

Research Article

Identification of the Impacts of Climate Changes and Human Activities on Runoff in the Jinsha River Basin, China

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Quantifying the impacts of climate changes and human activities on runoff has received extensive attention, especially for the regions with significant elevation difference. The contributions of climate changes and human activities to runoff were analyzed using rainfall-runoff relationship, double mass curve, slope variation, and water balance method during 1961–2010 at the Jinsha River basin, China. Results indicate that runoff at upstream and runoff at midstream are both dominated by climate changes, and the contributions of climate changes to runoff are 63%~72% and 53%~68%, respectively. At downstream, climate changes account for only 13%~18%, and runoff is mainly controlled by human activities, contributing 82%~87%. The availability and stability of results were compared and analyzed in the four methods. Results in slope variation, double mass curve, and water balance method except rainfall-runoff relationship method are of good agreement. And the rainfall-runoff relationship, double mass curve, and slope variation method are all of great stability. The four methods and availability evaluation of them could provide a reference to quantification in the contributions of climate changes and human activities to runoff at similar basins in the future.

1. Introduction

Flood and drought are increasing with frequency, which can primarily be attributed to climate changes and human activities [1–3]. Global warming becomes an unchangeable truth and may cause a series of consequences as precipitation pattern change and evaporation alternates, which may cause direct and dramatic effects on runoff [4–8].

Exploring runoff responses to climate changes and human activities has become a hot topic due to dramatic global warming and intensive urbanization. However, the great uncertainties of human activities and the scarcity of available data determine the difficulty in understanding runoff responses to climate changes and human activities [9, 10]. At present, an increasing number of studies have investigated the contributions of climate changes and human activities to runoff using hydrological modeling and statistical methods [11–16]. First, hydrological modeling is followed by calibrating the model parameters on the basis of previous available field data and later projecting runoff variations under the assumption of different future scenarios. Even though a great amount of remote sensing data with higher

spatial and temporary resolution has become available for use, uncertainties with climate variability are still unavoidable [17]. Moreover, parameter calibration in the process of model construction and the lack of knowledge in model structure are also derivations of the uncertainties within outputs, and the lack of high-accuracy data is another important reason for modeling work to be limited [18, 19]. Several statistical methods were developed and widely applied, such as the rainfall-runoff relationship [20], slope variation [21], double mass curve [22, 23], and water balance method [16, 20]. However, studies in high elevation-difference regions and comparative analysis of methods are still lacking [24].

As the upper reaches of the Yangtze River, Jinsha River basin was chosen as a case study. The four methods (rainfall-runoff relationship, double mass curve, slope variation, and water balance method) were applied to identify the impacts of climate changes and human activities on runoff, and their performance was also evaluated. The quantification of contributions of climate change and human activities on runoff would be helpful to understand runoff response under changing environment.

2. Methodology

2.1. Rainfall-Runoff Relationship Method. The rainfall-runoff relationship method is the earliest and simplest method to quantify the contribution of climate changes to runoff by using change-point identification and division of change period [25]. The contribution of climate changes to runoff was obtained by establishing relationship between precipitation and runoff in the method. The relationship of runoff (Q) and rainfall (P) could be described as follows:

$$Q = a + b \times P \times \sigma^c, \quad (1)$$

where σ is the variance of P ; a , b , and c are parameters obtained by the least square method [26]. The calibration procedure of the method is listed as follows:

- (a) The change point of measured annual runoff was identified by slide t -test [16]. The study period was divided into two parts (baseline period and change period) by the change point.
- (b) The contribution of human activities to runoff (C_H) could be calculated as follows:

$$C_H = \frac{(\bar{Q}_B - \bar{Q}_B) / \bar{Q}_B}{(\bar{Q}_B - \bar{Q}_A) / \bar{Q}_A}, \quad (2)$$

where A and B represent baseline period and change period, respectively. \bar{Q}_B is the mean simulated runoff in the change period by using the relationship defined in the baseline period. And \bar{Q}_B is the mean measured runoff in the change period. \bar{Q}_A represents the mean measured runoff in the baseline period.

