

The impact of Three Gorges Reservoir refill operation on water levels in Poyang Lake, China

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Abstract The refill operation of Three Gorges Reservoir (TGR) in the end of flood season significantly alters the water level regimes in Poyang Lake by reducing Yangtze River flow discharge. This study aims to investigate the impact of TGR refill operation on water level probability distribution of the Poyang Lake. The multiple linear regression model was established to estimate the water level with catchment inflow and Yangtze River flow as explanatory variables. A probability distribution of water level was derived and the refill operation effects were quantified by comparing the water level distribution at Xingzi station in the Poyang Lake before and after TGR. It is revealed that Yangtze River flow, rather than the catchment inflow is the dominant factor affecting the water level of Poyang Lake during TGR refill operation period. Results also show that the water level distribution estimated by the derived distribution method can be accepted as a theoretical distribution and has a comparable accuracy as the directly fitted distribution method before TGR. The derived method can be adapted to the environment change, thus is well suited for estimating the water level distribution after TGR. It is observed that Xingzi water levels with different design frequencies have been reduced due to the TGR refill operation. The water level reductions induced

by TGR refill operation are 1.28, 0.87, and 0.50 m corresponding with design frequencies of 50, 90 and 99 %, respectively. The results from this work would improve the understanding of the TGR effects on the downstream river–lake system and provide scientific evidences for formulating better scheme for water resources management in this region.

Keywords Water level · Probability distribution · Three Gorges Reservoir · Refill operation effect · Yangtze River · Poyang Lake

1 Introduction

Lakes not only provide valuable economic resources for human beings but also play important roles in regional environmental and ecological issues, such as hydrologic cycle and wetland vegetation growth. Water level, a key hydrologic variable, is often considered as the critical indicator of water regime in lake area. Changes in lake water levels are significant for local water resources management, hydraulic design and ecological development along lake coasts. In recent years, this issue has become increasingly important as recent global climate changes and increasing human activities have reformed the behavior of traditional lake level fluctuations (Guo et al. 2012; Yuan et al. 2015).

Poyang Lake, the largest freshwater lake in China, located in the middle Yangtze River reaches, is one of few lakes that remain naturally connected to the Yangtze River (Fig. 1). It receives water inflows from its catchment, and discharges to the Yangtze River at Hukou (the junction of the Yangtze River and Poyang Lake) in the north. The Lake is essential to the regional development of Jiangxi

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Fig. 1 Locations of Poyang Lake and its catchment: **a** river networks of the lake catchment and the locations of gauging stations; and **b** locations of the Yangtze River, the Three Gorges Reservoir (TGR), Poyang Lake and the Hankou station



Province and water supply for millions of people downstream (Li et al. 2015a). It is also recognized as a wetland of international importance for its remarkable biodiversity and habitat for various rare or endangered species, such as

Yangtze finless porpoise, Siberian crane, and Oriental stork. Because of its worldwide ecological value, Poyang Lake has attracted international concerns (Li 2009; Feng et al. 2012; Zhang et al. 2014a).

The function and extent of the lake ecosystem are sensitive to water level changes. The water level regime modification impacts not only water supply security but also environmental requirements of the ecosystem (Sun et al. 2014a). It has been observed that Poyang Lake water levels have been declined significantly in the last decade (Liu et al. 2013; Wang et al. 2014; Lai et al. 2014d), which results in water supply and irrigation problems for the 12.4 million inhabitants in the surrounding region. Changes in the Lake's hydrological regime may also lead to substantial impacts on the surrounding wetland vegetation and ecosystem health more generally (e.g., Hervé et al. 2011; Zhang et al. 2012; Feng et al. 2013).

Poyang Lake has complex water regimes because of its strong interaction with the Yangtze River. Its water level not only depends on inflows from the rivers in the catchment, but also the Yangtze River flow (Hu et al. 2007; Li et al. 2015b; Dai et al. 2015). Numerous studies have shown that except for the climate anomalies, intensified human activities in the lake catchment and the upstream of the Yangtze River, such as agriculture, dam construction, reservoir operation, river channelization etc., would affect the lake hydrological processes and change water level (Altinbilek 2002; Xu and Milliman 2009; Zhang et al. 2015a). Among the reservoirs be constructed in the upper Yangtze River, the Three Gorges Reservoir (TGR) is one of the world's largest hydraulic projects (about 800 km upstream of the Poyang Lake), which began to be built in 1994 and firstly impounded water in 2003. The coincidence between occurrence of abnormal low water levels in the Poyang Lake and the refill operation of TGR has attracted much attention (Xu and Milliman 2009; Dai et al. 2010).

A number of studies have indicated that the refill operation of the TGR altered the natural flow regime of the middle and lower reaches of Yangtze River, which in turn considerably affected the water level variation of the Poyang Lake (Guo et al. 2012; Wang et al. 2013; Gao et al. 2013; Lai et al. 2014b; Zhang et al. 2014b). Guo et al. (2012) used a method of "analogous years" was used to isolate and quantify the TGR effects. They found that the discharge changes in the Yangtze River caused by the TGR have altered the interaction between the Yangtze River and Poyang Lake; the weakened blocking effect of the Yangtze River due to the TGR in autumn allows more lake water flow into the river. Constructed a generalized additive model (GAM), Zhang et al. (2012) examined the impact of TGR on both the Yangtze River and Poyang Lake quantitatively. Comparison of modeling results before and after TGR for 2003–2008 indicated an average 2 m water level drop at Hukou station. This analysis revealed considerable impacts of the TGR on Poyang Lake, particularly a reduced water level over the dry period in the late autumn. Wang et al. (2013) quantified

