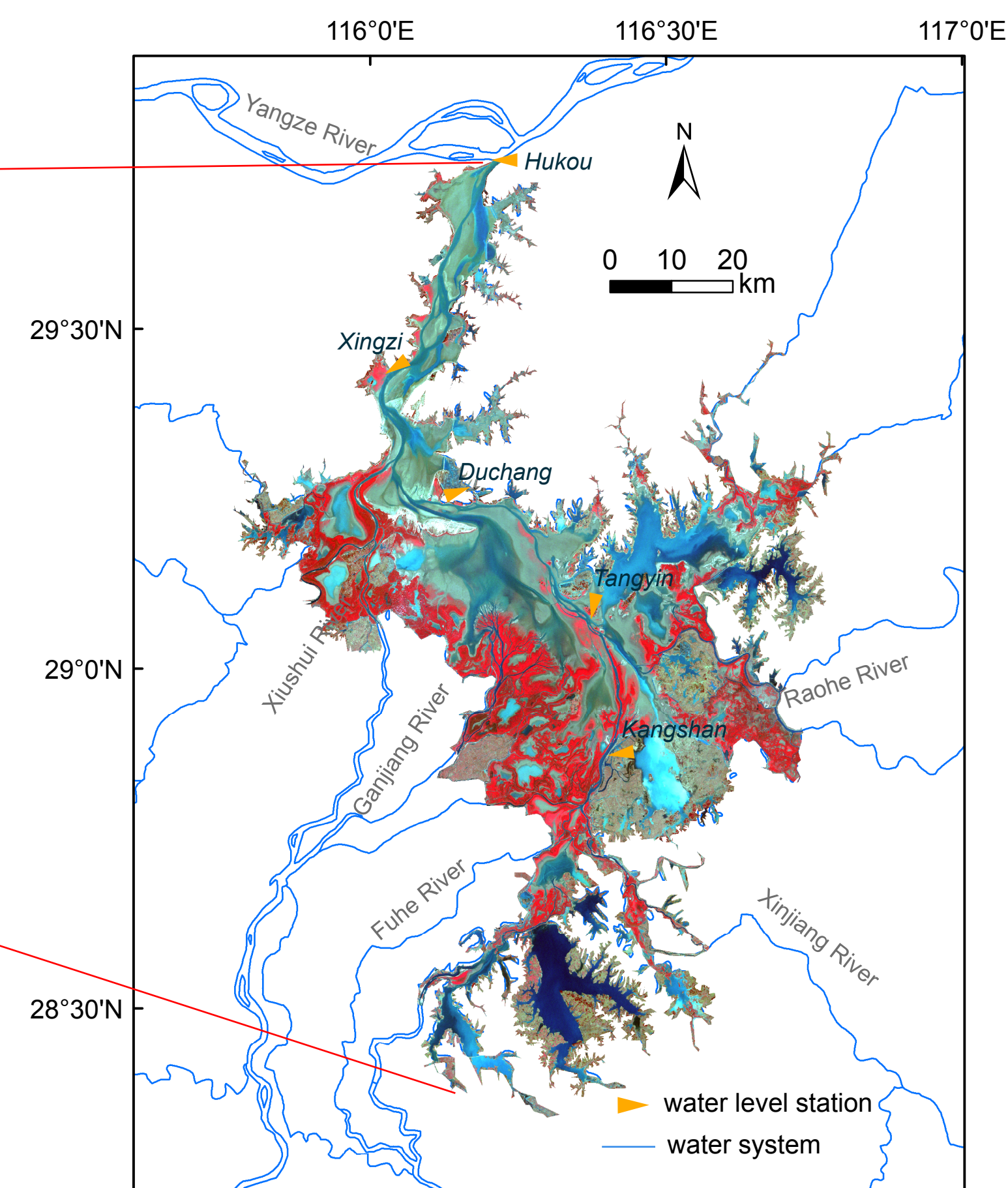
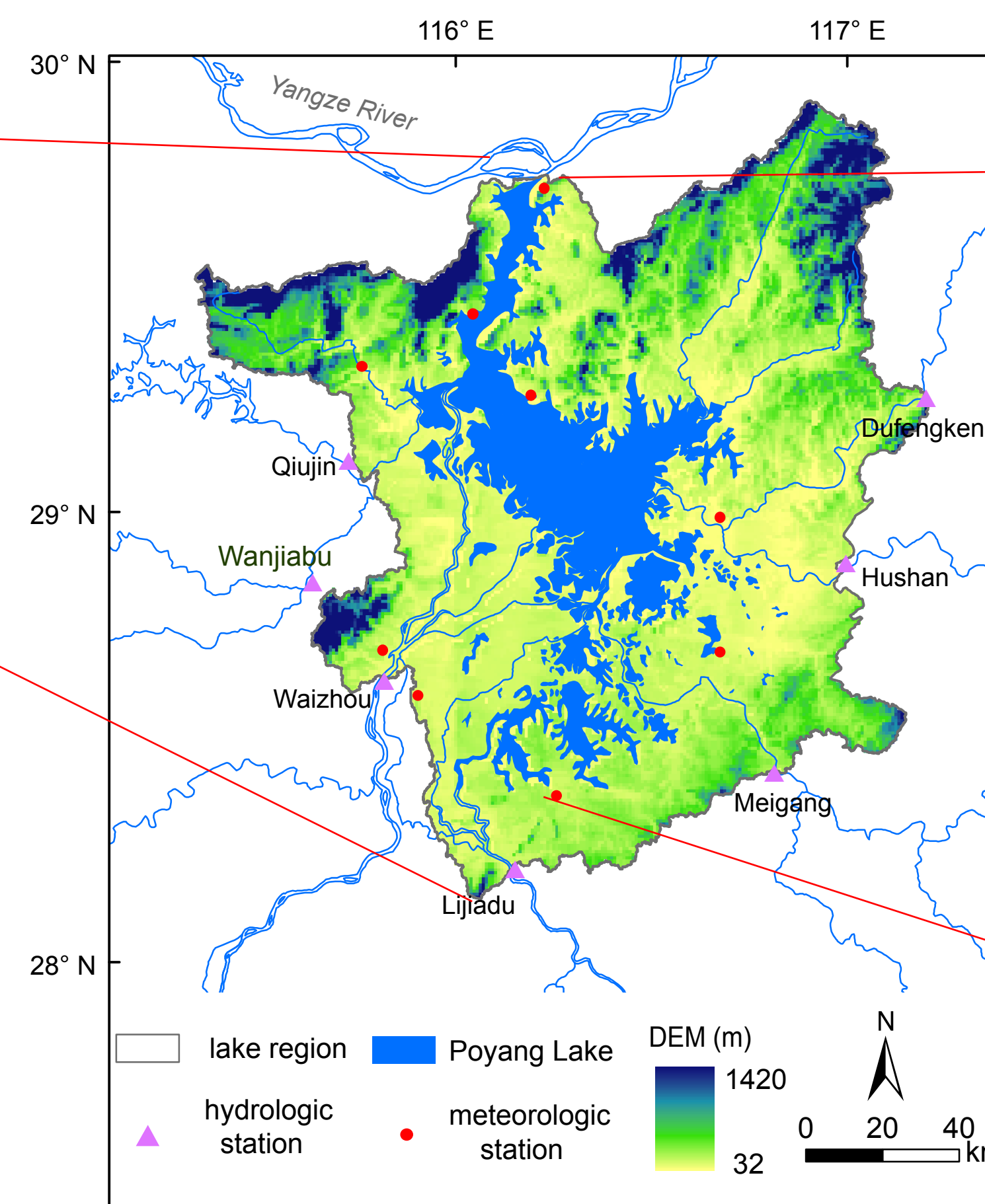
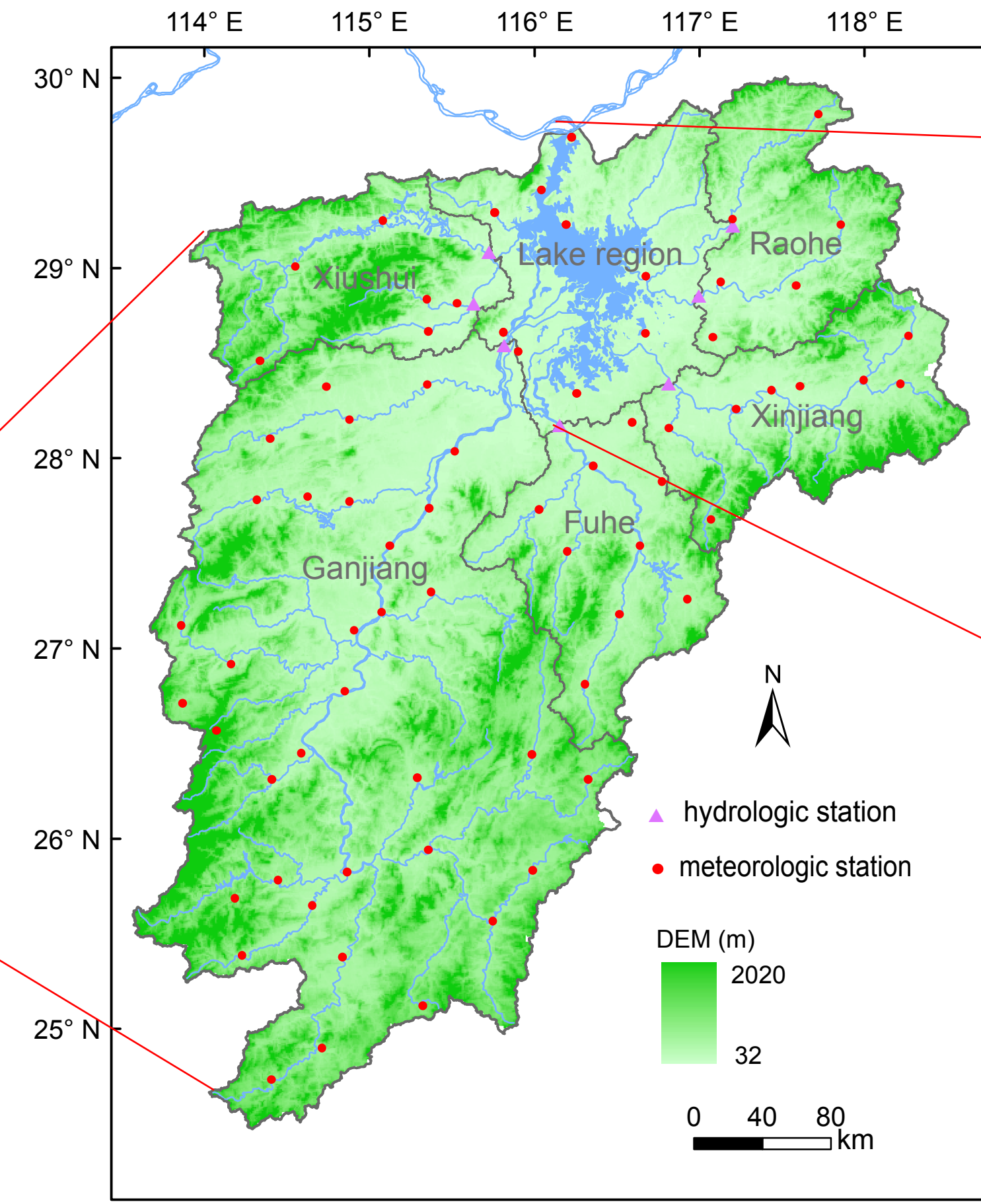