- (c) The contribution of climate changes (C_C) is then computed as follows:

$$C_C = 1 - C_H. \quad (3)$$

2.2. Slope Variation Method. Similar to the rainfall-runoff relationship method, the change-point identification is also needed in the slope variation method [21]. The effect of climate change is decomposed into precipitation and actual evapotranspiration, which are quantified by a slope variation comparison. The specific procedure can be described as the following steps:

- (a) Determine the change point in cumulative runoff, precipitation, and evaporation, which divides the study period into two parts (baseline period and change period, that is, A and B).
- (b) Calculate slopes of cumulative runoff, precipitation, and evaporation in baseline period and change period, which were marked as k_{QA} , k_{QB} , k_{PA} , k_{PB} , k_{EA} , k_{EB} , respectively. Then, slope variability could be calculated:

$$S_Q = \frac{(k_{QB} - k_{QA})}{k_{QA}},$$

$$S_P = \frac{(k_{PB} - k_{PA})}{k_{PA}},$$

$$S_E = \frac{(k_{EB} - k_{EA})}{k_{EA}}, \quad (4)$$

where S_Q , S_P , and S_E are slope variability for cumulative runoff, precipitation, and evaporation, respectively.

- (c) The contributions of precipitation (C_P) and evaporation (C_E) to runoff are listed as follows:

$$C_P = \frac{S_P}{S_Q}, \quad (5)$$

$$C_E = \frac{S_E}{S_Q}.$$

The contribution of climate changes is

$$C_C = C_P + C_E. \quad (6)$$

- (d) The contribution of human activities could be calculated:

$$C_H = 1 - C_C. \quad (7)$$

2.3. Double Mass Curve Method. Similar to the previous two methods, the double mass curve method is also based on the change-point identification to divide the study period into two parts (baseline period and change period). In the method, the relationship of cumulative runoff and cumulative precipitation and evapotranspiration was built. The main procedure is listed as follows:

- (a) Determine the change point to divide the study period into baseline period and change period like the previous two methods.
- (b) The linear relationship between cumulative runoff, cumulative precipitation, and cumulative potential evapotranspiration in the baseline period was established as

$$\sum Q = k_1 \sum P + k_2 \sum E_T + k_3, \quad (8)$$

where E_T refers to potential evapotranspiration. k_1 , k_2 , and k_3 are parameters. The cumulative runoff in the change period was calculated using the linear relationship defined in the baseline period.

- (c) The runoff variation ΔQ is

$$\Delta Q = \bar{Q}_B - \bar{Q}_A. \quad (9)$$

- (d) The variation induced by human activities ΔQ_H is

$$\Delta Q_H = \bar{Q}_B - \bar{Q}_B. \quad (10)$$

- (e) The contribution of human activities could be calculated:

$$C_H = \frac{\Delta Q_H}{\Delta Q}. \quad (11)$$

The contribution of climate changes is

$$C_C = 1 - C_H. \quad (12)$$

TABLE 1: Contributions of climate change and human activities to runoff by rainfall-runoff relationship method.

Divisions	Contributions (%)		Relationship between Q and P	R^2
	Climate changes	Human activities		
I	46	54	$Q = 162.9 + 8.659 \times P \times \sigma^{-0.7428}$	0.96
II	38	62	$Q = 20.99 + 11.41 \times P \times \sigma^{-0.4863}$	0.95
III	12	88	$Q = 0.5759 + 0.6653 \times P \times \sigma^{0.395}$	0.97

Note. R^2 is the coefficient of determination.

2.4. *Water Balance Method.* The water balance in a basin is described as

$$P = E + Q + \Delta S, \quad (13)$$

where E is evapotranspiration and ΔS is the variation of water storage in the basin, which is considered to be zero over a long period of time, such as 5–10 years [16]. The long-term annual evapotranspiration could be calculated as [27]

$$\frac{E}{P} = \frac{1 + w(E_T/P)}{1 + w(E_T/P) + (E_T/P)^{-1}}, \quad (14)$$

where w is a parameter relating to vegetation types. The relationship between runoff, precipitation, and potential evapotranspiration changes is defined as [28]

$$\Delta Q_C = \beta \Delta P + \gamma \Delta E_T, \quad (15)$$

where ΔQ_C describes the variation of runoff induced by climate changes. ΔP and ΔE_T are the variations of precipitation and potential evapotranspiration, respectively. β is the sensitivity coefficient of runoff to precipitation, and γ is the sensitivity coefficient to potential evapotranspiration. The two parameters (β and γ) can be calculated by

$$\beta = \frac{1 + 2z + 3wz}{(1 + z + wz^2)^2}, \quad (16)$$

$$\gamma = -\frac{1 + 2wz}{(1 + z + wz^2)^2},$$

where z is a dryness index (E_T/P). In addition, w is a parameter to reflect vegetation and soil conditions in the study area and equals 2.0 in this study with the proposal given by Liu and Zhang [29].