the blocking and draining effects of TGR's water regulation on Lake Poyang by altering Hukou level and gradient, and concluded that the seasonality of downstream Yangtze levels are considerably altered, primarily reflected by the significant and persistent level changes under TGR's four major water dispatch modes. Liu et al. (2013) examined the change in lake size and water balance and showed that the recent lake decline was principally triggered by the weakened blocking effect of the Yangtze River. Lai et al. (2014c) used a coupled hydrodynamic model to analyze the effects of TGR refill operation on outflow of lake and water level and clarified dynamic mechanism of hydrological responses. Their results showed that the rapid Yangtze River flow drawdown drives an instant increase of hydraulic gradient at the lake outlet, which obviously accelerates lake drainage to the Yangtze River and subsequently lowers the lake level earlier than normal. Zhang et al. (2014b) employed a physically-based hydrodynamic model to explore catchment and Yangtze River controls on the Poyang Lake's hydrology. Model simulations demonstrated that the drainage effect of the Yangtze River was the primary causal factor. Compared to climate variability impacts on the Lake catchment, modifications to Yangtze River flows from the TGR have had a much greater impact on the seasonal (September–October) dryness of the Lake. Zhang et al. (2015b) pointed out that the conjunction of extreme droughts in the Poyang Lake and the upper Yangtze reaches coincided with the TGR refill operation is the main cause of the low water level in the 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 refill period. These insightful studies confirmed that the TGR altered flow regimes of Poyang Lake and demonstrated possible hydrological changes linking with the TGR refill operation.

Frequency analysis of hydrological event, such as rainfall, flood, low flow, annual runoff and water level, is essential for planning, designing and evaluating water management measures. The objective of frequency analysis is to relate the magnitude of a hydrological event to its frequency of occurrence through probability distribution. Until now, a quantitative assessment method is still lacking. This paper focuses on evaluating the impact of TGR refill operation on water level by modifying probability distribution. The main objectives of this study are: (1) Establish a multiple linear regression model to estimate the water level of Poyang Lake with catchment inflow and Yangtze River flow as explanatory variables, and further explore whether the catchment inflow or Yangtze River flow is the dominant factor? (2) Develop a derived probability distribution for water level of Poyang Lake from

catchment inflow and Yangtze River flow; (3) Quantify refill operation effects by comparing the water level probability distribution before and after TGR.

2 Study area and data

2.1 Study area

Poyang Lake (28°22′–29°45′N, 115°47′–116°45′E), located in the south bank of the middle reaches of the Yangtze River basin, is the largest freshwater lake in China. The Poyang Lake basin covers an area of 162,255 km², which accounts for about 97 % of Jiangxi Province and 9 % of the Yangtze River basin (Guo et al. 2011). The catchment of the Lake varies in elevation from 2200 m (above sea level) in mountainous regions to about 30 m in alluvial plains downstream of the major watercourses and around the Lake. Land use in the catchment consists of forest (46 %), shrub land (25 %), crop land (25 %) and small areas of pasture, urban centers and open water. The basin belongs to a subtropical monsoon climate zone with a mean annual precipitation of 1680 mm and an annual average temperature of 17.5 °C (Ye et al. 2011; Hong et al. 2014a; Tao et al. 2014).

Poyang Lake receives inflows from five major rivers (Xiushui, Ganjiang, Fuhe, Xinjiang and Raohe) within the catchment, and discharges to the Yangtze River at Hukou in its northern part (Fig. 1). Catchment runoff varies considerably throughout the year, and Lake water levels demonstrate a distinct seasonal variation, with a time lag in the peak water level relative to the maximum catchment runoff. The catchment runoff starts to increase in February and reach peaks in June, while the Lake water level starts to rise in February and reach peaks in July, before dropping some 8.8 m (on average) to minimum values during December and January. Accordingly, the Lake area varies significantly. The lake level rises and the lake coverage expands to an area of about 3800 km² in the wet season and shrinks to an approximate river channel in the dry season (Ye et al. 2011).

Located in Yichang, Hubei province, about 800 km upstream of Poyang Lake along Yangtze River, TGR is the largest hydraulic project in the world. The contributing area of TGR is 1,000,000 km², and the annual average discharge and runoff volume at the dam site are 14,300 m³/s and 4510 × 10⁸ m³, respectively. The total storage capacity of the TGR is 393 × 10⁸ m³, of which 221.5 × 10⁸ m³ is flood control storage. It plays a key role in the flood control, power generation, navigation etc. for the Yangtze River basin, which is a social-economically developed area in China (Li et al. 2013; Zhang et al. 2015c).

The TGR started to refill in 2003 and reached to normal water level of 175 m in 2010. According to the current refill rules of TGR proved by the Ministry of Water Resources (MWR 2009; Li et al. 2014), the TGR storage 221.5 × 10⁸ m³ water to reach normal water level of 175 m from 145 m in the end of flood season (generally from September 15 to October 31, lasting 47 days). During the refill operation period, the mean outflow discharge will be reduced by 5460 m³/s. The Poyang Lake is strongly interacted with the Yangtze River flow and is inevitably affected by the TGR operation.

2.2 Data

The available data in this study includes observed daily river flows at seven gauging stations in five tributary rivers, Hankou gauging station in the main Yangtze River, and observed daily water levels at Xingzi gauging station in the Poyang Lake for the period of 1953–2013 (see Fig. 1; Table 1), which were obtained from the Hydrological Bureau of Jiangxi province and Yangtze River Water Resources Commission of China. The sum of the seven gauging stations in five tributary rivers as chosen as the catchment inflow of the Poyang Lake, river flows at Hankou gauging station were used to represent the Yangtze River flow regime, and water levels of Xingzi gauging station were considered to best reflect the hydrological regime of Poyang Lake (Li et al. 2015b).

For the Ganjiang, Fuhe and Xinjiang River basins, only one gauging station at each main stream was selected. For the Xiushui and Raohe River basins, gauging stations at tributaries (Wanjiabu station for the Xiushui River, Hushan and Dufengken stations for the Raohe River) were included to account for the runoff contributions to the main stream (Table 1). Hydrological gauging stations are upstream of the Lake's maximum inundated area, and hence Lake surface expansion does not have an impact on these recordings. The total drainage area of these gauging stations is 137,143 km², leaving an ungauged area of 25,082 km² (15.5 % of the whole catchment area, including the Lake water surface).

