ASSESSING THE IMPACT OF CLIMATE CHANGE AND HUMAN ACTIVITIES ON RUNOFF IN THE DONGTING LAKE BASIN OF CHINA

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Abstract. Global climate change and intensifying human activities have dramatically changed the runoff of Dongting Lake. This study investigated the runoff variations and associated impacts of climate change and human activity for the four inflow sub-basins of Dongting Lake. Multiple linear regression method and double-mass curve method were used to quantify the effects of climate change and human activities on water discharge. Results showed that the streamflow of the Xiangjiang, Zishui and Yuanjiang rivers exhibited an abrupt change in 2003, 2003 and 2005, respectively, whereas no significant turning year was detected for Lishui River. The impacts of climate factors and human activities were consistent using the two methods. The contribution rate of climate change to runoff reduction in Xiangjiang River was about 85–92% and the impact of human activities ranged from 8 to 15%. For the runoff changes in the Zishui and Yuanjiang River basins, results showed that the impact of climate factors ranged from 63 to 88% and from 62 to 82%, respectively. In comparison, the anthropogenic impact ranged from 12 to 37% and from 18 to 38%, respectively. This study will provide important insights into water resource management and planning for Dongting Lake basins.

Keywords: *streamflow, precipitation, evapotranspiration, human activities, Dongting Lake*

Introduction

River runoff changes are mainly affected by climate factors, such as precipitation and evapotranspiration. However, as an indirect influencing factor, increasing human activities (e.g. land utilisation change, water diversion for agricultural irrigation, hydropower engineering, water and soil conservation, etc.) have caused a change in water circulation (Allen and Ingram, 2002; Millán, 2014; Amin et al., 2016). Various studies have revealed a contradiction between water resources supply and demand due to the runoff changes in many river basins worldwide (Fu et al., 2004; Xu et al., 2010, 2013a, b). An analysis of the trends and characteristics of runoff changes and a quantitative evaluation on the effects of climate variability and human activities are important for the assessment and management of regional water resources.

Quantifying the impacts of climate change and anthropogenic activities on hydrological processes has become a hot topic in climatic and hydrologic studies (Zhang et al., 2015; Ahn and Merwade, 2014; Buendia et al., 2016; Griffioen, 2016). Extensive research has been conducted on several typical watersheds, such as the Nile River basin (Hasan et al., 2018), Columbia River basin, Colorado River basin, Mississippi River basin (Naik and Jay, 2011; Timilsena and Piechota, 2008), Mekong basin (Raghavan et al., 2012), Brahmani River basin (Islam et al., 2012), and in China,

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the Yangtze River basin (Zhao et al., 2015), Yellow River basin (Wang et al., 2014; Kong, 2017), Wei River basin (Huang et al., 2016; Zhang et al., 2015) and Hei River basin (Luo et al., 2016). Two methods are commonly used for evaluating the contribution rates of the main influencing factors on runoff changes, including hydrological modelling (Huang et al., 2016; Liu et al., 2016) and quantitative evaluation method [e.g. climatic elastic coefficient method (Ahn and Merwade, 2014; Ye et al., 2013), multivariate regressive (Jiang et al., 2011), sensitivity analysis (Zuo et al., 2016) and double-mass curve (DMC) method (Li and Xu et al., 2016)]. Although these studies quantitatively evaluated the comprehensive effects of climate change and human activities on runoff change, some shortcomings and deficiencies were observed. For example, although the hydrological model has a good physical foundation, its structure and parameter sensitivity possess several uncertainties. Furthermore, while the quantitative evaluation method requires less data, a longer data series is needed to reach the effect of quantitative assessment, and noise in the long-time data series interferes with the evaluation results (Sankarasubramanian et al., 2001). Improvement of the accuracy to identify the change points of runoff variation and comprehensive application of various methods to quantify the contribution of climate change and human activities are necessary to obtain reasonable results.

Dongting Lake, the second largest freshwater lake in China, plays an important role in regulating the amount of water in Yangtze River, China’s longest river. In recent decades, especially after the Three Gorges project operation, lake runoffs were changed greatly and the surrounding basins suffered from frequent droughts (Mao, 1998), which seriously disrupted water supply for agricultural production, human consumption and ecological water requirement. Several studies have discussed the variation trend of runoff and sediment discharge in Dongting Lake basin. Li and Gu et al. (2016) revealed that the annual discharge of the Dongting outlet lake has shown a decreasing trend since 1983, with the most obvious decrease from 2003 to 2014. The results also indicated that runoff and rainfall synchronised within a certain range of fluctuations. Qin et al. (2012) analysed the long-term changes of runoff and sediment discharge of the Four Rivers in Dongting Lake basin and pointed out that the annual runoff change is mainly affected by the abundance and deficiency of precipitation. Zhang and Liu (2018) investigated the runoff and sediment discharge change trend in Xiangjiang River basin and its relationship with rainfall, drought regime, dam engineering construction and vegetation change. These studies indicated that the variations of streamflow are considerably related to regional climate, especially precipitation. However, to our knowledge, the present studies have paid little attention to quantifying the contribution rate of the driving factors of runoff changes in Dongting Lake basin. Furthermore, quantifying the impacts of climate variability and human activities with a single method is challenging because of the complex processes involved. Thus, further studies are needed to provide a conclusive interpretation of the changes observed. The present study is essential not only for an improved understanding on the mechanism of hydrological response in the basin but also for local water resources management as well as flood and drought protection and disaster mitigation.