3. Case Study

3.1. *Study Area.* The Jinsha River basin (Figure 1) is located in the upstream of the Yangtze River basin. As the most important economic center in China, Yangtze River basin holds approximately 30% of population of the country. The Jinsha River basin covers an area of $3.4 \times 10^5 \text{ km}^2$ with a total length of 2316 m, and it plays a significant role in water supply and ecological barriers for the Yangtze River basin. The Jinsha River basin is also characterized by the significant elevation difference of 5231 m. According to elevation, the basin could be divided into three parts (I: above 4000 m, II:

3000~4000 m, and III: below 3000 m). The source of water vapor over the basin mainly includes the Bay of Bengal, the South China Sea, and the Western Pacific [30]. The areal mean annual precipitation in I, II, and III regions is 344 mm, 614 mm, and 900 mm, respectively.

3.2. *Data.* The daily precipitation and evaporation data (1961–2010) about 25 meteorological stations in the basin was downloaded from the China Meteorological Data Service Center (<http://data.cma.cn/>) (Figure 1). The daily streamflow data at Zhimenda (upstream), Shigu (midstream), and Pingshan (downstream) was obtained from the Hydrology Bureau, Changjiang Water Resources Commission. The Digital Elevation Model (DEM) data with 90 m resolution was downloaded from the Consortium for Spatial Information (CGIAR-CSI).

The potential evapotranspiration was estimated by equations introduced by Li et al. [31]. The areal mean annual precipitation and potential evapotranspiration of I, II, and III region were used by interpolating the data of relevant 25 meteorological stations with the Inverse Distance Weighted (IDW) method. Zhimenda, Shigu, and Pingshan are regarded as outlets of the I, II, and III regions, respectively. To quantify the contributions of climate changes and human activities to runoff, rainfall-runoff relationship method, slope variation method, double mass curve method, and water balance method were employed in the study. And the annual data of rainfall and runoff during 1961~2010 was used.

4. Results

Identifying the change point in streamflow, precipitation, actual and potential evapotranspiration, and their cumulative time series at up-, mid-, and downstream is the first step for the four quantitative methods. According to slide t -test [16], the year of 1985 was detected as the change point. Figure 2 showed the time series of streamflow, precipitation, and actual and potential evapotranspiration during the whole study period, and the fitted lines for the baseline period and the change period are separated by the year of 1985.

4.1. *Results of Rainfall-Runoff Relationship Method.* The relationships between streamflow and precipitation and actual evapotranspiration were established as in Table 1 in the rainfall-runoff relationship method. Three relationship equations at upstream, midstream, and downstream are of great confidence in determining coefficient of 0.96, 0.95, and 0.97, respectively. Results showed that the contributions of precipitation to runoff at upstream and midstream were 46%