The main objective of this study is evaluating the impact of TGR refill operation on water level of Poyang Lake from the perspective of hydrological frequency analysis. One of the basic assumptions in hydrological frequency analysis is that all observations of the random variable of interest are mutually independent (Vogel and Wilson 1996; De Michele and Salvadori 2002; Xiong et al. 2014). Therefore, the hydrological data should be properly selected so that the assumption of independence is satisfied. Since the daily series of discharges or water levels are not independent, the yearly mean values (a common practice in hydrological frequency analysis) in TGR's refill period are selected as

Table 1 List of hydrological gauging stations used in this study

Gauging station	Location	Coordinates	Gauged area (km ²)
Qiujiu	Xiushui	(115.41°, 29.10°)	9914
Wanjiabu	Liaohe tributary of Xiushui	(115.65°, 28.85°)	3548
Waizhou	Ganjiang	(115.83°, 28.63°)	80,948
Lijiadu	Fuhe	(116.17°, 28.22°)	15,811
Meigang	Xinjiang	(116.82°, 28.43°)	15,535
Hushan	Le'an tributary of Raohe	(117.27°, 28.92°)	6374
Dufengken	Changjiang tributary of Raohe	(117.12°, 29.16°)	5013
Hankou	Yangtze River	(114.28°, 30.58°)	1,488,036
Xingzi	Poyang Lake	(116.03°, 29.45°)	–

random variables of interest. Specially, the mean values of daily catchment inflow, river flow at Hankou gauging station (Hankou flow) and water level at Xingzi gauging station (Xingzi water level) during the refill operation period were calculated with corresponding series from 1953 to 2013. These defined series were used in the multiple linear regression model and estimation of the water level probability distribution of Poyang Lake before and after TGR.

In general, TGR starts to store water on September 15 and finishes on October 31, lasting 47 days. The travel time of Yangtze flow from TGR to Hankou is approximately 5 days and Hukou (the outlet of Poyang Lake) is about 7 days during refill operation period (Wang et al. 2013; Gao et al. 2013; Lai et al. 2014c). To guarantee the synchronism of data, it is necessary to adjust the refill-impacted periods for Hankou flow based on the Yangtze flow's travel time. However, catchment inflow to Poyang Lake is propagated within the Poyang tributary catchment, where discharge routing is independent from the Yangtze flow's travel time upstream to Hukou. Furthermore, Poyang level is influenced by both the Yangtze flow and catchment inflow and simply adjusting Poyang level using the travel time from TGR to Hukou mismatches the timing of catchment inflow. Therefore, the unadjusted Poyang levels and catchment inflows, along with the Hankou flows adjusted by the travel time from TGR to Hukou (Hankou flows need to be adjusted to be synchronous to Hukou flows) are used for analysis in this study.

3 Methodologies

3.1 Water level function

Catchment inflow and the Yangtze River flow are the two substantial influencing factors that determine the water level of Poyang Lake (Ye et al. 2014b). The water level can be expressed using a function of its influencing factors. Multiple linear regression model (Xiong et al. 2013) was

employed to estimate Xingzi water level using catchment inflow and Hankou flow as explanatory variables:

$$Z = g(X, Y) = aX + bY + c \tag{1}$$

where Z , X and Y represent Xingzi water level, catchment inflow and Hankou flow, respectively; c is a constant term; a and b are regression coefficients.

The F -test was used to test significance of the regression equation. The determination coefficient R^2 and relative error (RE) were employed to assess the accuracy of simulation. These indexes have been commonly used in assessing hydrological model efficiency. To explore whether catchment inflow or Hankou flow is the dominant influencing factor for the Xingzi water level, the standardized regression coefficient is used to compare the relative importance of these two influencing factors (Myoung et al. 2011; Ye et al. 2013, 2014a).

$$\beta_X = a \cdot \frac{\sigma_X}{\sigma_Z} \tag{2a}$$

$$\beta_Y = b \cdot \frac{\sigma_Y}{\sigma_Z} \tag{2b}$$

where β_X and β_Y are standardized regression coefficient of explanatory variables X and Y ; σ_Z , σ_X and σ_Y represent standard deviation of Z , X and Y . If the absolute value of β_X is larger than β_Y , then it means that catchment inflow has a greater effect on the Xingzi water level, and vice versa.

3.2 Fitted probability distribution method

Frequency analysis of hydrological variable is normally carried out by fitting an assumed theoretical probability distribution function to the observed data and then estimate quantile for a given return period (Vogel and Wilson 1996). The main modeling problem of this so-called fitted probability distribution method is the selection of a probability distribution coupled with the choice of parameter estimation procedures (Cunnane 1989). Probability distributions provide the essential basic formula to model a hydrological variable quantile in terms of its exceedance probability.

Once a distribution is selected, the next step is to estimate its parameters.

The Pearson type three distribution (P3) is widely accepted as the best probability density function (PDF) to fit river flow and water level series in China (Yang et al. 2010; Hong et al. 2014b). Therefore, the P3 distribution was chosen to fit the catchment inflow, Hankou flow and Xingzi water level series before TGR. The PDF of P3 distribution can be expressed as

$$f(x) = \frac{\beta^\alpha}{\Gamma(\alpha)}(x - \gamma)^{\alpha-1} e^{-\beta(x-\gamma)}, \quad x > \gamma, \tag{3}$$

where α , β and γ are the shape, scale and location parameters, respectively. $\Gamma(\alpha)$ is the Gamma function.