In this study, Sen’s slope method, moving t-test, Pettitt test, multiple linear regression and DMC method were used to explore the streamflow variations of the Dongting Lake sub-basin and quantify the relative impacts of climate variability on human activity. The specific objectives of this study were as follows: (1) analyse the variability of long-term historical records of hydrological and climate data of the main tributaries in Dongting Lake basin, (2) investigate the abrupt change points of runoff variations and (3) estimate quantitatively the contribution rate of climate factors and human activities to runoff changes.

Dataset and methodology

Study area

Dongting Lake, the second largest freshwater lake in China, is located at 28°30’N–30°20’N and 111°40’E–113°10’E (*Fig. 1*). With a drainage area of 2.63×10^5 km^2, it occupies a large part of Hunan Province and a small part of Hubei, Chongqing, Guizhou, the Guangxi Zhuang Autonomous Region and Jiangxi provinces. Dongting Lake is connected to Yangtze River. The lake receives water flows mainly from Yangtze River and four tributaries from upstream (Xiangjiang, Zishui, Yuanjiang and Lishui) and discharges into Yangtze River through an outlet in the north. Runoffs from four rivers account for 54.6% of the total runoff (Qin et al., 2012), and changes in the runoffs directly impact the water quantity of Dongting Lake, The basin has well-developed river systems and includes four sub-basins: Xiangjiang, Zishui, Yuanjiang and Lishui River basins. Dongting Lake basin belongs to the subtropical monsoon climate zone. Its annual mean precipitation ranges from 1200 to 1400 mm depending on the position in the basin (Cui et al., 2012) and average annual runoff is 2608×10^8 km^2.

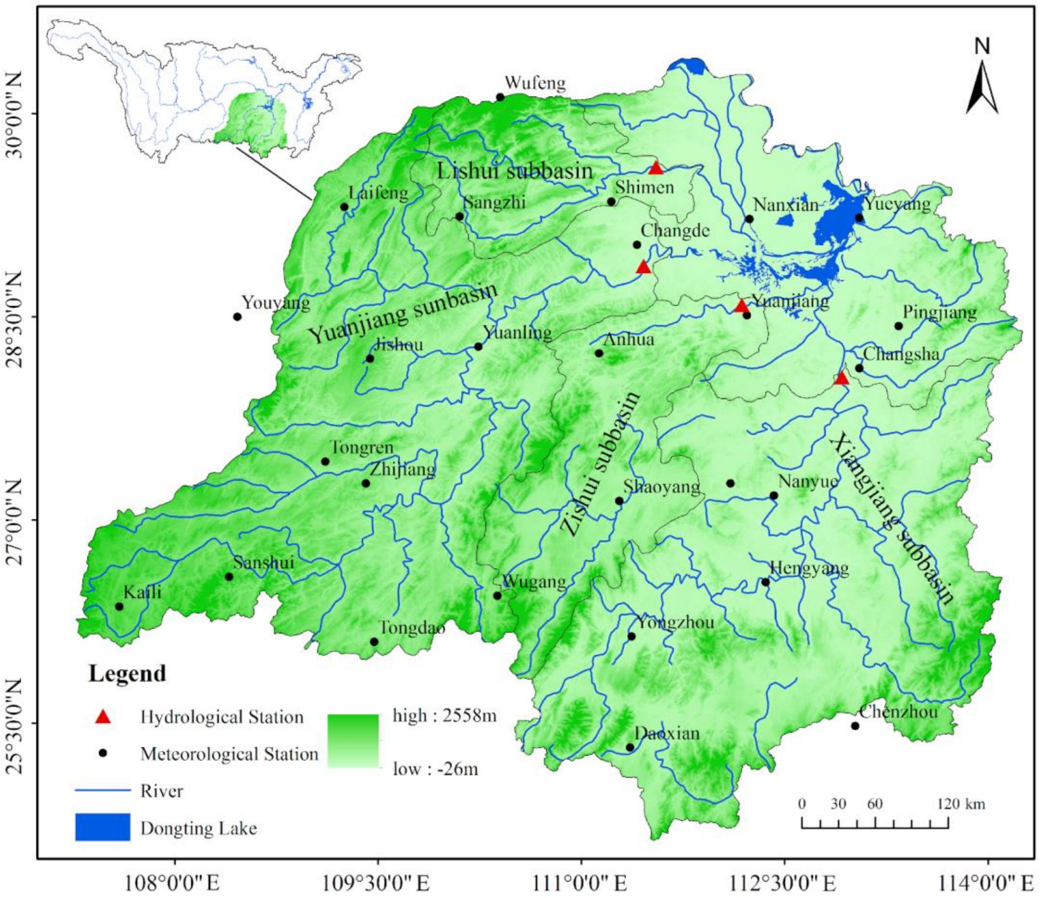

Figure 1. *Location of the study area and the distribution of meteorological stations and hydrological stations*

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Dataset

Daily runoff observations (1980–2014) from four gauging stations, including Xiangtan, Taojiang, Taoyuan and Shimen stations, were derived from the *Yangtze River Hydrological Data*. The meteorological data from 25 weather stations inside the catchment (*Fig. 1*) were obtained from the National Meteorological Information Center (http://data.cma.cn). The stations provide daily observations on precipitation, temperature, maximum temperature, minimum temperature, actual vapour pressure, relative humidity, sunshine duration and wind speed. Potential evaporation is calculated using the Penman–Monteith formula (Penman, 1948). Considering the uneven distribution of meteorological stations, the precipitation and potential evaporation in each basin are calculated using the Thiessen polygon method on the ArcGIS platform.