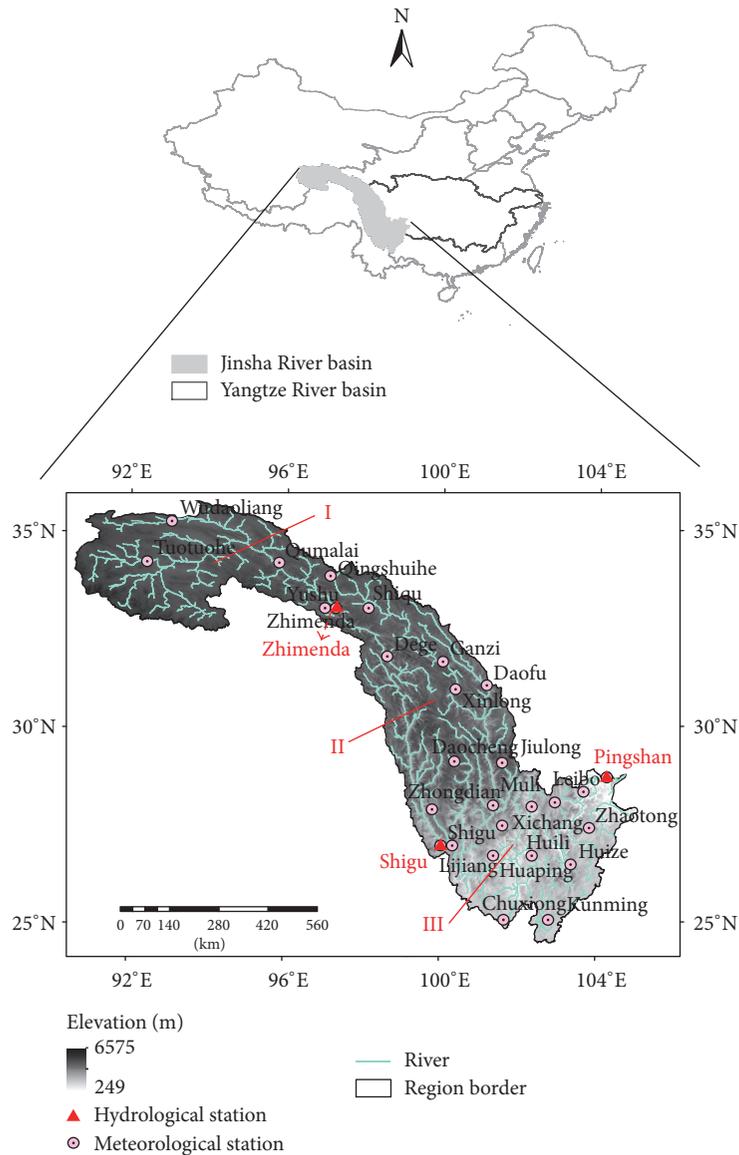


FIGURE 1: Map of the Jinsha River basin.

and 38%, respectively, and only 12% at downstream (Table 1). The contributions of human activities were 54%, 62%, and 88% at upstream, midstream, and downstream, respectively. Therefore, human activities have more significant impacts on runoff, especially at the downstream.

4.2. Results of Slope Variation Method. The slopes in cumulative runoff, precipitation, and evaporation during the baseline and change periods were calculated as in Table 2 in the slope variation method. In the baseline period, streamflow at upstream, midstream, and downstream decreased and the slope is negative, especially at midstream and downstream. However, streamflow at upstream increased in the change period. Precipitation at midstream and downstream decreased in both periods. Evaporation increased at midstream but decreased at downstream. In the slope variation

method, the contribution of climate changes to runoff was 68%~69% at upstream and midstream, but 18% at downstream (Table 3). Human activities were identified as the largest contributor to runoff at downstream with 82%.

4.3. Results of Double Mass Curve Method. In Figure 3, variations of streamflow, precipitation, and actual and potential evapotranspiration were shown from the baseline period to the change period. The variation of potential evapotranspiration is least in them. For actual evapotranspiration, its variation is largest. Precipitation increased 7% at midstream, decreased 2% at upstream, and decreased 12% at downstream. In the double mass curve method, the contributions of climate changes were 63% and 53% at upstream and midstream, respectively (Table 3). However, the contribution of climate