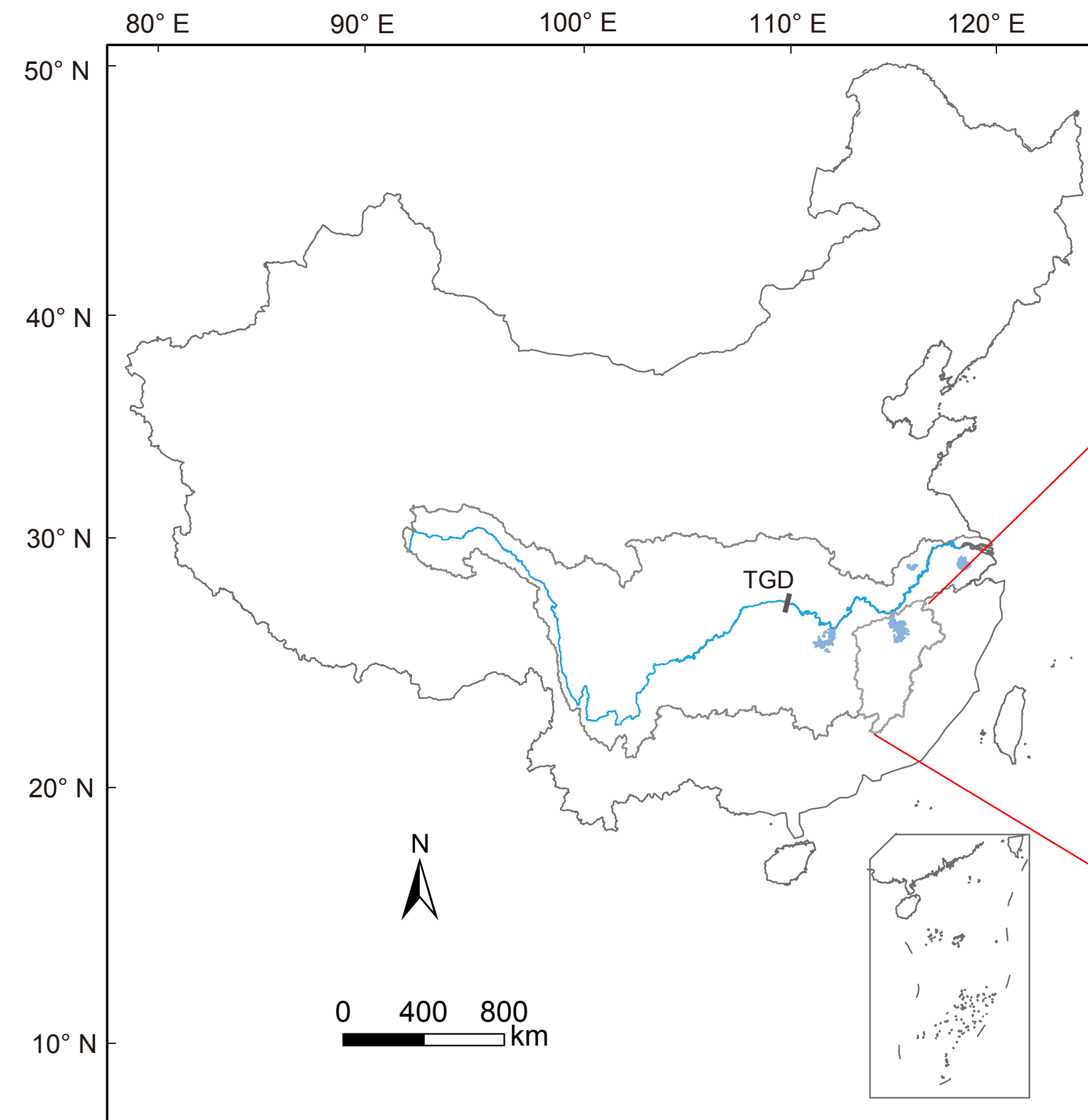
**Table 2.** Water components (unit in mm) of the Poyang Lake region and of the basin for the drought periods. The values in parenthesis are the anomaly of a component against the multi-year mean in 1961-2010. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.

