

Quantitative estimation of the impacts of climate change and anthropogenic activities on inflow variations in the Poyang Lake Basin during the last 55 years

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Abstract. The Poyang Lake Basin is a typical flood- and drought-prone region in China. This study applied methods of cumulative anomaly, Hurst exponent, and slope change ratio of cumulative quantity (SCRCQ) to analyse the impacts of climate change and anthropogenic activities on inflow changes of Poyang Lake during the last 55 years. Taking the period of 1961 to 1991 as the base period, results show that the contribution rates of precipitation and anthropogenic activities to inflow changes were 58.7% and 41.3% during the period of 1992 to 2002 and 6.5% and 93.5% during the period of 2003 to 2015, respectively. These results indicate that the impacts of anthropogenic activities on the inflow changes have reinforced gradually and have become the major factor during the last decade. In general, this study provides a reliable scientific basis for water resource management in similar basins.

1. Introduction

River runoff is a key part of the hydrological cycle in basins, providing valuable water resources for human life and regional economic development [1]. Many previous studies have shown that hydrological processes in basins are directly or indirectly influenced by both climate change and anthropogenic activities [2]. Changes in runoff can affect the rational allocation and utilization of water resources and even lead to influences on the physical, chemical, and biological processes of river ecosystems [3]. Currently, the exploration of the runoff variation under the joint influences of climate change and anthropogenic activities is a new issue in the field of water science [4]. The quantitative assessment of the contribution of the two main driving factors to runoff variation has been a subject of intense study in hydrology and water resources research [5].

In recent years, a large number of researches have used various methods for distinguishing the quantitative response of runoff to changes in climate and anthropogenic activities, and these methods can mainly fall into three groups: (1) empirical statistical methods, such as linear regression [6], double-mass curve [7], and slope change ratio of cumulative quantity (SCRCQ) [8]; (2) elasticity-based methods, such as Budyko-based methods [9,10]; and (3) hydrological model methods, such as SWAT [11],



GBHM [12], VIC[13], and so on.

Currently, many researchers have conducted numerous relevant studies on the arid and semi-arid regions in the north of China, such as the Yellow River Basin, the Nenjiang River Basin, the Hei River Basin, and the Wei River Basin. However, runoff in humid regions has received little attention to date. In this study, we will focus on the basin in which China's largest freshwater lake is located, i.e. the Poyang Lake Basin (PYLB). The PYLB has the highest annual average runoff, precipitation, and evapotranspiration in the Yangtze River Basin [14]. However, under the influence of uneven seasonal precipitation, the PYLB has now become one of the regions that most vulnerable to floods and droughts in China. The total inflow of Poyang Lake is a key indicator of the lake's hydrological regime change, and the analysis of the inflow plays an important role in revealing the variation law of drought and flood in the PYLB. Furthermore, the study of the driving mechanisms of climate change and anthropogenic activities on inflow changes and the quantification of their relative roles is of great importance in the management of water resources, protection of ecological environment, and promotion of socioeconomic development in the PYLB.

2. Study area and data

2.1. Description of the study area

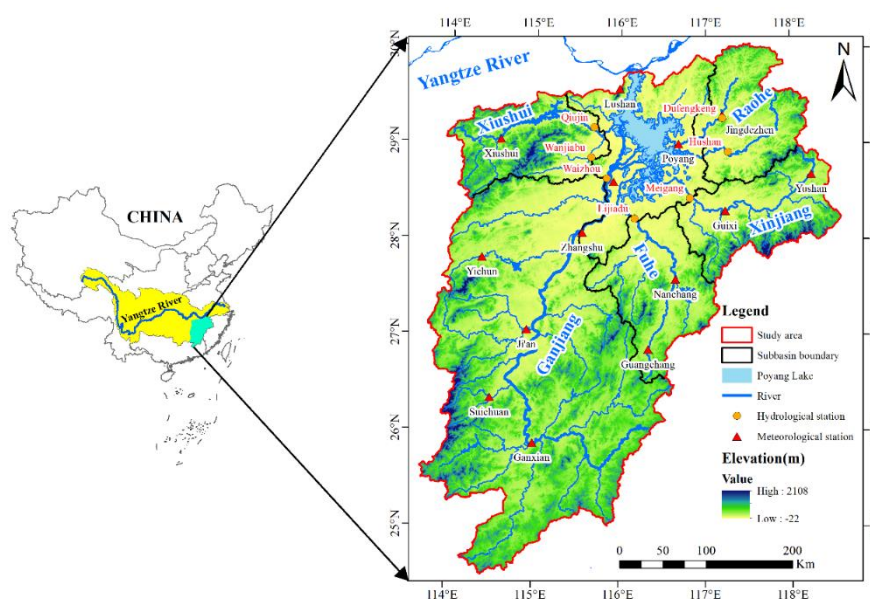


Figure 1. Locations of the Poyang Lake Basin and the hydrological and meteorological stations.