Methodology

Trend test

Sen’s slope, a non-parametric estimation method, can reflect the magnitude of the monotonic (Sen, 1968) trend and is given as *Equation 1:*

$$\beta = Median\left(\frac{X_i - X_j}{i - j}\right) 1 < j < i < n \qquad \text{(Eq.1)}$$

where β is the median over all combinations of record pairs for the whole data set and is, therefore, not affected by extreme values in the observations (Hirsch et al., 1982). A positive value of β indicates the variables increase with time, whereas a negative value represents a decreasing trend.

Change-point analysis

Various methods can be used to detect abrupt climate change, such as Mann–Kendall method (Mann, 1945), moving t-test (Buishand, 1982), Pettitt test (Pettitt, 1979) and cumulative anomaly method (Weber and Stewart, 2010). According to the characteristics and virtues of these methods, moving t-test and Pettitt test methods are used to analyse the change points of runoff.

Moving t-test is used to test the significant difference of two random samples’ mean. The method is simple, reliable and capable of avoiding artificial interference on the subsequence selection (Chen and Gupta, 2000). The method assumes the distribution functions before and after the change point as $F_1(x)$ and $F_2(x)$ and extracts two samples with the capacity of n_1 and n_2 from them, respectively. A T statistic is then constructed as follows:

$$T = \sqrt{\frac{\overline{x_1} - \overline{x_2}}{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{1/2}}} \qquad \text{(Eq.2)}$$

In the above equation, $\overline{x_i}$ and S_i are the means and variances of the samples, respectively. At a given confidence level α, if $|T| > T_{\alpha/2}$, then the sequence has a significant difference. Among all the points satisfying $|T| > T_{\alpha/2}$, the point where T reaches the maximum is the most possible change point.

Pettitt test, put forward by A. N. Pettitt (1979), is used to determine the occurrence of a change point. This approach considers a time series as two samples represented by $X_1, \cdots X_t$ and $X_{t+1}, \cdots X_N$. The Pettitt index $U_{t,N}$ is based on Mann–Whitney's statistical function and can be calculated using *Equation 3:*

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} \mathrm{sgn}(x_t - x_j)\ (t = 2, \cdots, N) \tag{Eq.3}$$

where if $x_t - x_j > 0$, then $\mathrm{sgn}(x_t - x_j) = 1$; if $x_t - x_j = 0$, then $\mathrm{sgn}(x_t - x_j) = 0$; and if $x_t - x_j < 0$, then $\mathrm{sgn}(x_t - x_j) = -1$.

The test statistic counts the number of times a member of the first sample exceeds that of the second. Moreover, the null hypothesis does not change in the distribution of a sequence of random variables. The most significant change point is selected where the value of $U_{t,N}$ is the largest (*Eq. 4*), and a change point occurs at time t when the statistic $k(t)$ is significantly different from zero at a given level. For $P \le 0.5$, the approximate significant level is given by *Equation 5* (Pettitt, 1979).

$$k(t) = Max_{1 \le t \le N} |U_{t,N}| \tag{Eq.4}$$

$$P \cong 2\exp\{-6(K_N)^2 / (N^3 + N^2)\} \tag{Eq.5}$$

Contribution rate analysis

Multi-regression method

Runoff changes involve the superposition of the effects of climate change and human activities, while climate factors influence the runoff mainly by precipitation and evaporation. Jiang et al. (2011) suggested a linear regression approach to estimate the monthly runoff using a function of precipitation and potential evapotranspiration (PET). On a monthly time scale, groundwater storage may play a role in runoff generation. Therefore, the original equation is modified by adding the precipitation from the previous month. Liu et al. (2016) showed that a three-variable linear regression model that considers precipitation, PET and precipitation from the previous month fitted well. The equation is given as

$$Q_i = aP_i + bP_{i-1} + cPET_i + d \tag{Eq.6}$$

where Q, P and PET represent the runoff, precipitation and potential evapotranspiration during the natural period, respectively, for month i; and a, b, c and d are constants estimated by least square estimation. Then, simulated runoff is estimated for the impact period using *Equation 6*. The difference between the observed runoff and the calculated runoff will represent the contribution from human activities in the impact period. The runoff change caused by climate factors and human activities can be quantified respectively according to *Equations 7* and *8*.

$$\Delta Q_h = \left|\overline{O_{\mathrm{m}}} - \overline{Q_m}\right| \quad \text{(Eq.7)}$$

$$\Delta Q_{\mathrm{c}} = \left|\overline{O_{\mathrm{n}}} - \overline{Q_m}\right| \quad \text{(Eq.8)}$$

$$\Delta Q_{\mathrm{t}} = \Delta Q_c + \Delta Q_h \quad \text{(Eq.9)}$$

where ΔQ_{h} and ΔQ_{c} represent the change in mean annual runoff due to human activities and climate factors, respectively; $\overline{O_m}$ and $\overline{O_n}$ are the average observed monthly runoff during the impact period and the natural period, respectively; and $\overline{Q_m}$ represents the calculated average monthly runoff during the impact period.