	lake region						lake basin			
	$P_R$	$E_R$	$I$	$O$	$P_R-E_R+I$	$P_R-E_R+I-O$	$P_B$	$E_B$	$P_B-E_B$	$P_B-E_B-O$
2001.06-2001.11	133.6	106.6	333.9	432.5	360.9	-71.6	755.9	575.3	180.6	-251.9
	(-15.9)	(24.8)	(-19.6)	(-58.5)	(-60.2)	(-1.7)	(-23.3)	(55.1)	(-78.4)	(-19.9)
2003.11-2004.08	246.0	122.1	367.0	463.2	490.9	27.7	1282.4	666.7	615.7	152.5
	(-39.9)	(28.1)	(-284.2)	(-320.5)	(-352.2)	(-31.7)	(-210.3)	(85.1)	(-295.4)	(24.7)
2005.04-2005.05	81.2	31.2	225.2	203.3	275.2	72.0	489.5	149.9	339.6	136.3
	(-8.3)	(9.1)	(6.9)	(-39.1)	(-10.4)	(28.7)	(19.3)	(14.6)	(4.7)	(43.8)
2006.07-2007.07	241.9	182.0	584.3	711.3	644.2	-67.1	1469.4	1010.3	459.1	-252.2
	(-100.9)	(44.8)	(-210.7)	(-296.3)	(-356.4)	(-60.1)	(-321.2)	(152.1)	(-473.3)	(-177.0)
2007.10-2008.08	258.6	134.3	536.3	673.1	660.6	-12.6	1312.0	717.1	594.9	-78.2
	(-39.0)	(31.6)	(-141.9)	(-175.1)	(-212.5)	(-37.4)	(-248.0)	(72.5)	(-320.5)	(-146.6)
2009.01-2009.02	24.1	7.7	26.3	37.3	42.7	5.4	101.4	42.8	58.6	21.3
	(-8.2)	(1.2)	(-30.1)	(-30.1)	(-39.5)	(-9.4)	(-74.7)	(4.9)	(-79.6)	(-49.5)
2009.04-2009.07	129.9	72.5	268.1	307.0	325.5	18.5	698.8	401.2	297.6	-9.4
	(-44.9)	(16.3)	(-169.9)	(-171.8)	(-231.1)	(-59.3)	(-194.4)	(51.8)	(-246.1)	(-74.3)
2009.09-2010.01	49.9	45.1	93.4	167.5	98.2	-69.3	328.2	256.5	71.7	-95.8
	(-12.0)	(11.2)	(-39.6)	(-68.6)	(-62.8)	(5.8)	(-11.8)	(35.4)	(-47.2)	(21.4)
2010.10-2010.12	46.0	20.9	79.7	170.9	104.8	-66.1	228.9	123.1	105.8	-65.1
	(12.0)	(15.5)	(6.0)	(24.2)	(12.6)	(-11.6)	(48.6)	(13.4)	(35.1)	(10.9)
overalls	1211.1	722.3	2514.2	3166.1	3003.0	-163.1	6666.4	3942.9	2723.5	-442.5
	(-257.1)	(172.5)	(-883.1)	(-1135.9)	(-1312.5)	(-176.7)	(-1016.0)	(484.8)	(-1500.8)	(-366.5)