For easier understanding and more convenient analysis, the parameters in the PDF are transformed into three common sample statistics, that is, the expectation (Ex), the coefficient of variation (Cv), and the coefficient of skew (Cs). The transformation relationships between the P3 distribution parameters and these sample statistics are described as below:

$$Ex = \frac{\alpha}{\beta} + \gamma, \quad Cv = \frac{\sqrt{\alpha}}{\alpha + \beta\gamma}, \quad Cs = \frac{2}{\sqrt{\alpha}}, \tag{4}$$

L-moment method was used to estimate P3 distribution parameters for given data series (Hosking 1990). The Kolmogorov–Smirnov’s (K–S) test (Tsai et al. 2001; Rahman et al. 2010) based on statistic D was used to verify the null hypothesis that the catchment inflow, Hankou flow and Xingzi water level series follow the P3 distributions. In this paper, the 95 % confidence level was selected to reject or accept a fitted distribution.

3.3 Derived probability distribution method

The assumption of traditional fitted probability distribution method is that the probability distribution estimated from historical data is unchanged. However, the probability distribution of Xingzi water level has been altered by TGR refill operation. Consequently, this method of fitting and extrapolating the assumed distribution based on the historic observations would not be suited to estimate future water resources situation.

To consider the impact of environment change, e.g., TGR refill operation, on the probability distribution of Xingzi water level, the derived probability distribution method is a very promising tool to estimate the Xingzi water level distribution from its influencing factors. The idea of the derived probability distribution method was first proposed by Eagleson (1972) and intended to replace the traditional fitting-and- extrapolation method in frequency analysis for nonstationary hydrological systems. De

Michele and Salvadori (2002) had made a very nice summary of the derived probability distribution method in terms of the probability theory. The major advantage of this method is the direct inclusion of the relationship between a dependent variable, i.e., the hydrological variable of concern and several independent variables in the formulation of the probability distribution of the dependent variable. With the explicit use of the influencing factors, the impacts of environment change on the distribution of the dependent variable can be comprehensively investigated, thus making the derivation method useful in the estimation of the magnitude and frequency of hydrological events under nonstationary circumstances (De Michele and Salvadori 2002; Xiong et al. 2014).

The derived distribution method has been widely used in flood, low flow and annual runoff frequency analysis (Eagleson 1978a, b; Diaz-Granados et al. 1984; Gottschalk and Weingartner 1998; De Michele and Salvadori 2002; Sivapalan et al. 2005; Xiong et al. 2014). In this paper, this method was extended to derive the distribution of Xingzi water level from catchment inflow and Hankou flow.

Let $F_X(x)$ and $F_Y(y)$ be the cumulative distribution function (CDFs) of catchment inflow X and Hankou flow Y , respectively. Their corresponding PDFs are $f_X(x)$ and $f_Y(y)$, with the joint PDF of X and Y denoted as $f(x,y)$. For the proposed derivation approach, given the water level function $g(X,Y)$ expressed by Eq. (1) and the joint probability density distribution $f(x,y)$, the probability distribution of Xingzi water level $F_Z(z)$ can be derived according to the following equation:

$$F_Z(z) = \iint_{\Omega: g(x,y) < z} f(x,y) dx dy \tag{5}$$

where Ω is the integration domain consisting of all (x, y) values that satisfy the constraint of $g(x,y) < z$.

Based on the physical mechanism analysis, the Xingzi water level increases as catchment inflow and Hankou flow increases, which demonstrates that both the regression coefficients a and b in Eq. (1) are positive (Lai et al. 2014a). In this case, integration domain can be specifically expressed as follows

$$x < w(y, z) = \frac{z - (c + by)}{a} \tag{6}$$

Accordingly, Eq. (5) can be represented as:

$$F_Z(z) = \int_{-\infty}^{+\infty} \left[\int_{-\infty}^{w(y,z)} f(x,y) dx \right] dy \tag{7}$$

If X and Y are independent, then

$$f(x,y) = f_X(x) \cdot f_Y(y) \tag{8}$$

Substituting Eq. (8) to Eq. (7), then it leads to

$$F_Z(z) = \int_{-\infty}^{+\infty} \left[\int_{-\infty}^{w(y,z)} f_X(x) dx \right] f_Y(y) dy = \int_{-\infty}^{+\infty} F_X[w(y,z)] f_Y(y) dy \tag{9}$$

Let $u = F_Y(y)$, Changing the integral variable from y to u , with the corresponding integral interval from $(-\infty, +\infty)$ to $[0, 1]$, then Eq. (9) can be rewritten as

$$F_Z(z) = \int_0^1 F_X \left[\frac{z - c - bF_Y^{-1}(u)}{a} \right] du \tag{10}$$

where $F_Y^{-1}(u)$ is the inverse function of CDF $F_Y(y)$. From Eq. (10), the probability distribution of Xingzi water level $F_Z(z)$ can be estimated by applying the Monte Carlo sampling technique (Yu et al. 2014; Xiong et al. 2014).

The proposed derived probability distribution method in this paper can be used to estimate the probability distribution of Xingzi water level both before and after TGR. Before TGR, the probability distributions of catchment inflow and Hankou flow are firstly estimated using the fitted probability distribution method; then the derived probability distribution of Xingzi water level is obtained from Eq. (10). The goodness-of-fit of the derived probability distribution of Xingzi water level can be also assessed by statistic D of the K–S test. In addition, to further verify the accuracy of derived probability distribution, it was compared with the fitted probability distribution of Xingzi water level.

After TGR, the probability distributions of Hankou flow and Xingzi water level are altered. To quantify the effects of TGR refill operation, it is assumed that the probability distribution of catchment inflow keeps unchanged. Let Y' and Z' represent Hankou flow and Xingzi water level after TGR, respectively. It is assumed that the Hankou flow is reduced by discharge ΔY during the refill operation period, and then Y' is calculated as follows

$$Y' = Y - \Delta Y \tag{11}$$

Based on this relationship described in Eq. (11) and the CDF $F_Y(y)$, the probability distribution of Y' can be easily derived as follows

$$F_{Y'}(y') = F_Y(y + \Delta y) \tag{12}$$

where $F_{Y'}(y')$ is the probability distribution of Y' .