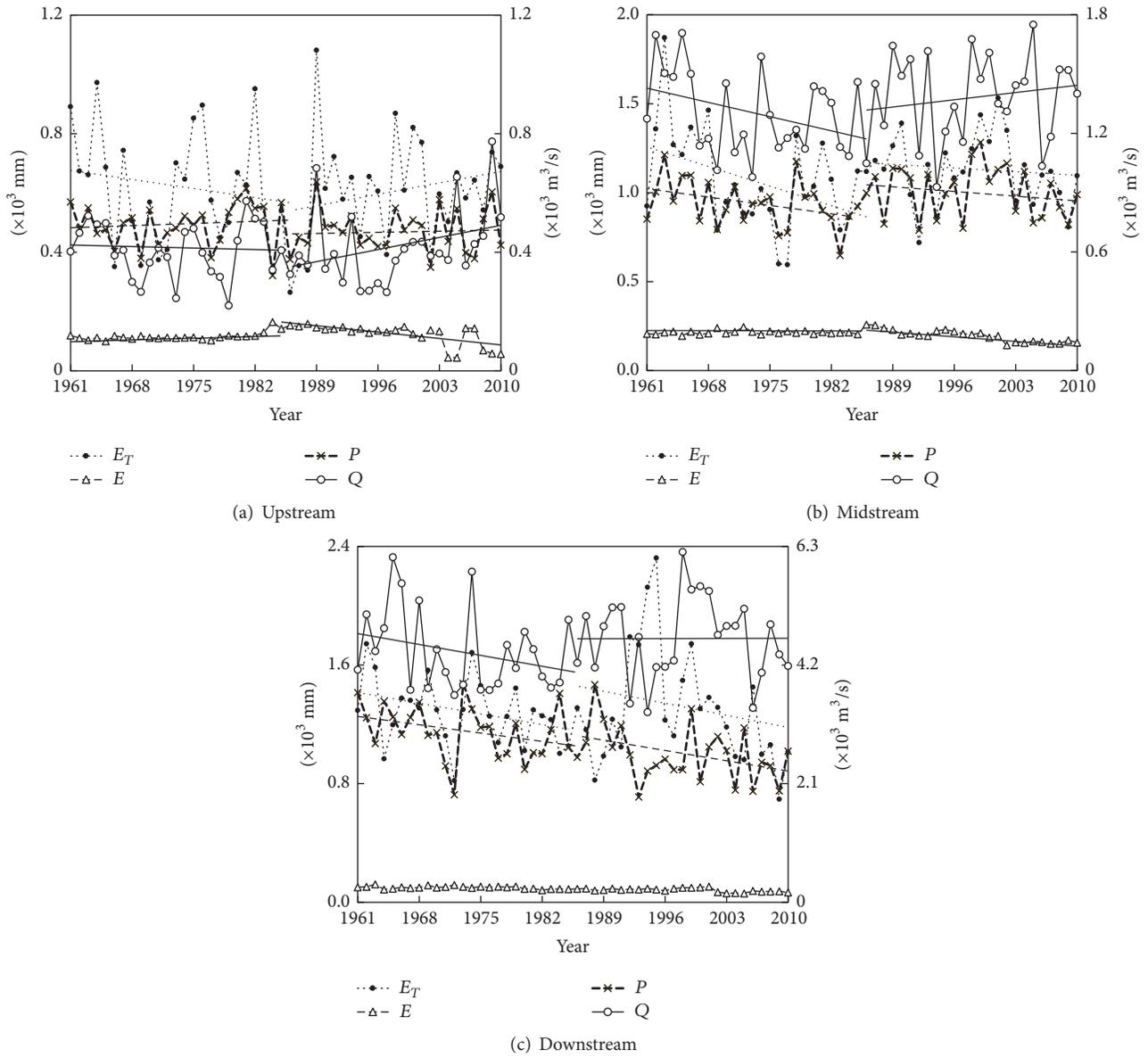


FIGURE 2: Streamflow, precipitation, potential and actual evapotranspiration, and their trend-lines at upstream, midstream, and downstream.

TABLE 2: Slope in cumulative runoff, precipitation, and evaporation during the baseline period (A) and change period (B).

Divisions	Q		P		E	
	k_{QA}	k_{QB}	k_{PA}	k_{PB}	k_{EA}	k_{EB}
I	-0.05	0.37	0.02	-0.04	0.62	-0.68
II	-0.37	0.04	-0.31	-0.16	0.06	0.04
III	-0.30	-0.04	-0.28	-0.37	-0.33	-0.28

Note. k_{QA} , k_{QB} , k_{PA} , k_{PB} , k_{EA} , k_{EB} refer to slope of cumulative runoff, precipitation, and evaporation in the baseline period and change period.

TABLE 3: Contributions of climate change and human activities by slope variation, double mass curve, and water balance method.

Divisions	Slope variation method		Double mass curve method		Water balance method	
	C	H	C	H	C	H
I	69%	31%	63%	37%	72%	28%
II	68%	32%	53%	47%	63%	37%
III	18%	82%	14%	86%	13%	87%

Note. C refers to the contributions of climate changes to runoff, and H refers to the contributions of human activities to runoff.