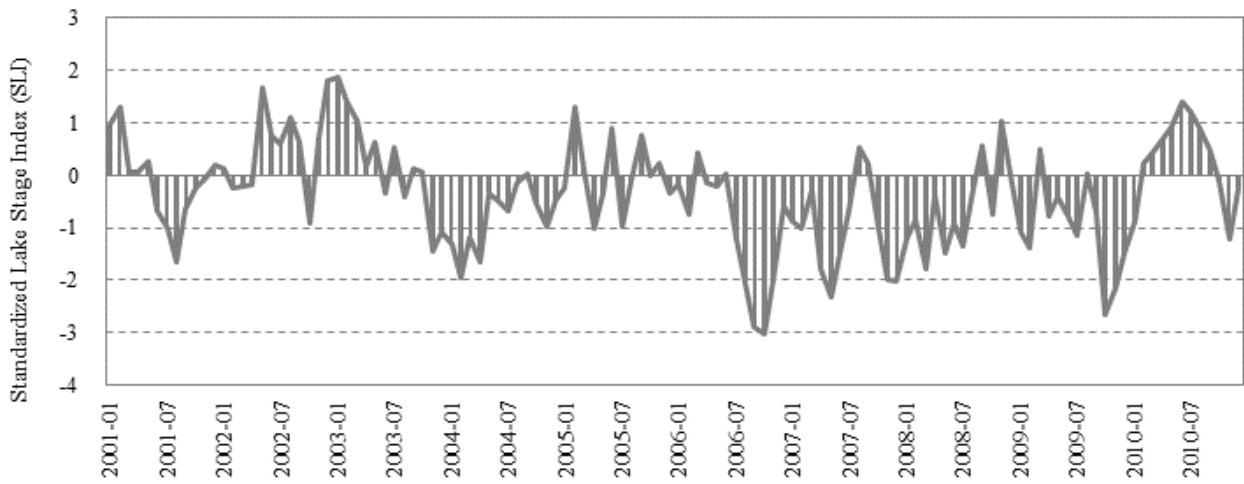
**Table 3.** Contribution of water components (unit in 100%) to a water anomaly of the water budget at the lake region and lake basin for nine lake drought events.