The PYLB is situated in the middle and lower reaches of the Yangtze River on the south shore (figure 1), covering an area of $16.22 \times 10^4 \text{ km}^2$. The basin is located between $24^\circ 29' \text{N}$ - $30^\circ 05' \text{N}$ and $113^\circ 35' \text{E}$ - $118^\circ 29' \text{E}$. The well-developed river system is primarily composed of Ganjiang River, Fuhe River, Xinjiang River, Raohe River, and Xiushui River that flow into Poyang Lake from the south, east and west and pour into the Yangtze River from the north. The PYLB belongs to the subtropical humid monsoon climate zone with a mild climate and abundant rainfall. The annual mean precipitation in the PYLB was 1641.40 mm during the period of 1961-2015. Approximately 45% of the annual precipitation is concentrated between April and June. The annual mean temperature is 17.97°C , and its inner-annual variation characteristics show a single peak structure, reaching the hottest in July and the coldest in January. Between these two months the temperature difference exceeds 20°C . The annual mean potential evapotranspiration (PET) is 1092.18 mm, and its inner-annual changing characteristics are similar to

temperature. In this study, the total inflows of the Poyang Lake include the sum runoff of 7 hydrological stations, i.e., Waizhou (Ganjiang), Lijiadu (Fuhe), Meigang (Xinjiang), Hushan and Dufengkeng (Raohe), Qiujin and Wanjiabu (Xiushui). The total drainage area of these hydrological stations is $13.71 \times 10^4 \text{ km}^2$, accounting for 84.5% of the entire basin area.

2.2. Data

The inflow data from 7 hydrological stations during the period of 1961 to 2015 were obtained from the Jiangxi Hydrological Bureau, China. The meteorological data (e.g., daily precipitation, temperature, wind speed, sunshine hours and relative humidity) from 14 meteorological observatory stations were provided by the China Meteorological Data Sharing Service System (<http://data.cma.cn/>). In this study, the PET of each meteorological station was estimated applying the Penman-Monteith method.

3. Methods

3.1. Cumulative anomaly

The cumulative anomaly is an effective method for distinguishing the change trend of discrete data, such as runoff, precipitation, temperature and other hydro-meteorological data [15]. For the series x_i , the calculation equation of cumulative anomaly (S_t) can be expressed as below:

$$S_t = \sum_{i=1}^t (x_i - \bar{x}), \quad (t = 1, 2, \dots, n) \quad \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

3.2. Hurst exponent analysis

The Hurst exponent analysis was pioneered by Harold Edwin Hurst in 1951 [16] and was improved by Mandelbrot and Wallis in 1969 [17]. The basic idea of this method is to study the statistical law of the sequence in different time scales by changing the time scale size of the data sequence, thus completing the conversion between large and small time scale. The specific calculation formula can be found in the literature [18]. The Hurst exponent value (H) ranges from 0 to 1. When $H > 0.5$, it indicates that the future trend of the process will be consistent with the past. When $H = 0.5$, the time series is random. When $H < 0.5$, it indicates that the future trend is opposite to that of the past, that is, the process has anti-persistence. The detailed classification of the Hurst exponent is shown in table 1.

Table 1. Grading table of Hurst exponent.

Grade	Range of Hurst exponent (H)		Strength
	Persistence	Anti-persistence	
I	(0.50, 0.55]	[0.45, 0.50)	Weak
II	(0.55, 0.65]	[0.35, 0.45)	Weaker
III	(0.65, 0.75]	[0.25, 0.35)	Stronger
IV	(0.75, 0.85]	[0.15, 0.25)	Strong
V	(0.85, 1.00]	[0.00, 0.15)	Very strong