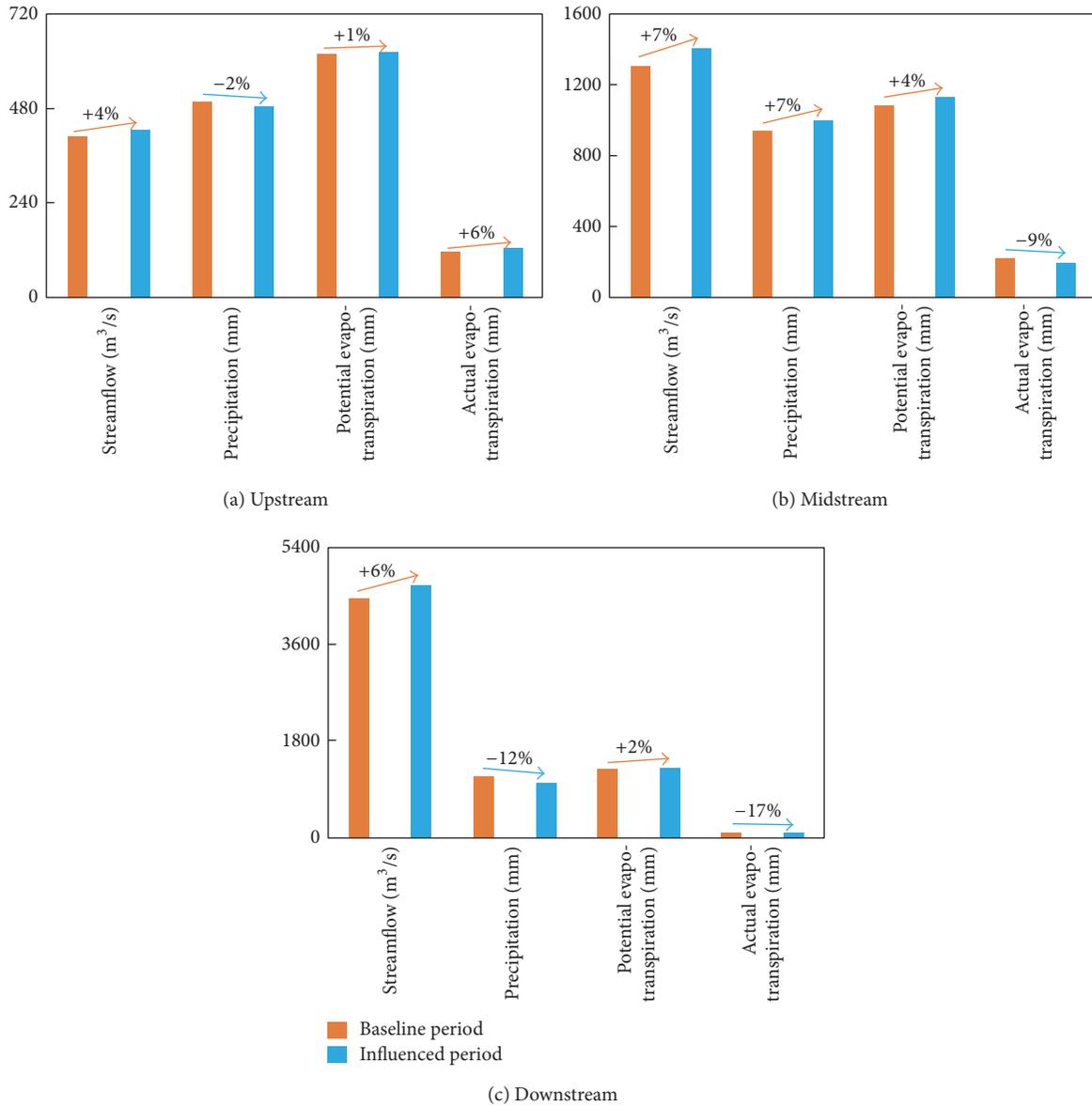


FIGURE 3: Variations of streamflow, precipitation, and potential and actual evapotranspiration from the baseline period to the change period at upstream, midstream, and downstream.

changes was 14% at downstream. These results are of great similarity with the slope variation method.

4.4. Results of Water Balance Method. In the water balance method, contributions of climate changes to runoff were 72% and 63% at upstream and midstream, respectively (Table 3). Similar to the results obtained by slope variation and double mass curve method, the impact of climate changes was dominant in the runoff at upstream and midstream in the water balance method (Figure 4). At downstream, the impact of human activities was dominant.

5. Discussion

The identified change points with discrepancies distribute between 1980 and 1990 by using different methods. The

adaptability was analyzed by 11 scenarios in change points for rainfall-runoff relationship, slope variation, and double mass curve method. The results of contribution of climate changes under 11 change points were shown in Figures 5(a)–5(c). Moreover, it illustrates that the contribution of climate changes based on change point in 1985 is centered among results of 11 change points. In addition, all results by different change points only vary within a tiny range in no more than 8%. The largest range of 8% occurs at upstream in rainfall-runoff relationship method. In the double mass curve method, the contributions of climate changes were 63%, 53%, and 14% at upstream, midstream, and downstream, respectively, for change point in 1985. According to change points from 1980 to 1990, the contributions at upstream, midstream, and downstream had ranges of (60%, 66%), (50%, 56%) and (11%, 17%), respectively.