Subsequently, let $u' = F_{Y'}(y')$, the probability distribution of Z' can be derived similarly, by replacing the $F_Y^{-1}(u)$ in Eq. (10) with $F_{Y'}^{-1}(u')$

$$F_{Z'}(z') = \int_0^1 F_X \left[\frac{z' - c - bF_{Y'}^{-1}(u')}{a} \right] du' \tag{13}$$

where $F_{Y'}^{-1}(u')$ is the inverse function of CDF $F_{Y'}(y')$. By comparing the water level probability distribution of Xingzi water level before TGR $F_Z(z)$ and after TGR $F_{Z'}(z')$, the refill operation effects can be quantified.

4 Results and analysis

4.1 Calibration and validation of the water level function

The data from 1953 to 2013 was divided into two periods: 1953–2002 and 2003–2013. The former was used for model calibration and the latter for model validation. On the basis of catchment inflow, Hankou flow and Xingzi water level data from 1953 to 2002, the multiple linear regression equation, i.e. water level function is calculated as follows.

$$Z = 5.36 \times 10^{-4}X + 2.34 \times 10^{-4}Y + 6.431435 \tag{14}$$

The regression for Eq. (14) is statistically significant (F statistic is 393.17, $p < 0.001$). Figure 2a, b shows the correlation of the simulated and observed Xingzi water level in the model calibration and validation periods, respectively. The results of R^2 and RE in the calibration period are 94.23 and 0.80 %, in the verification period are 96.73 and -3.45 %, respectively. Figure 2c shows comparisons of simulated and observed Xingzi water level from 1953 to 2013. It is observed that the simulated Xingzi water levels can fit the observed Xingzi water levels very well. The results show that the Xingzi water level can be reasonably estimated by the linear combination of catchment inflow and Hankou flow both before and after TGR.

On the other hand, the standardized regression coefficients of catchment inflow and Hankou flow are 0.237 and 0.939, respectively. This result demonstrates that the Hankou flow is much more important than the catchment inflow in explaining the Xingzi water level. That is, the Yangtze River flow is the dominant factor during the refill operation period.

4.2 Estimation of fitted distributions before TGR

The catchment inflow, Hankou flow and Xingzi water level series before TGR were assumed to follow P3 distributions. The parameters of P3 distributions were estimated by the L-moment method and the results were listed in Table 2. The K–S test was used to verify the null hypothesis that catchment inflow, Hankou flow and Xingzi water level follow the P3 distributions. Table 2 shows that the null

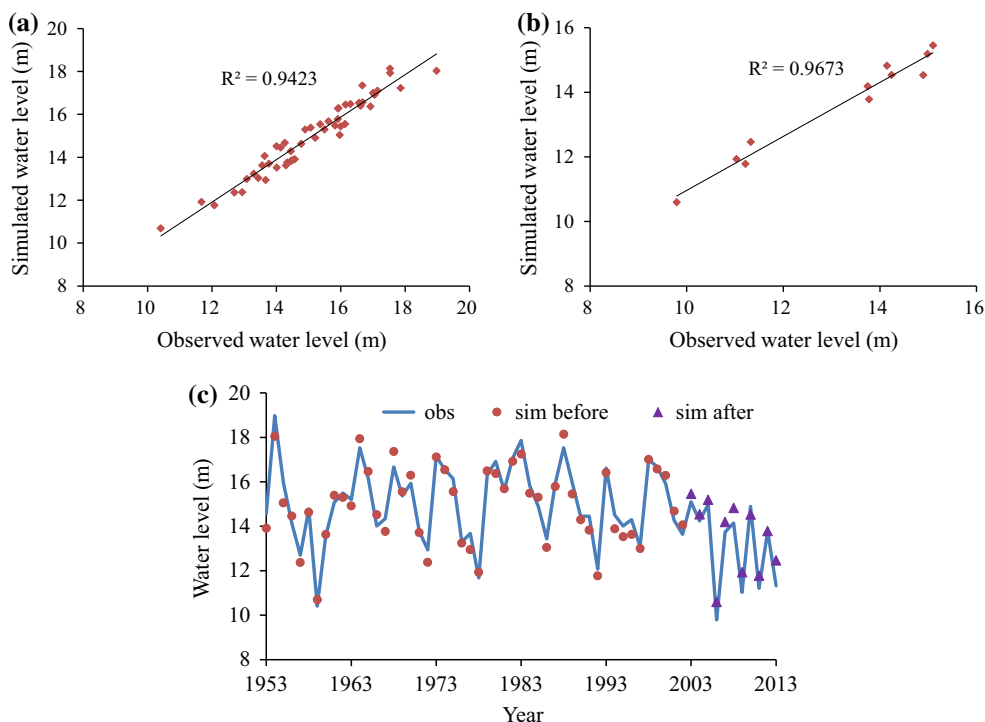


Fig. 2 Comparison of simulated and observed water levels at Xingzi station. **a** From 1953 to 2002, **b** from 2003 to 2013 and **c** from 1953 to 2013

Table 2 Estimated parameters of P3 distribution and sample statistics

Variables	P3 parameters			Sample statistics			K–S statistics D
	α	β	γ	Ex	Cv	Cs	
Catchment inflow	2.13	0.0016	575.09	1922	0.48	1.37	0.0897
Hankou flow	16.00	0.0005	1286.32	32,158	0.24	0.50	0.0792
Xingzi water level	69.44	4.6020	0	15.09	0.12	0.24	0.0889

hypothesis could not be rejected at the 95 % confidence level (critical value is 0.1923). Figure 3a–c presents the frequency curve of catchment inflow, Hankou flow and Xingzi water level, respectively. It can be seen that the theoretical frequency values calculated by the P3 distributions can fit the observed values calculated by the Gringorten plotting-position formula (Zhang and Singh 2006) very well.