lake droughts	lake region				lake basin to	
	$P_R$	$E_R$	$I$	$O$	$I$	
	$P_B$	$E_B$				
2001.06-2001.11	0.20	0.19	0.30	0.31	0.39	0.61
2003.11-2004.08	0.17	0.06	0.86	-0.09	0.79	0.21
2005.04-2005.05	0.21	-0.04	0.68	0.15	0.80	0.20
2006.07-2007.07	0.18	0.11	0.23	0.48	0.53	0.47
2007.10-2008.08	0.18	0.07	0.46	0.28	0.83	0.17
2009.01-2009.02	0.28	0.03	0.65	0.04	0.96	0.04
2009.04-2009.07	0.20	0.07	0.85	-0.11	0.83	0.17
2009.09-2010.01	0.11	0.07	0.25	0.56	0.64	0.36
2010.09-2010.12	-0.05	0.05	0.02	0.97	0.19	0.81
overalls	0.17	0.09	0.46	0.28	0.71	0.29

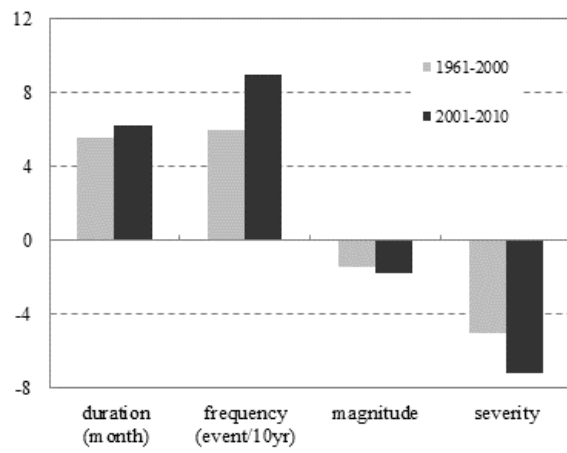




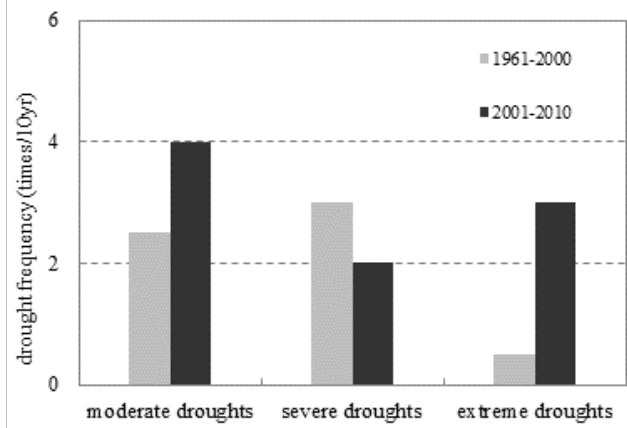
(a)



(b)



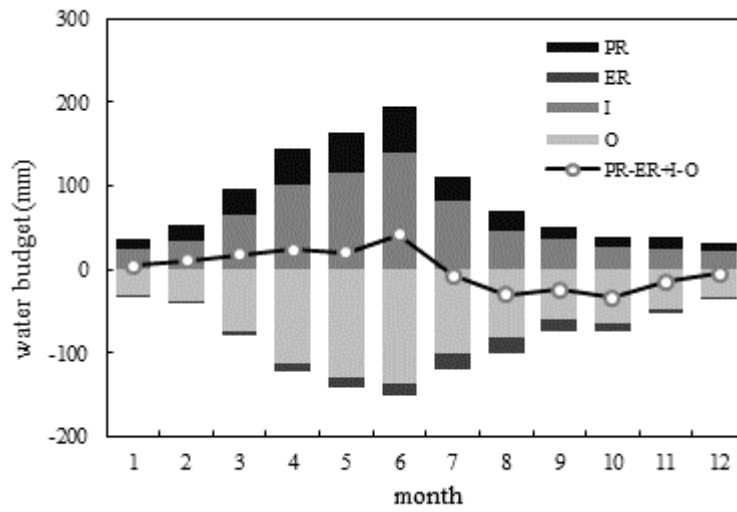
(c)