Nash–Sutcliffe Coefficient (NSC) was used to evaluate the model performance as follows:

$$NSC = 1 - \frac{\sum_{\mathrm{t}-1}^{T} (O_t - Q_t)^2}{\sum_{t-1}^{T} (O_t - \overline{O_t})^2} \quad \text{(Eq.10)}$$

where O and Q are the observed and simulated monthly runoffs, respectively. NSC changes between -∞ and 1, and the closer this value is to 1, the higher the reliability of the model. Moriasi et al. (2007) suggested that the accuracy of simulations is satisfactory if the value of NCS is greater than 0.5.

Double mass curve analysis

DMC was first proposed by C. F. Merriam (1937) for the consistence analysis of a rainfall series in the Susquehanna Valley of the United States. Recently, DMC has been widely used in identifying the hydrological regime changes caused by anthropogenic disturbances (Huo et al., 2010; Gao et al., 2015). DMC is a plot of the accumulated values of one variable against the accumulated values of another related variable for the same period. Theoretically, it is a straight line when affected by climate change only. A break in the slope of the DMC indicates that human activities began to significantly influence runoff. In this study, precipitation and PET were the reference variable, and runoff was the tested variable. For a detailed description of this method, see Li et al. (2016).

Results

Variations of precipitation and potential evaporation

The results of Sen’s slope of annual precipitation and annual potential evaporation in Dongting Lake basin from 1980 to 2014 are shown in *Fig. 2a* and *b,* respectively. The annual precipitation did not show the same upward or downward trending in the whole basin. Overall, the trend of precipitation change in the Xiangjiang River basin was more significant, and the precipitation of some weather stations in the Yuanjiang River basin had an upward tendency. The trend of precipitation change of weather stations failed to achieve a significant level, except for Wufeng Station (*Table 1*). As shown in *Fig. 2b*, potential evaporation in the whole basin showed an upward trend. From the spatial distribution, the trend of potential evaporation change decreased progressively from the eastern to the western region. Similarly, compared with the Lishui and Yuanjiang River basins, the increasing trend of PET in the Xiangjiang and Zishui River basins was more significant (*Table 1*).

Table 1. *Sen's slope of precipitation and PET of meteorological stations in Dongting Lake*

Basin	**Station**	**Sen's slope**	
		P (mm/a)	**PET (mm/a)**
Lishui	Sangzhi	1.31	0.20
	Shimen	-2.95	**2.40**
	Wufeng	**-7.63**	0.84
Yuanjiang	Jishou	-0.17	1.74
	Yuanling	0.01	1.49
	Changde	0.64	**5.50**
	Zhijiang	1.39	0.30
	Tongdao	-5.78	1.36
	Laifeng	-5.46	1.01
	Youyang	-2.22	1.71
	Tongren	-0.70	-0.08
	Kaili	-1.23	1.68
	Sansui	0.28	0.48
Zishui	Anhua	0.60	**3.40**
	Yuanjiang	-3.76	2.03
	Shaoyang	-4.34	**2.77**
	Wugang	-6.29	**3.69**
Xiangjiang	Changsha	-0.90	**6.07**
	Pingjiang	-4.69	**3.17**
	Shuangfeng	-1.26	0.76
	Nanyue	-4.75	**2.88**
	Yongzhou	-2.93	1.95
	Hengyang	-6.38	**5.18**
	Daoxian	1.58	0.12
	Chenzhou	-2.45	1.51

Positive values mean an increase, negative values mean a decrease. The bold font indicates the trend of change is significant at the 95% confidence interval

Figure 3a and *b* shows the respective long-term trends and mean annual value of annual precipitation and potential evaporation in Dongting Lake basin. The annual average precipitation in the basin was 1391.65 mm from 1980 to 2014 and great inter-annual variations could be observed, with the largest ratio at 1.89. Furthermore, the precipitation indicated a decreasing trend with a Sen of -1.57 mm/a (P = 0.39) (*Fig. 3a*).

Compared with other periods, rainfall was relatively abundant in the 1990s. However, the PET of Dongting Lake basin showed a significant increasing trend ($P < 0.05$) at a rate of 2.33 mm/a. The average PET was 1013.01 mm in 1980–2014, during which PET fluctuated greatly especially after 2000.