3.3. SCRCQ method

The slope change ratio of cumulative quantity (SCRCQ) method was developed by Wang et al. in 2012 to detecting the quantitative response of runoff to climate change and anthropogenic activities [8]. The calculation equations are the following:

$$C_p = 100 \times ((S_{Pa} - S_{Pb}) / S_{Pb}) / ((S_{Ra} - S_{Rb}) / S_{Rb}) \quad (2)$$

$$C_E = -100 \times ((S_{Ea} - S_{Eb}) / S_{Eb}) / ((S_{Ra} - S_{Rb}) / S_{Rb}) \quad (3)$$

$$C_H = 100 - C_P - C_E \quad (4)$$

where C_P , C_E , and C_H (unit: %) are the contribution rates of precipitation, PET, and anthropogenic activities to runoff variations, respectively. S_{Rb} (unit: $10^8 \text{ m}^3/\text{year}$), S_{pb} (unit: mm/year), and S_{Eb} (unit: mm/year) are the slopes of the linear relationship between the year and cumulative data (runoff, precipitation, and PET) before the inflexion point. S_{Ra} (unit: $10^8 \text{ m}^3/\text{year}$), S_{pa} (unit: mm/year), and S_{Ea} (unit: mm/year) are the slopes of the linear relationship between the year and cumulative data (runoff, precipitation, and PET) after the inflexion point.

4. Results

4.1. Trend characteristics

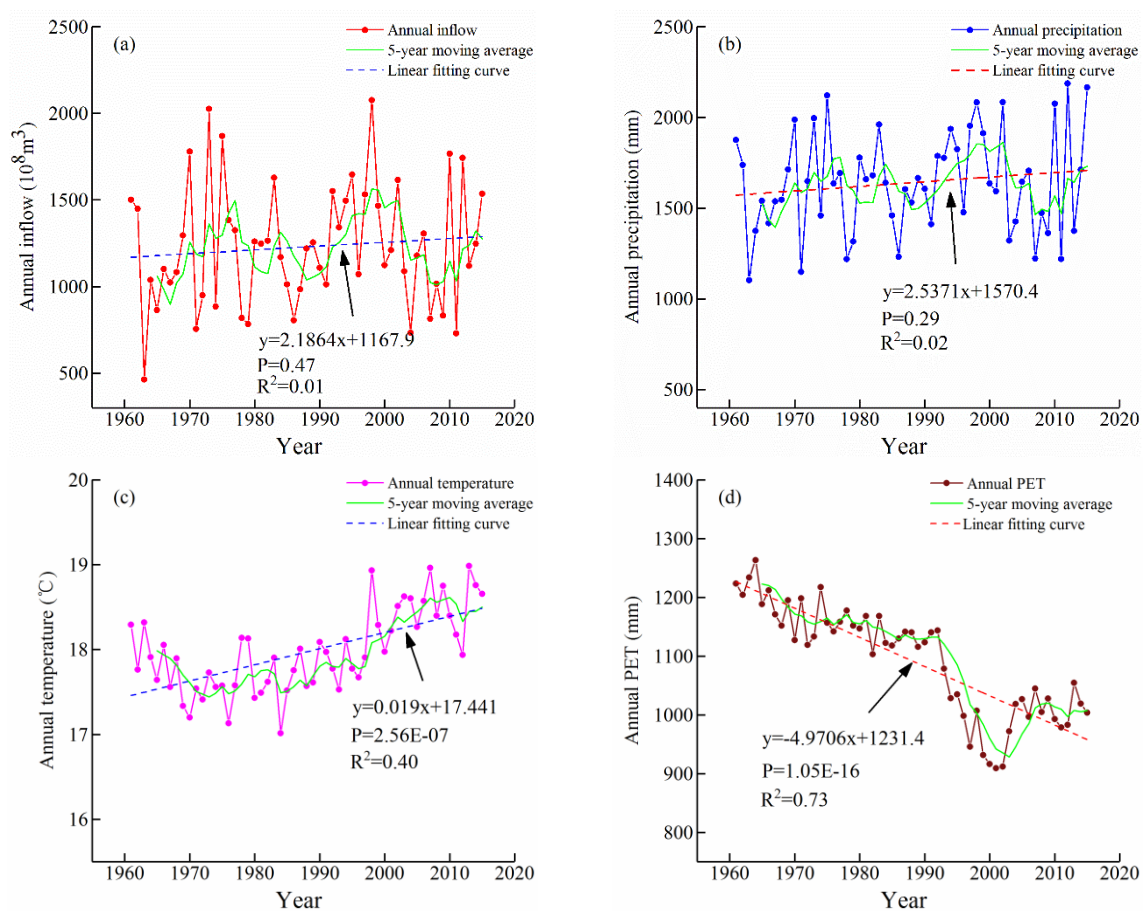


Figure 2. Temporal variations of mean annual (a) inflow, (b) precipitation, (c) temperature, and (d) PET in the Poyang Lake Basin.