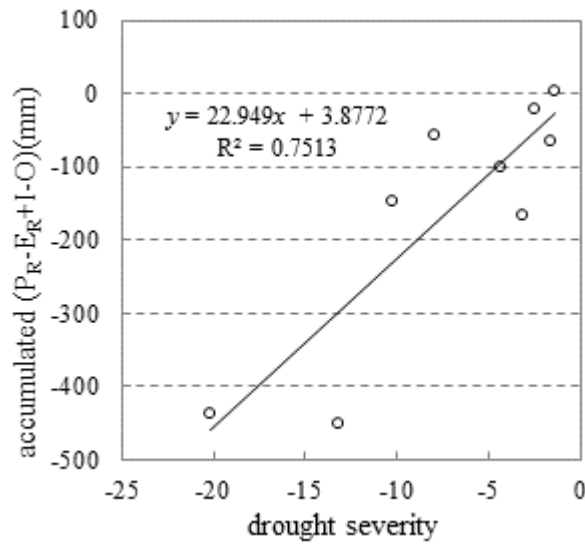
**Figure 2.** Poyang Lake droughts in 2001-2010. (a) Variation in standardized lake stage index (SLI). (b) Drought duration, frequency, magnitude and severity. Vertical axis indicates values for the four indices. (c) Drought frequency for moderate, severe and extreme droughts, compared to 1961-2000.



(a)

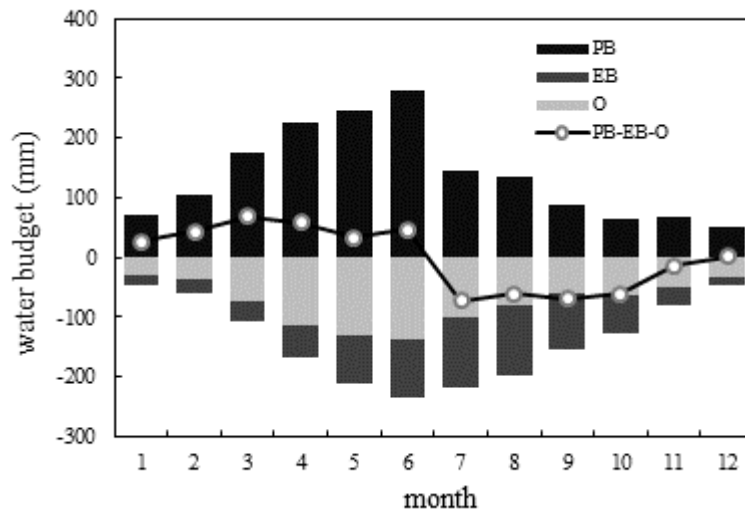


(b)

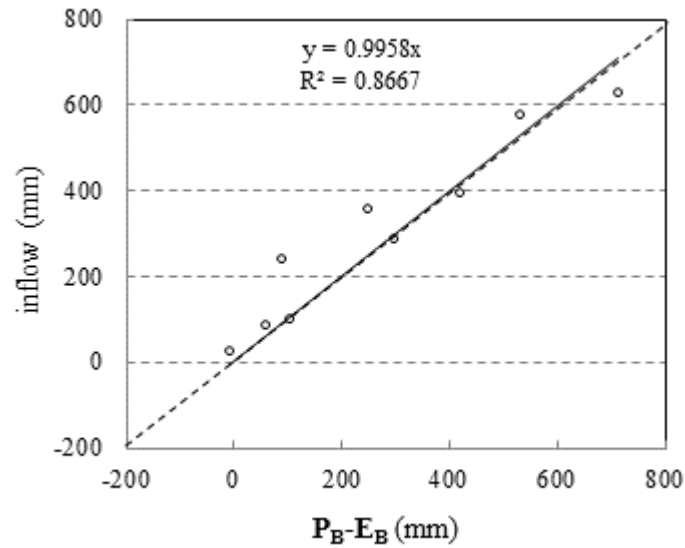


**Figure 3.** (a) Multi-year mean of monthly precipitation ( $P_R$ ) and evapotranspiration ( $E_R$ ) for the Poyang Lake region, lake inflow ( $I$ ) from five major rivers of the Poyang Lake Basin, and outflow ( $O$ ) into the Yangtze River. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin. (b) The relationship between drought severity and total water anomaly of ( $P_R-E_R+I$ ) of each event for nice cases of Poyang Lake droughts.