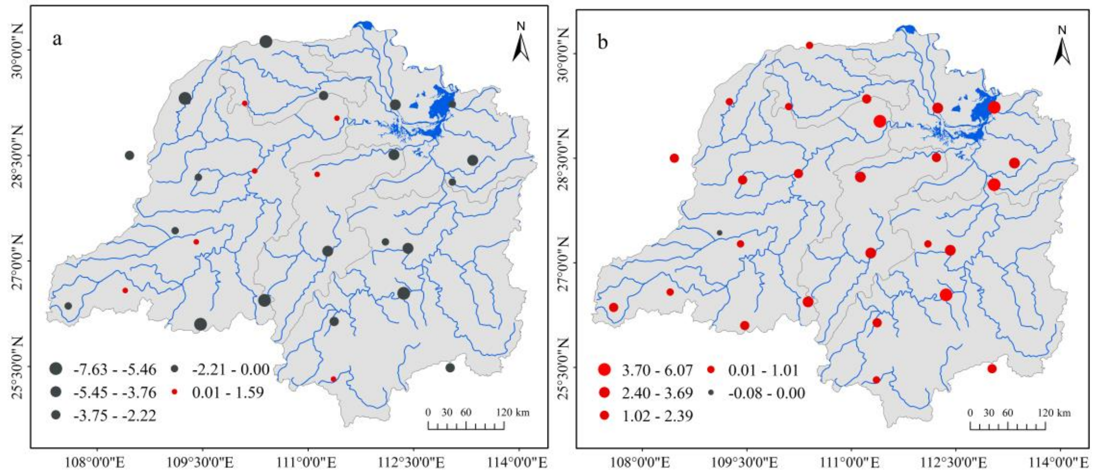

Figure 2. *Spatial variations of precipitation and potential evaporation in Dongting Lake basin for 1980–2014 (a: Sen's slope of annual precipitation; b: Sen's slope of annual potential evaporation)*

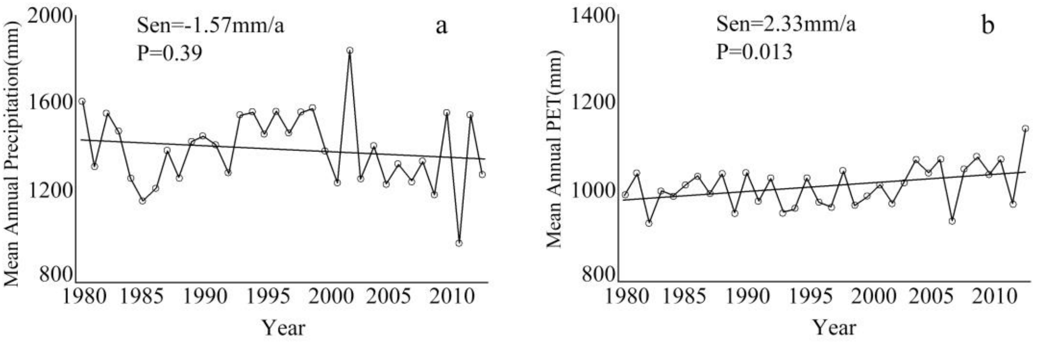

Figure 3. *Variations of mean annual precipitation (a) and potential evaporation (b) from 1980 to 2014*

Trend and change-point analysis of runoff

The variations of mean annual runoff for the four sub-basins in Dongting Lake basin are illustrated in *Figure 4a1*, *b1*, *c1* and *d1*, respectively. Xiangjiang River basin had the highest annual runoff (667×10^8 m^3, about 40% of the total), followed by Yuanjiang (629×10^8 m^3) and Zishui (227×10^8 m^3) and the lowest was Lishui River basin at only 145×10^8 m^3. Except for Lishui River basin, the runoff of the other three basins had similar inter-annual fluctuation patterns, firstly decreasing, then increasing and again decreasing. Similar to the precipitation changes, the annual runoff in the 1990s was significantly higher than that in the 1980s and the 2000s. The runoffs of four sub-basins were all lower than the previous record for the period after 2003. The annual runoff in Lishui had no clear increasing or decreasing trend.

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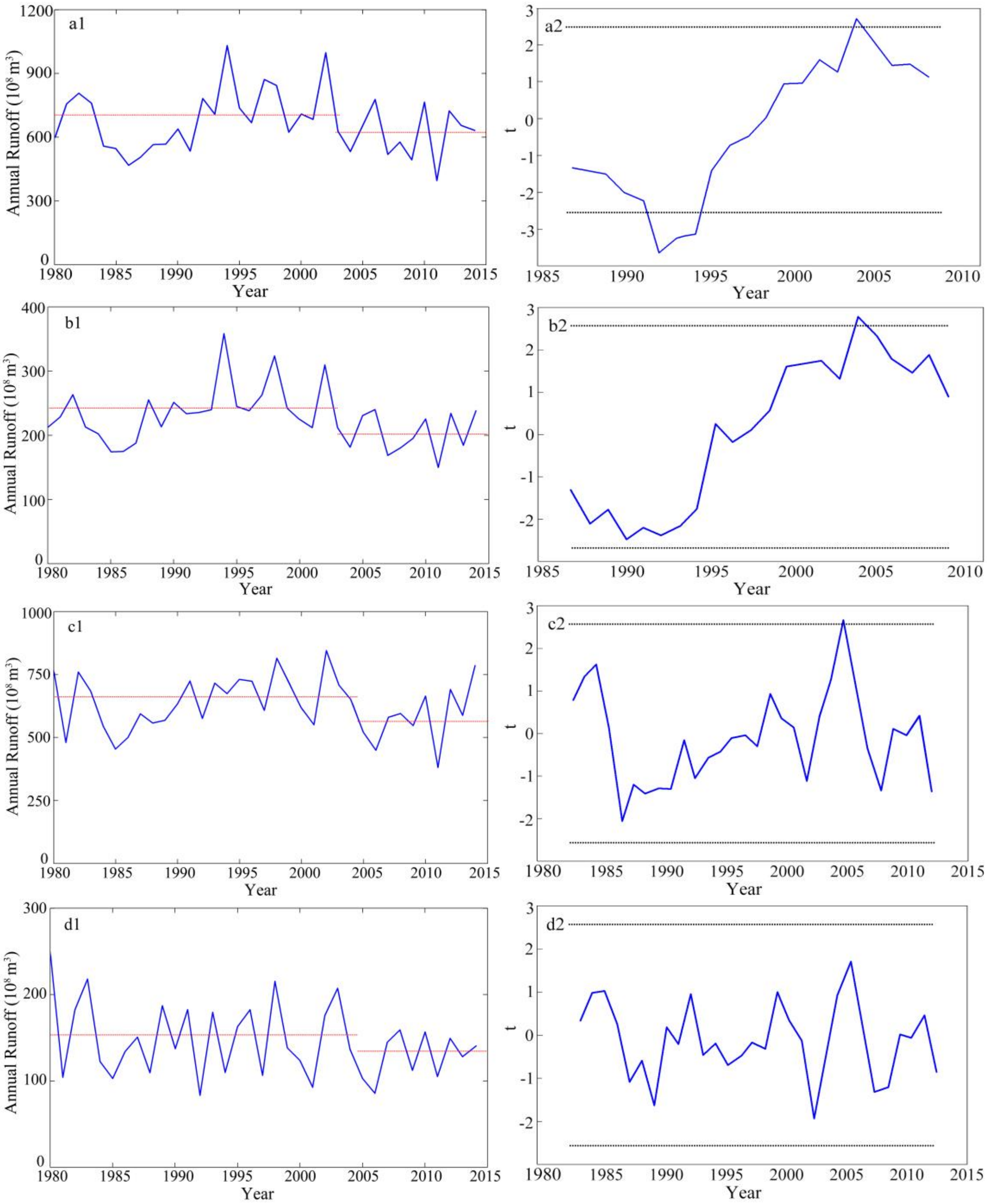