During the period from 1961 to 2015, the annual inflow presented an overall increasing trend with the inclination rate of $2.19 \times 10^8 \text{ m}^3/\text{year}$ (figure 2(a)), and the annual mean inflow was $1229.16 \times 10^8 \text{ m}^3/\text{year}$. From the 5-year moving average curve of inflow, annual inflow has experienced a repeated “up-down” process over the past 55 years. In figure 2(b), the annual precipitation also showed an increasing trend for which the inclination rate was 2.54 mm/year. Additionally, the 5-year moving average curve during 1961–2015 was demonstrated to be similar to the inflow. As figure 2(c) shows, the phenomenon of climate warming also existed in the PYLB, and its increasing rate was $0.02^\circ\text{C}/\text{year}$. In

contrast, annual PET data series in the basin showed the opposite change (decline) with the inclination rate of -4.97 mm/year (figure 2(d)).

4.2. Abrupt change characteristics

To analyse the inflexion point of the inflow in the PYLB from 1961 to 2015, the cumulative anomaly method was used in this study, and the result is shown in figure 3. As cumulative anomaly curve shows that there were two inflexion points of the inflow change in 1991 and 2002. In other words, inflow had a downward trend and an upward trend before and after 1991, and the opposite trend occurred in approximately 2002. Therefore, the entire study period can be divided based on the two inflexion points. The period of 1961 to 1991 can be designated the reference baseline period (T_a); other periods (i.e., 1992-2002 and 2003-2015) can be regarded as the measurement periods (T_b and T_c).

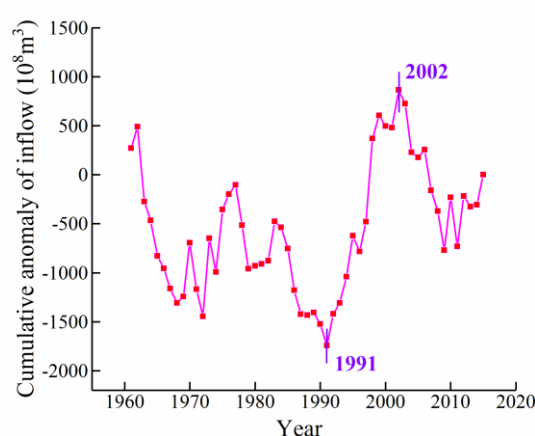


Figure 3. Change trend of the cumulative anomaly of annual inflow and inflexion points in the whole basin.

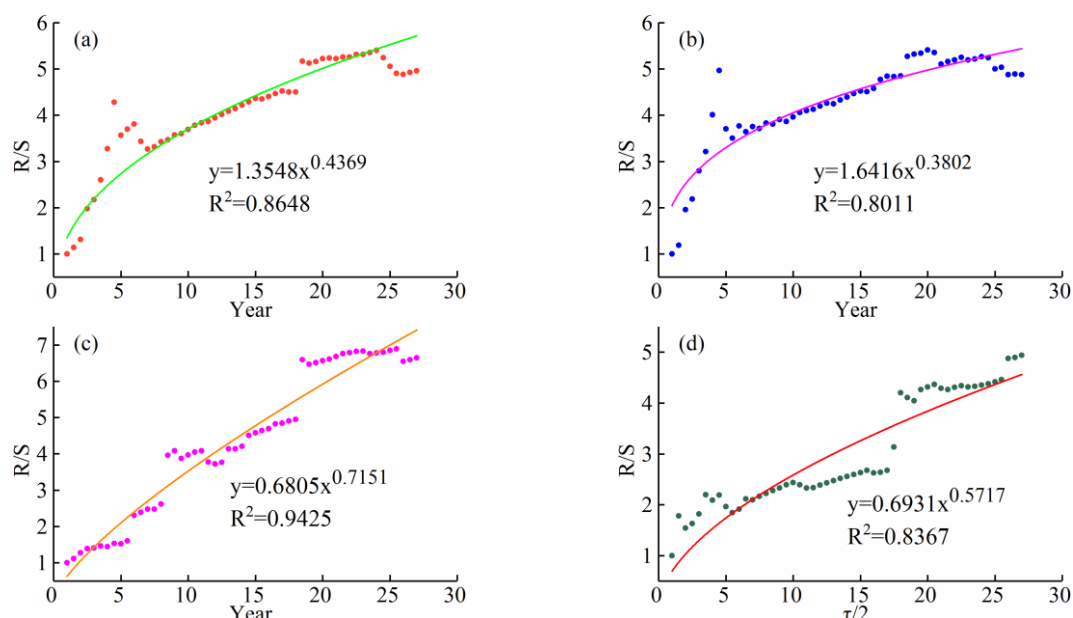


Figure 4. The results of Hurst exponent analysis of (a) inflow, (b) precipitation, (c) temperature, and (d) PET.