4.3 Derived distribution of Xingzi water level before TGR

Besides the fitted probability distribution method, the probability distribution of Xingzi water level before TGR can be also estimated by the derived probability distribution method. To detect the dependence between catchment inflow and Hankou flow, the Pearson’s correlation coefficient r , Kendall’s tau correlation coefficient τ , and Spearman’s rho correlation coefficient ρ_S (Sun et al. 2014b; Xiong et al. 2014) were adopted in this study. The r , τ , and

ρ_S values are calculated as -0.081 with p value 0.574, -0.024 with p -value 0.802, and -0.031 with p -value 0.833, respectively. It is concluded that catchment inflow and Hankou flow are statistically uncorrelated. In practical engineering application, the catchment inflow and Hankou flow can be considered as independent variables (Jiang et al. 2015).

Since the probability distributions of catchment inflow and Hankou flow have been estimated using the fitted probability distribution method in Sect. 4.2, then the derived probability distribution of Xingzi water level is obtained from Eq. (10). The derived frequency curve of Xingzi water level before TGR is shown in Fig. 4, the directly fitted frequency curve is also shown for comparison purpose. Overall, it is seen that the theoretical frequency values calculated by derived probability distribution method fitted the observed values well. The statistic D of the K–S test is 0.0940, which is less than 0.1923 (the critical value at the 95 % confidence level). This indicates the derived probability distribution can be

Fig. 3 Frequency curves of catchment inflow, Hankou flow and Xingzi water level before TGR. **a** Catchment inflow, **b** Hankou flow and **c** Xingzi water level

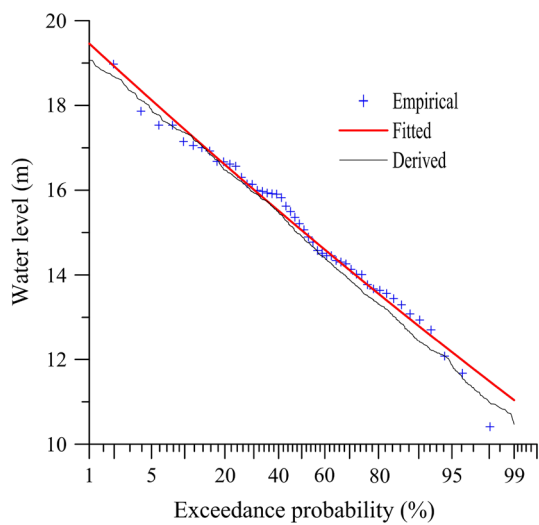
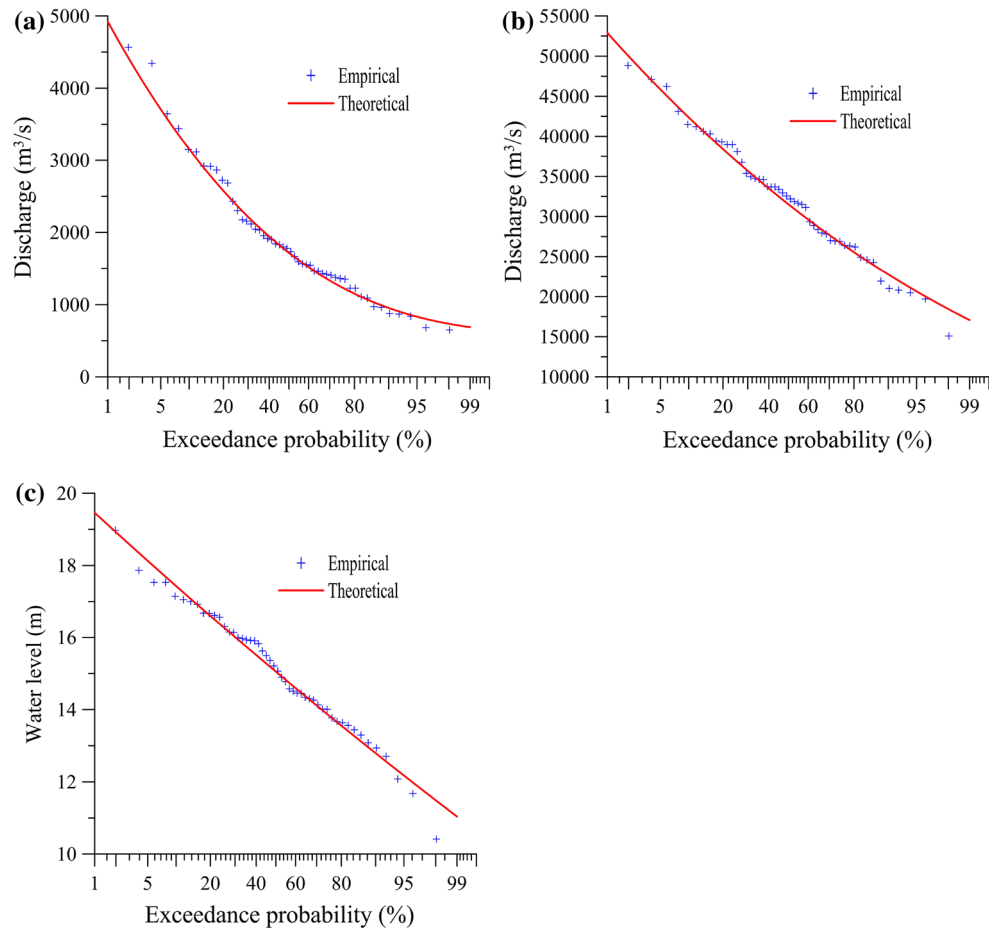


Fig. 4 Comparison of the fitted, derived and empirical frequency curves of Xingzi water level before TGR

accepted as the theoretical distribution of Xingzi water level. Furthermore, it also has a comparable accuracy as the directly fitted probability distribution method since

the statistic D of the derived probability distribution (0.0940) is slightly larger than that of the fitted probability distribution (0.0889). These results confirm that the derived probability distribution method for Xingzi water level is reasonably accurate and well suited for estimating the probability distribution of Xingzi water level after TGR.