Figure 4. *Variations and moving t-test on runoff in Dongting Lake basin (a: Xiangjiang River basin, b: Zishui River basin, c: Yuanjiang River basin and d: Lishui River basin). The red dotted line stands for mean annual runoff before and after the turning years on the left. The dotted line means the significance level of 0.05 on the right*

The moving t-test and non-parametric Pettitt test were applied to detect the change point of the annual runoff series of the sub-basins. Similar results were obtained (*Table 2*). As shown in *Figure 4a2, b2, c2, d2* and *Table 2*, the turning years in the runoff changes were 2003 for Xiangjiang River basin, 2003 for Zishui and 2005 for Yuanjiang River basin. No significant change point was found for Lishui River basin. On the basis of this finding, this study will analyse the runoff trend of the other three sub-basins. Through trend and change-point analysis, the runoff series will be divided into a natural period series and an impact period series. The comparison and analysis of the mean runoff before and after the abrupt change indicated that the annual runoff of every sub-basin had a remarkable decline after the abrupt change. The drops were 11.46%, 14.87% and 8.77% in Xiangjiang, Zishui and Yuanjiang River basins, respectively.

Table 2. *Summarised result of moving t-test and Pettitt test on the runoff change points for different sub-basins*

Sub-basin	**Moving t-test**		**Pettitt test**	
	Change-point	***P***	**Change-point**	***P***
Xiangjiang	1992, 2003	0.05	2003	0.43
Zishui	2003	0.05	2003	0.12
Yuanjiang	2005	0.05	2005	0.45
Lishui	-	-	2003	1.06

‘-’ means the test results were not significant

Quantification of climatic and anthropogenic influences

Multi-regression method

The natural period was taken as a baseline, and the effects of climate change and human activities on runoff of each sub-basin were estimated for the impact period using two methods.

Multi-regression equations of the three sub-basins were developed based on the monthly average precipitation and potential evaporation of the natural period (*Table 3*). The coefficients of determination (R^2) were all greater than 0.75 (significance level of 0.001), and the NSCs were all greater than 0.65. These results indicate that the multi-regression models can accurately simulate runoff. The simulated runoff series was obtained with the use of precipitation and PET of the impact period as input. The contribution of climate factors and human activities to runoff were calculated according to *Equations 7* and *8,* respectively. The quantitative results are shown in *Table 4*.

Double mass curve analysis

The DMCs of precipitation–runoff and PET–runoff, along with the linear regression lines, are shown in *Figures 5* and *6,* respectively. Clearly, the DMCs showed the turning points for runoff, which indicated that the runoff changes were influenced by both climate factors and human activities in the three sub-basins of Dongting Lake. This result further verifies the correctness of the test for abrupt change.

The contribution rates of climate factors and human activities in runoff changes in these sub-basins were calculated and shown in *Table 5*. For Xiangjiang River basin, the annual average observed runoffs in the natural period and the impact period were 694.02×10^8 m^3 and 611.40×10^8 m^3, respectively. Based on the DMCs, the influence quantities of precipitation and evaporation on runoff reduction were 48.39×10^8 m^3 and 27.56×10^8 m^3, respectively. Accordingly, the contribution rates of precipitation and PET accounted for 58.58% and 33.35% of the runoff change, respectively. The reduction ratio due to human activities was only 8.07%. Similarly, the contribution rates of climate factors and human activities to the runoff reduction in Zishui and Yuanjiang River basins were 62.56% and 37.44% and 61.68% and 38.32%, respectively.