4.3. Future trend prediction

The Hurst exponent (H) was used to analyse the persistence of inflow and climatic factors. The fitting curves of $R/S \sim \tau/2$ and $V(\tau) \sim \lg^T$ were generated and plotted in figures 4 and 5, respectively. As table 2 shows, the Hurst exponent values (H) of inflow, precipitation, temperature, and PET were 0.44, 0.38, 0.72, and 0.57, respectively. According to table 1, we can know that the future tendencies of precipitation and inflow opposed those of the past; in contrary, the future tendencies of temperature and PET will be consistent with the past. Therefore, precipitation and inflow will show downward trend in the future, whereas the temperature trend remains increase, and the PET trend remains decreasing. According to table 1, the persistent strengths of inflow, precipitation, and PET were weaker (Grade II), and that of temperature was stronger (Grade III). Additionally, the persistent times for precipitation and inflow were both 9 years (figure 5).

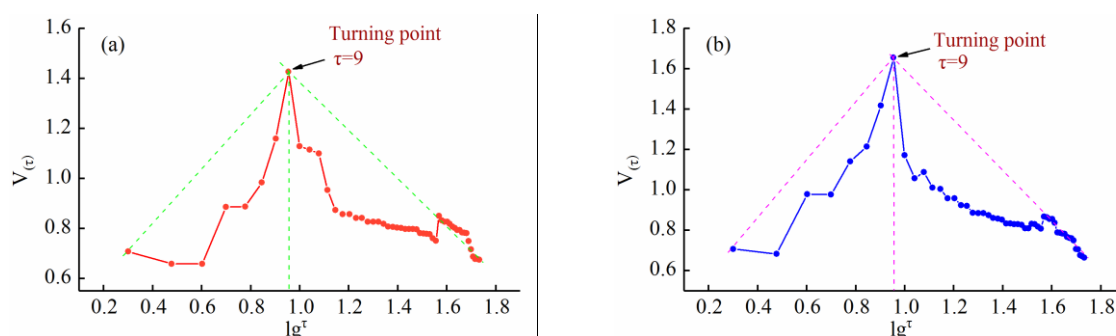


Figure 5. Persistent times of (a) inflow and (b) precipitation.

Table 2. The results of Hurst exponent analysis and persistence of inflow, precipitation, temperature, and PET (“↑” is upward trend, “↓” is downward trend).

Name	H	T	Change trend	
			Historical	Future
Inflow	0.44 weaker	9	↑	↓
Precipitation	0.38 weaker	9	↑	↓
Temperature	0.72 stronger	-	↑	↑
PET	0.57 weaker	-	↓	↓

4.4. Roles of climate change and anthropogenic activities

Correlation analyses indicated that inflow in the PYLB correlated closely with precipitation with the correlation coefficient of 0.92 that passed the significant level of 0.01. However, the correlational relationships between inflow and temperature or PET were both not significant. The results suggested that temperature and PET in the PYLB had less influence on Poyang Lake inflow, whereas precipitation was the main climatic factor. Thus, in this study, the quantification of effects of climate change on inflow changes only considered precipitation.

Figure 6 illustrates the relationships the year and cumulative data (inflow and precipitation, respectively) before and after the inflexion points (i.e., 1991 and 2002) for the PYLB. The coefficient of determination (R^2) between the year and each factor was high and > 0.99 . In addition, the confidence level of P values was < 0.0001 . Therefore, the correlation between the year and each factor was high.

Table 3 lists the slope (S_R and S_P) of each fitted line from the equations presented in figure 6. Based on equations (1)-(3) and S_R and S_P data in table 3, the contribution rates of precipitation and anthropogenic activities to inflow variations were 58.7% and 41.3% during the period of T_b (1992-2002), respectively, and were 6.5% and 93.5% during the period of T_c (2003-2015), respectively (table 4).