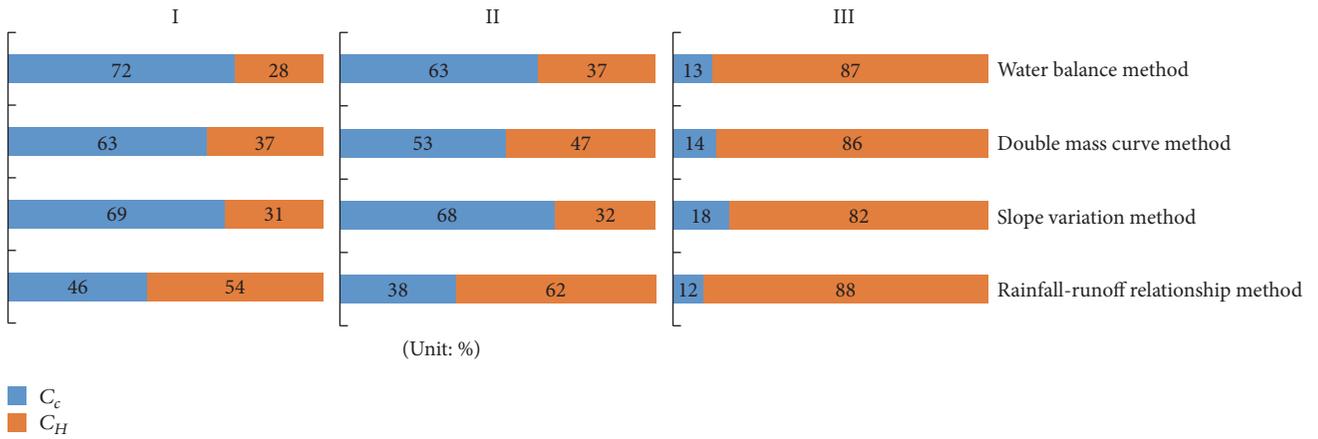


FIGURE 4: Contributions of climate changes and human activities to runoff in the different methods at upstream, midstream, and downstream.