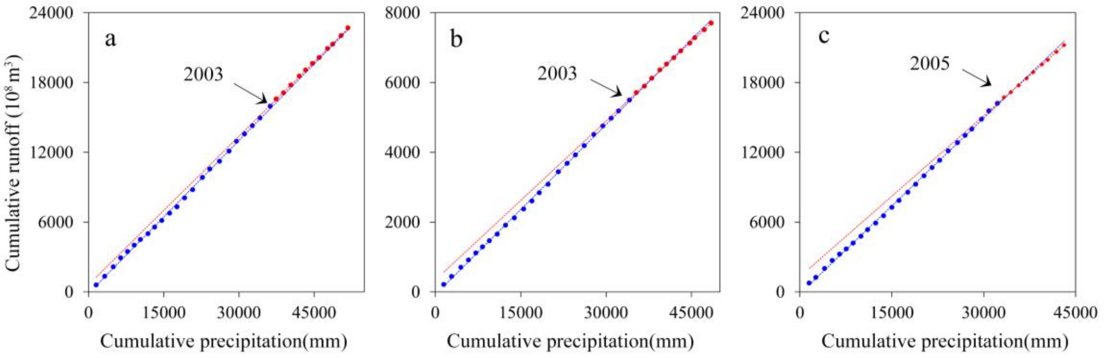

Figure 5. *DMCs of annual runoff and precipitation at different sub-basins. The blue and red lines are the regression lines for the cumulative data before and after the change-point years, respectively (a: Xiangjiang River basin, b: Zishui River basin and c: Yuanjiang River basin)*

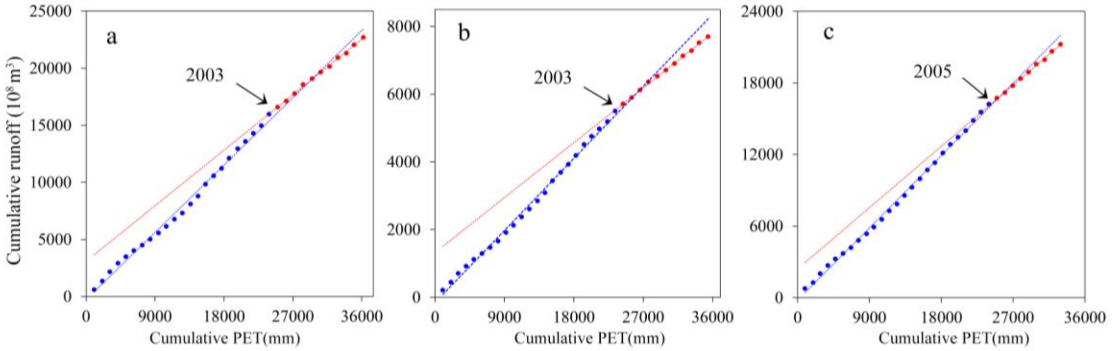

Figure 6. *DMCs of annual runoff and PET at different sub-basins. The blue and red lines are the regression lines for the cumulative data before and after the change-point years, respectively (a: Xiangjiang River basin, b: Zishui River basin and c: Yuanjiang River basin)*

Table 3. *Multiple linear regressions for the series of monthly runoffs during the natural period in the three sub-basins of Dongting Lake basin*

Sub-basin	Regression equation	R^2	Significance level	*NSC*
Xiangjiang	$Q=0.460P-0.117PET+0.255P'-12.855$	0.804	$P < 0.001$	0.805
Zishui	$Q=0.418P-0.123PET+0.206P'-3.157$	0.754	$P < 0.001$	0.716
Yuanjiang	$Q=0.524P-0.235PET+0.228P'-3.611$	0.839	$P < 0.001$	0.738

Table 4. *Effects of climate variability and human activities on runoff change using multi-regression method*

	Xiangjiang	Zishui	Yuanjiang
Climate change (%)	84.93	88.45	81.91
Human activities (%)	15.07	11.55	18.09

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Table 5. *Effects of climate variability and human activities on runoff change using DMC analysis*

Sub-basin	**Periods**	$\bar{O}$	**P**			**PET**			C_H
			$\overline{Q_{m\_P}}$	ΔQ_{c_P}	C_P	$\overline{Q_{m\_PET}}$	ΔQ_{c_P}	C_{PET}	
Xiangjiang	1980-2003	694.02							
	2004-2014	611.40	645.62	48.39	58.58	666.47	27.56	33.35	8.07
Zishui	1980-2003	239.06							
	2004-2014	200.03	223.86	15.20	38.96	229.85	9.21	23.60	37.44
Yuanjiang	1980-2005	648.39							
	2006-2014	557.25	615.32	33.02	36.24	625.16	23.18	25.44	38.32

The units $\overline{O}$, $\overline{Q_m}$, ΔQ_c : $\times 10^8\,m^3$; C_P, C_{PET}, C_H : %