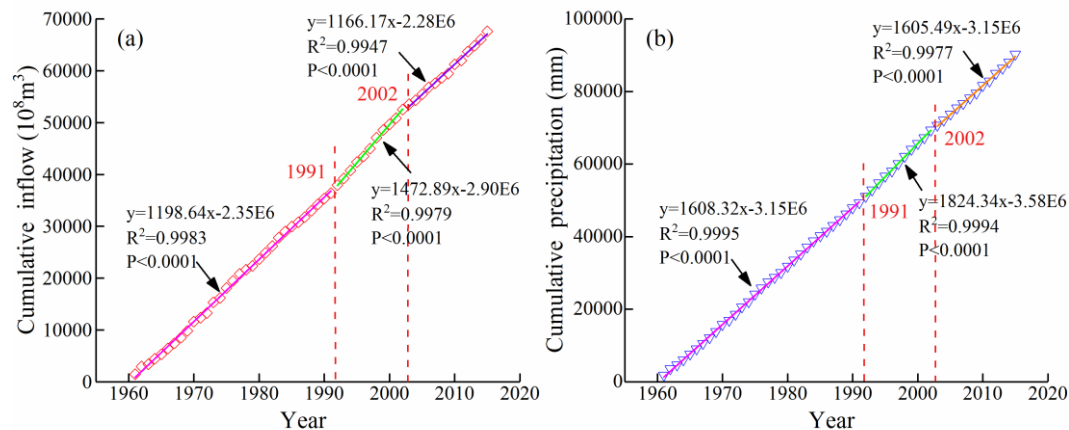


Figure 6. Relationships between year and cumulative data in the PYLB: (a) inflow and (b) precipitation.

Table 3. Slopes of the relationships between year and cumulative data of inflow (S_R) and precipitation (S_P).

Slope	T_a (1961-1991)	T_b (1992-2002)	T_c (2003-2015)
S_R ($10^8 \text{m}^3/\text{a}$)	1198.64	1472.89	1166.17
S_P (mm/a)	1608.32	1824.34	1605.49

Table 4. Contribution rates of climate change (precipitation) and anthropogenic activities to inflow variations in the PYLB (based on T_a).

Impact factor	Contribution rates to the inflow variations	
	T_b	T_c
C_p	58.7%	6.5%
C_H	41.3%	93.5%

5. Discussion and conclusions

In this study, the Poyang Lake Basin was taken as a study area. We applied several methods, including cumulative anomaly, Hurst exponent analysis, and SCRCQ, to analyse the change trend, abrupt change, future trend characteristics of inflow and climatic factors, and the relative impacts of climate change and anthropogenic activities on inflow variations during the period of 1961 to 2015. Our results indicate the following:

- From 1961 to 2015, inflow, precipitation, and temperature showed overall upward trends, whereas PET presented a downward trend. The future tendencies of inflow and precipitation will exhibit weaker anti-persistent features with the same persistent times of 9 years.
- Two inflexion points of the inflow change in 1991 and 2002, respectively, were identified for the PYLB. With the inflexion points, one reference baseline period (1961-1991) and two measurement periods (1992-2002 and 2003-2015) were divided.
- Taking period T_a (1961-1991) as the base period, the dominant factor impacting inflow change was precipitation with the contribution rate of 58.7% during period T_b (1992-2002). However, the impacts of anthropogenic activities on inflow change have reinforced gradually, and they became the major factor (93.5%) during the last decade (period T_c (2003-2015)). This predominance of anthropogenic activities over climate change on runoff variations is similar to that for many other study regions, such as the Yellow River, Pearl River, Songhua River and Huaihe River.

Moreover, it should be noted that anthropogenic activities have a complex impact on the inflow changes in the PYLB because the different types of anthropogenic activities (e.g., agricultural irrigation, domestic and industrial water consumption, water and soil conservation, land use/land cover (LULC) change) can enhance or weaken the impacts of each other, and the inflow changes under their joint action. This study has analysed the comprehensive effects of various anthropogenic activities on inflow variations for the PYLB but has not attempted to separate their specific impacts. Accordingly, future research should focus effectively on separating the detailed influences of anthropogenic activities and climate change. In conclusion, detecting the relative impacts of climatic change and anthropogenic activities on basin hydrology has important theoretical and practical significance for the planning and management of basin water resources.

Acknowledgment

This research was financially supported by the National Basic Research Program of China (No. 2016YFC0401701), National Natural Science Foundation of China (No. 51479219, No. 51439007), Program for Innovative Research Team of IWHR (No. WE0145B592017), Special Project for Basic Research of IWHR (No. WE0145B532017).

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