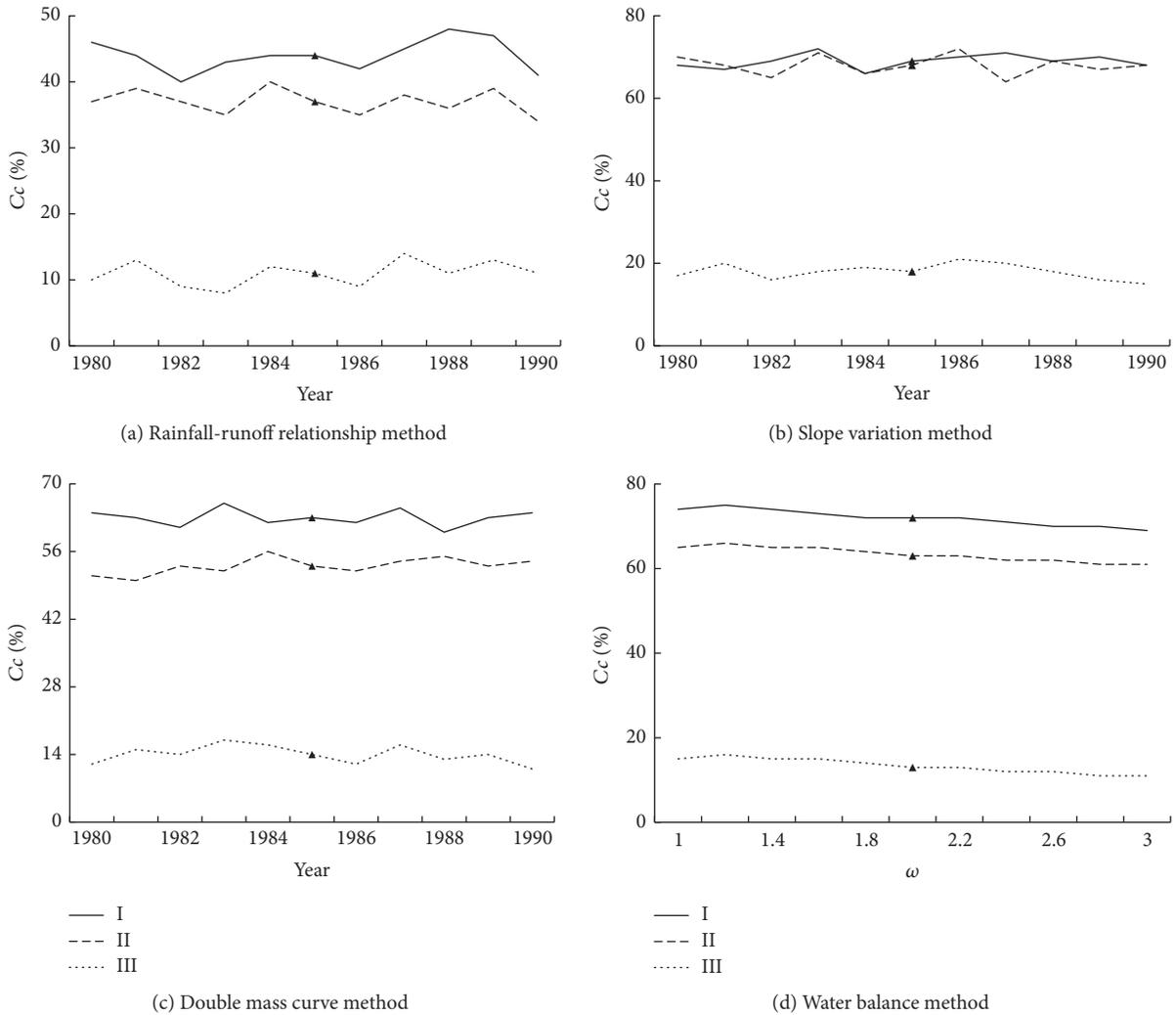


FIGURE 5: Adaptability in rainfall-runoff relationship, slope variation, double mass curve, and sensitivity in water balance method.

For the water balanced method, parameter ω was determined by previous studies [29] and there was uncertainty in the parameter. Due to ω closely related to vegetation and soil conditions, the survey of vegetation was performed. Results showed that ω was generally in the range of (1, 3). Therefore, the scenarios (ω varying within 1–3) were designed for sensitivity of water balance method. In Figure 5(d), the contribution of climate changes to runoff decreased weakly. In sum, results of water balance method are of great consistency with slope variation and double mass curve method.

Except the rainfall-runoff relationship method, the other three methods perform consistently in results (Figure 4). Based on the adaptability in slope variation, double mass curve method, and sensitivity analysis in water balance method, the contributions of climate changes and human activities were determined as the ranges derived from the three methods. At upstream and midstream, the contributions of climate changes to runoff were 63%–72% and 53%–68%, respectively. However, the contribution of human activities to runoff was 82%–87% at downstream.

6. Conclusions

In the Jinsha River basin, impacts of climate changes and human activities on runoff were analyzed by four quantitative methods, that is, rainfall-runoff relationship, slope variation, double mass curve, and water balance method. The conclusions could be summarized as follows:

- (1) Climate changes play a significant role in runoff at upstream and midstream with contributions of 63%–72% and 53%–68%, respectively.
- (2) At downstream, the impact of human activities was dominant in the runoff with contribution of 82%–87%.
- (3) The slope variation, double mass curve, and water balance method perform well in the case study. However, the result of rainfall-runoff relationship method is not satisfactory without consideration of other climate factors, except precipitation.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

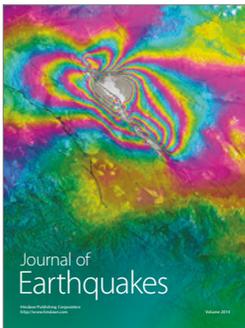
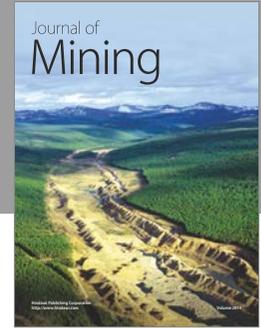
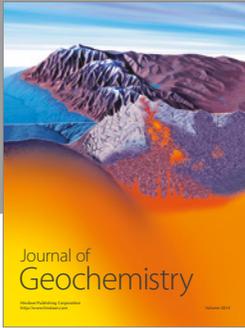
Acknowledgments

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