4.4 Derived distribution of Xingzi water level after TGR

To quantify the effects of TGR refill operation, it is assumed that the probability distribution of catchment inflow keeps unchanged. According to the current refill rules of TGR proved by the Ministry of Water Resources (MWR 2009; Li et al. 2014), the TGR storage $221.5 \times 10^8 \text{ m}^3$ water to reach normal water level of 175 m from 145 m (generally from September 15 to October 31, lasting 47 days), the mean outflow discharge will be reduced by $5460 \text{ m}^3/\text{s}$. Based on the fitted probability distribution of Hankou flow before TGR listed in Table 2, the probability distribution of Hankou flow after TGR was obtained from Eq. (12).

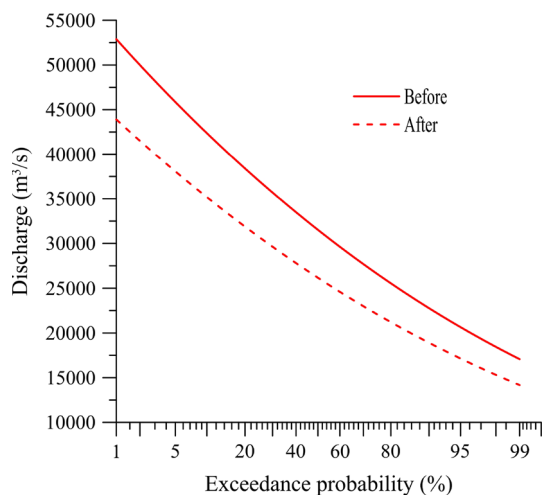


Fig. 5 Comparison of the frequency curves of Hankou flow before and after TGR

The frequency curves of Hankou flow both before and after TGR were shown in Fig. 5. Subsequently, the derived probability distribution of Xingzi water level after TGR was obtained from Eq. (13). The comparison of frequency curves of Xingzi water level before and after TGR was shown in Fig. 6. For consistency, the probability distribution of Xingzi water level before TGR was also estimated by the derived distribution method.

4.5 Evaluating the impact of TGR refill operation on water level

By comparing the probability distribution of Xingzi water level before and after TGR, the impact of TGR refill operation on water level can be evaluated quantitatively.

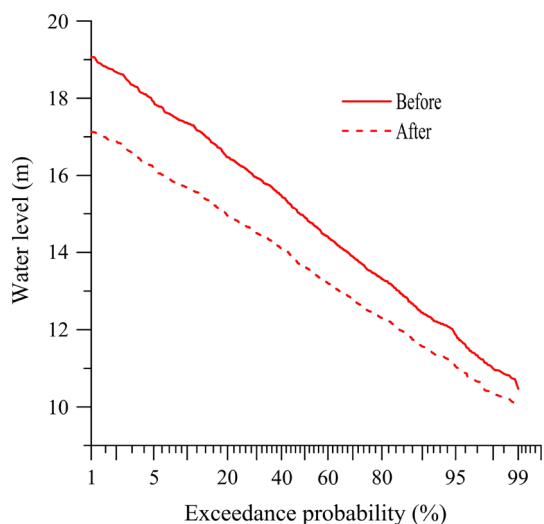


Fig. 6 Comparison of frequency curves of Xingzi water level before and after TGR

Table 3 Comparison of water levels at Xingzi station before and after TGR

Frequency	Before	After	Reduction
50 %	14.92	13.64	1.28
80 %	13.31	12.30	1.01
90 %	12.44	11.57	0.87
95 %	11.87	11.05	0.82
98 %	10.99	10.32	0.67
99 %	10.47	9.97	0.50
Mean	14.91	13.64	1.27

The Xingzi water levels with different design frequencies both before and after TGR were listed in Table 3. Accordingly, the water level reductions induced by the TGR refill operation were also summarized in Table 3.

It is observed that all the Xingzi water levels have been reduced due to the TGR refill operation. The mean of Xingzi water level has been reduced from 14.91 to 13.64 m with the corresponding reduction 1.27 m. The water level reduction decreases as the design frequency increases. Specifically, the water level reductions are 1.28, 0.87, and 0.50 m corresponding with design frequencies of 50, 90 and 99 %, respectively.

A further sensitive analysis is carried out in order to assess the impact of different Hankou flow reductions on the design water level reductions. Eight Hankou flow reductions scenarios are set up, i.e., 1000, 2000, 3000, 4000, 5000, 6000, 7000 and 8000 m³/s. For each scenario, the derived probability distribution of Xingzi water level after TGR can be obtained using the aforementioned procedure where outflow reduction is 5460 m³/s. Water level reductions with design frequencies induced by the TGR refill operation for eight scenarios were computed and shown in Fig. 7. The results indicate that water level reduction increases as the Hankou flow reduction increases for a certain design frequency. Taking design frequency of 50 % as an example, Hankou flow reduction of 1000, 2000, 3000, 4000, 5000, 6000, 7000 and 8000 m³/s decreased water levels by 0.25, 0.48, 0.71, 0.95, 1.17, 1.41, 1.64, and 1.88 m, respectively. It is also found that the water level reduction decreases as the design frequency increases for each scenario. For Hankou flow reductions of 4000 m³/s, water level reductions are 0.95, 0.72, 0.63, 0.59, 0.49 and 0.36 m corresponding with design frequencies of 50, 80, 90, 95, 98 and 99 %, respectively.