Discussion

The results above showed that the annual runoff decreased significantly in Xiangjiang, Zishui and Yuanjiang River basins. Decreasing precipitation and increasing PET play critical roles in affecting the reduced runoff changes. Some studies showed that temperature and precipitation were the predominant factors that caused the shortage of water resources and drought and flood. Guo et al. (2001) indicated that the runoffs of semi-humid regions in the north of China are more sensitive to climate change than those of humid regions such as Yangtze River basin. In the present study, the climate variation features are consistent with those of the runoff series, providing further evidence that climate change are the dominant factor decreasing runoff. From the whole basin, the climate change trend in Xiangjiang and Zishui River basin are more significant, which corresponds to the conclusion that the contribution rate of climate change in decreasing runoff was larger in the two basins. No significant change point was detected in the runoff variation of Lishui River basin, consistent with the results of Liu et al. (2014) and Zheng and Sun (2014). Their studies showed that the annual runoff of Lishui River basin has not changed significantly since the 1980s. On the one hand, the annual rainfall of the study period has not changed significantly; on the other hand, although the underlying surface conditions of the middle and upper reaches of Lishui River have been changing, human activities have not affected the annual runoff. This outcome may be related to the well-developed river system and abundant runoff. While human activities are gradually intensifying, they have not caused significant changes to the hydrological characteristics of Lishui River. The relevant physical mechanisms need to be further verified and determined as well.

Through multi-regression method and DMC analysis, the contribution rates of climate change and human activities to runoff changes in the four sub-basins were obtained. The conclusions from the two methods are consistent: runoff reduction was mainly caused by climate change in the whole basin and human activities played an assisting role in such a change, a finding that is consistent with the conclusion of Xiao (2014). Zhang and Liu (2018) also indicated that regional climate change (precipitation and PET) are the main factors influencing the runoff of Xiangjiang River basin. The two kinds of methods confirm each other and improve the reliability of the evaluated results. With the results of the two methods combined, the impact of human activities on the runoff change was revealed to be negative. In addition, owing to the discrepancy in regional climate and the intensive human activities in these sub-basins, the contribution of individual impacts varied under different regions. According to *Tables 4* and *5*, the contribution rate of human activities in decreasing runoff in Yuanjiang River basin was the largest at 18–38%. However, a percentage of the impact of climate change in Xiangjiang River basin was bigger than those in other sub-basins, and the impact of human activities accounted for 8–15% of decreasing runoff.

Human activities affect the basin hydrological process mainly through two aspects: changing the conditions of the underlying surface and developing hydropower engineering (Ye et al., 2009). The former involves the variation of land utilisation and land cover, urbanisation, water and soil conservation and vegetation restoration. Relevant documents show that the total population of Dongting Lake basin has increased by 12.07 million since 1980, and the areas for construction land have also increased (Xiao, 2014). In recent decades, according to statistics from the Hunan Water Conservancy Bureau (http://www.hnwr.gov.cn), the proportion of agricultural water use has dropped and industrial and domestic water use in urban and rural areas has increased. In addition, the forest coverage rate of the whole province increased from 36.7 to 57% during 1989–2010 (Xiao, 2014). Studies have shown that the implementation of soil and water conservation measures was conducive to increasing water storage capacity and reducing runoff (Ye et al., 2009). Water conservancy projects have a tremendous impact on runoff, in addition to changing channel characteristics. They likewise influence regional precipitation and evaporation by increasing the water area, especially through large reservoirs. According to the first water resources census of Hunan Province (http://hnrb.voc.com.cn), by the end of 2011, there were 14,121 reservoirs of various types with a total reservoir capacity of 53.07 billion m^3, of which the large reservoirs accounted for 68.2%. According to the statistical data of existing large reservoirs (Xiao, 2014), the ratio of control areas of reservoirs in Xiangjiang River basin was the smallest among all sub-basins. This fact is one of the possible causes for the results on the contribution rate of human activities in Xiangjiang River basin being the least. Overall, the effect of human activities on runoff is very complex, and the degree of influence of human activities on runoff change and the correlation between them need to be further verified.

Conclusions

On the basis of analysing the trend of runoff variation, this study used moving t-test and Pettitt method to detect turning points. Then, taking the natural period as the baseline, the impact of climatic factors and human activities on runoff variation was evaluated by multi-regression and DMC methods. The conclusions are as follows:

(1) During 1980–2014, the trend of runoff reduction in Dongting Lake basin was obvious. Besides Lishui River basin, the runoff of Xiangjiang, Zishui and Yuanjiang River basins showed abrupt changes in 2003, 2003 and 2005, respectively.

(2) Climate change was the dominant factor of runoff reduction in Dongting Lake basin, while human activities play a subsidiary role. The contribution rate of climate change to runoff reduction in Xiangjiang River Basin was approximately 85–92%, and the impact of human activities was 8–15%. In Zishui, the contribution of climate change accounted for 63–88% of the changes in runoff, while human activities were responsible for 12–37% of the change. Similarly, the impacts of climate change and human activities in Yuanjiang River basin were 62–82% and 18–38%, respectively.

The method adopted in this study can be easily used to quantify the impact of changing environments on runoff in areas that lack historical data. Some uncertainties exist because of the correlation of climate variability and anthropogenic activities. More attention should be directed to these uncertainties in future research on the quantitative estimation of influence of climate change and human activities on runoff in Dongting Lake basin. Furthermore, although the runoff reduction of Dongting Lake basin was caused by climate change, human disturbance will bring challenges to the utilisation of water resources. To maintain the ecosystem services of the river basin and ensure a certain degree of ecological water requirement, the dispatch and management of basin water resources should be strengthened.

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