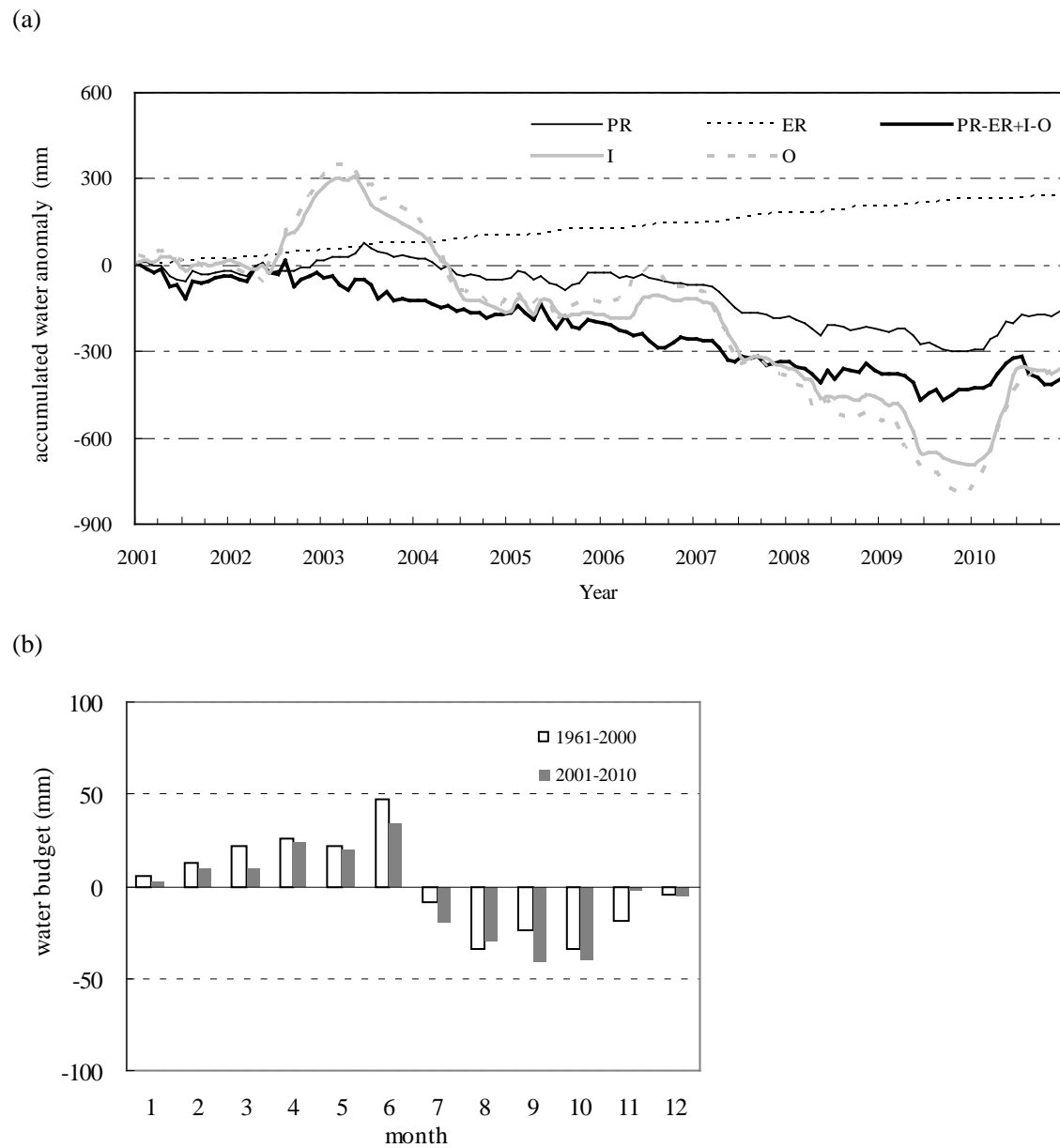
(a)



(b)



**Figure 4.** (a) Multi-year mean of monthly precipitation ( $P_B$ ) and evapotranspiration ( $E_B$ ) for the Poyang Lake Basin, and outflow ( $O$ ) into the Yangtze River. (b) The relationship between  $P_B - E_B$  and inflow for nine cases of Poyang Lake droughts. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.



**Figure 5.** (a) Accumulated anomaly of water components and (b) water budget at the Poyang Lake region for 2001-2010 compared to 1961-2000. All the water amounts are normalized to equivalent water height of the whole Poyang Lake Basin.