5 Discussion

Results of the standardized regression coefficients of multiple linear regressions in this study reveal that Yangtze River flow, rather than the catchment inflow is the

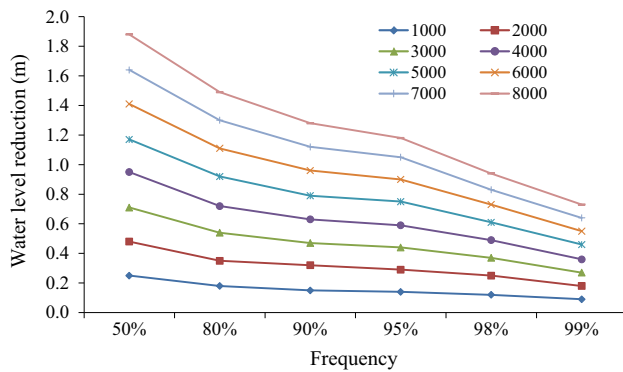


Fig. 7 Reductions of design Xingzi water levels corresponding to different Hankou flow reductions

dominant factor affecting the water level of Poyang Lake during the refill operation period. This is agreement with the findings of previous studies. Shankman et al. (2006) found that the Poyang Lake water level is determined primarily by the water surface elevation of the Yangtze River, and to a lesser extent by the discharge from the Catchment Rivers. Ye et al. (2014b) explored the factors influencing water level changes in Poyang Lake, and indicated that the Yangtze River discharge has a greater impact on annual lake level variations than the lake's catchment inflow. Zhang et al. (2014b) employed a physically-based hydrodynamic model to explore catchment and Yangtze River controls on the Lake's hydrology. Model simulations demonstrated that the drainage effect of the Yangtze River was the primary causal factor and modifications to Yangtze River flows from the TGR have had a much greater impact on the seasonal (September–October) dryness of the Lake, compared to climate variability impacts on the Lake catchment. Thus, it is highlighted again in this study that Yangtze River plays a primary role influencing the water level of the Lake, while the local catchment plays a complementary role during the refill operation period.

To mitigate the dryness of the Lake and to minimize the impacts on local socio-economic development and Lake Wetland functions, various management strategies are being proposed and discussed. More consideration should be given to the regulation of Yangtze River flow, given that management within the local catchment will probably have only a minor influence on the drying effect. It is essential to optimize the existing operation rules or develop new reservoir management schemes without significantly changing the main purposes of the TGR. Further advancing TGR refill operation may be an effective measure. For example, if the refill operation period is adjusted to September 1 ~ October 31 (61 days), the mean discharge of Hankou flow is corresponding reduced by 4200 m³/s.

Compared to the current refill operation period September 15 ~ October 31 (47 days), the mean discharge of Hankou flow is increased by 1260 m³/s. Results in Eq. (14) demonstrate that the Xingzi water level is increased by 0.32 m on average. In addition, the initial water level is another important factor influencing the refill operation. The higher the initial water level is, the less water volume is needed to be stored, resulting in lower reduction of the Hankou flow. Taking the year 2014 as an example, it combined the refill operation and flood control operation together, and the refill operation period was from September 15 to October 31 with initial water level 164.66 m (<http://www.ctgpc.com.cn/en/>). Consequently, the mean discharge of Hankou flow is reduced by 2350 m³/s. Compared to the current initial water level 145 m, the mean discharge of Hankou flow is increased by 3110 m³/s. Results in Eq. (14) further demonstrate that the Xingzi water level is increased by 0.78 m on average.

This study mainly focused on employing the probability-based statistical method to quantitatively explore the impact of TGR refill operation on water level of Poyang Lake. It is shown there are some limitations and opening perspectives for further studies in the future. The temporal scale used is the duration of TGR's refilling (about one and a half months), and the yearly mean values in TGR's refill period were selected as variables of interest. It is noted that this duration is usually longer than the lag time between local precipitation and surface discharge of TGR dam site, this temporal scale may disguise part of TGR's upper-interval impact on Poyang level. In addition, TGR's water regulation varies within each impoundment period, which leads to considerable fluctuation in daily downstream river and lake levels. To taking these factors into consideration, a shorter time scale, e.g. daily, will be used in further research work.

Nevertheless, the yearly mean values in TGR's refill period are still representative indicators of hydrological variables to some extent. Rather than the value of a specific year, the probability distribution of yearly mean water level in TGR's refill period represents the magnitude-frequency relationship under the long-term condition. This study provides a new perspective from hydrological frequency analysis for quantifying the TGR refill operation effects, and reveals that the long-term hydrological regime of Poyang Lake has been considerably altered after TGR. The proposed method can be adapted to the environment change, while traditional method of fitting and extrapolating the assumed probability distribution based on the historic observations would not be suited to estimate future water resources situation. Consequently, the findings from this work provide scientific evidences for formulating better scheme for water resources management in this region.

6 Conclusions

This study established a multiple linear regression model to estimate the water level of Poyang Lake, with catchment inflow and Yangtze River flow as explanatory variables. A derived probability distribution method for water level of Poyang Lake from catchment inflow and Yangtze River flow was proposed. The impact of TGR refill operation on water levels was quantified by comparing the probability distribution before and after TGR. The major findings were summarized as follows:

- (1) The multiple linear regression equation is statistically significant with a very good performance. The Xingzi water level can be reasonably estimated by the linear combination of catchment inflow and Hankou flow.
- (2) Results of the standardized regression coefficients of multiple linear regressions reveal that Yangtze River plays a primary role influencing the water level of the Poyang Lake, while the local catchment plays a complementary role during the refill operation period.
- (3) The proposed derived probability distribution from catchment inflow and Hankou flow has a comparable accuracy as the directly fitted probability distribution before TGR. It is reasonably accurate and well suited for estimating the probability distribution of Xingzi water level after TGR.
- (4) Water levels of Xingzi station with different design frequencies have been reduced due to the TGR refill operation. The water level reductions induced by TGR refill operation are 1.28, 0.87, and 0.50 m corresponding with design frequencies of 50, 90 and 99 %, respectively.

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