

Contributions of climate change and anthropogenic activities to runoff change in the Hongshui River, Southwest China

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Abstract. Changes in water resources are mainly affected by the combined effects of anthropogenic activities and climate change. The relative effects of anthropogenic activities and climate on a river basin are investigated to not only understand the hydrological response mechanism in a catchment but also manage local water resources and protect against floods and droughts. In this study, a variable infiltration capacity (VIC) model combined with a hydrologic sensitivity analysis was used to quantify the effects of anthropogenic activities and climate change on runoff in the upper reaches of the Hongshui River basin (UHRB). During 1970-2015, the runoff contribution for climate change and anthropogenic activities were 89.2% and 10.8%, respectively. This result suggests that climate is the major driver of runoff variation in the basin. However, during 1990-1999, anthropogenic activities played a decisive role in the reduction in streamflow, and the contribution percentage was 96.35%. Moreover, the impact of anthropogenic activities on runoff changed from positive to negative from the 1980s to the 2000s, and the negative effect showed a continuously increasing trend. Hydrologic sensitivity methods and hydrological modelling produced similar estimates. Our findings emphasize that the impacts of anthropogenic activities such as land use change and the operations of water conservancy projects should be properly managed.

1. Introduction

Environmental change and water resource evolution have become popular topics in global water science in recent years [1,2]. Anthropogenic activities and climate are important components of a changing environment that bring extensive attention to hydrological effects. The water cycle of a basin is a complex process affected by many factors that include anthropogenic activities and climate, which are both important driving factors [3,4]. In addition, the effects of anthropogenic activities and climate are often integrated, and factorizing these effects is a key issue in research. Many studies have been conducted on climate and runoff changes in individual basins, and those studies show that in recent years, anthropogenic activities have acutely influenced river discharge [5-8]. However, the influences of anthropogenic activities and climate change can vary across regions, which have led to opposing conclusions in previous studies [9-11]. Thus, the contribution rates of different factors at a local scale need to be identified based on watershed properties [6,12].



Many researchers have used different methods to discuss the different influences of climate change and anthropogenic activities on runoff changes [11,13-16]. In general, there are three methods widely used to quantitatively distinguish the effects of anthropogenic activities and climate on streamflow: (1) sensitivity analyses based on the Budyko theory [17], (2) hydrological physical process simulation methods [18], and (3) regression analysis methods [15,19]. The water balance method based on the Budyko theory of water and heat coupling balance has more obvious physical meaning compared with the traditional statistical and empirical methods. The calculation process for the Budyko method is relatively simple, and the parameters are easy to obtain, so it is an ideal analysis method [20]. Xu *et al* [21] analysed the main reasons for streamflow reduction in the Haihe River basin using the hydrological simulation method. The results show that anthropogenic activities are the main causes of runoff decrease and that the influence of anthropogenic activities mainly comes from the increase in vegetation. Xia *et al* [22] studied the effects of anthropogenic activities and climate on streamflow of the Yongding River catchment. The results show that anthropogenic activities contributed to 87.4-89.5% of the runoff reduction. The hydrological simulation has a strong physical basis and high resolution and can be applied to monthly or daily time scales. However, the range and variability in the model response are influenced by multiple factors such as uncertainties in model structure and parameters, topography, soil, vegetation in the basin and the complexity of the relationship between climates. Therefore, the selection of a suitable hydrological model is essential [20]. Zhang *et al* [11] used the Australian water balance model (AWBM) and multivariate regression to analyse the driving factors of runoff reduction in the Poyang Lake catchment. The results showed that anthropogenic activities and climate change contributed 73.2% and to 26.8%, respectively, of the Poyang Lake runoff reduction. Zeng *et al* [23] used the SIMHYD model to study the possible factors on streamflow variation of the Zhanghe basin. The results show that compared with the factors of anthropogenic activities, climate change has a greater impact on runoff. Most of the studies on quantitative analysis of runoff response to climate change and anthropogenic activities are based on a single method of assessment. Different methods often result in differences in the evaluation results or even the exact opposite results. Zuo *et al* [24] and Gao *et al* [25] used different methods to detect the change of streamflow in the same basin and obtained contradictory results. Similarly, Ye *et al* [26] used sensitivity coefficient method to study the change of runoff in the Poyang Lake catchment and reported different findings with Zhang *et al* [11]. Therefore, to accurately and quantitatively assessment the response of runoff to climate change and anthropogenic activities and ensure the accuracy of the results, it is necessary to use two different cross-validation methods.

In this study, the upper reaches of the Hongshui River basin (UHRB) were chosen as the research object. The natural water circulation in the basin has changed greatly due to hydraulic projects and other anthropogenic activities. It is particularly important to study the characteristics of runoff in the UHRB to make better use of the basin water resources. The objectives of this study are to (1) analyse the changing patterns of hydrological and meteorological factors such as temperature, precipitation, evapotranspiration and runoff, (2) quantitatively estimate the contributions of anthropogenic activities and climate to the change in runoff by using the hydrological simulation and the sensitivity coefficient method and (3) analyse the factors driving runoff reduction in the watershed. This study is of great significance for understanding the respective contributions of anthropogenic activities and climate to the streamflow evolution in the UHRB. At the same time, this study has important practical significance for water resource planning and management, disaster prevention and mitigation.

2. Description of the study area and datasets

2.1. Study area

The Hongshui River is the main stream of the Xijiang River in the Pearl River basin, which has abundant water power resources and is one of the twelve bases for hydropower construction in China. The UHRB is located in the southwest part of China (between 102°14'E-107°32'E and 23°11'N-27°01'N, figure 1). The total area of the drainage basin is 98,500 km², accounting for 71.2% of the

Hongshui River basin [27]. The mean annual runoff is $508 \times 10^9 \text{ m}^3$, which had a decreasing trend from 1961 to 2015. The annual precipitation in the basin ranged from 760 to 1,860 mm during 1961-2015, and more than 82.8% of this precipitation occurs from May to October [28]. There are four large hydropower stations (figure 1) built on the drainage basin, and the installed capacity accounts for 62-79% of the overall development capacity of the Hongshui River. Therefore, the four stations play a significant role in energy regulation and storage and serve as an irreplaceable flood control reservoir that decreases flood disasters in the lower reaches of the river basin. Due to climate change and anthropogenic activities (such as afforestation, operation of reservoirs, agricultural irrigation, etc.), great changes have taken place in the natural water cycle of the basin.

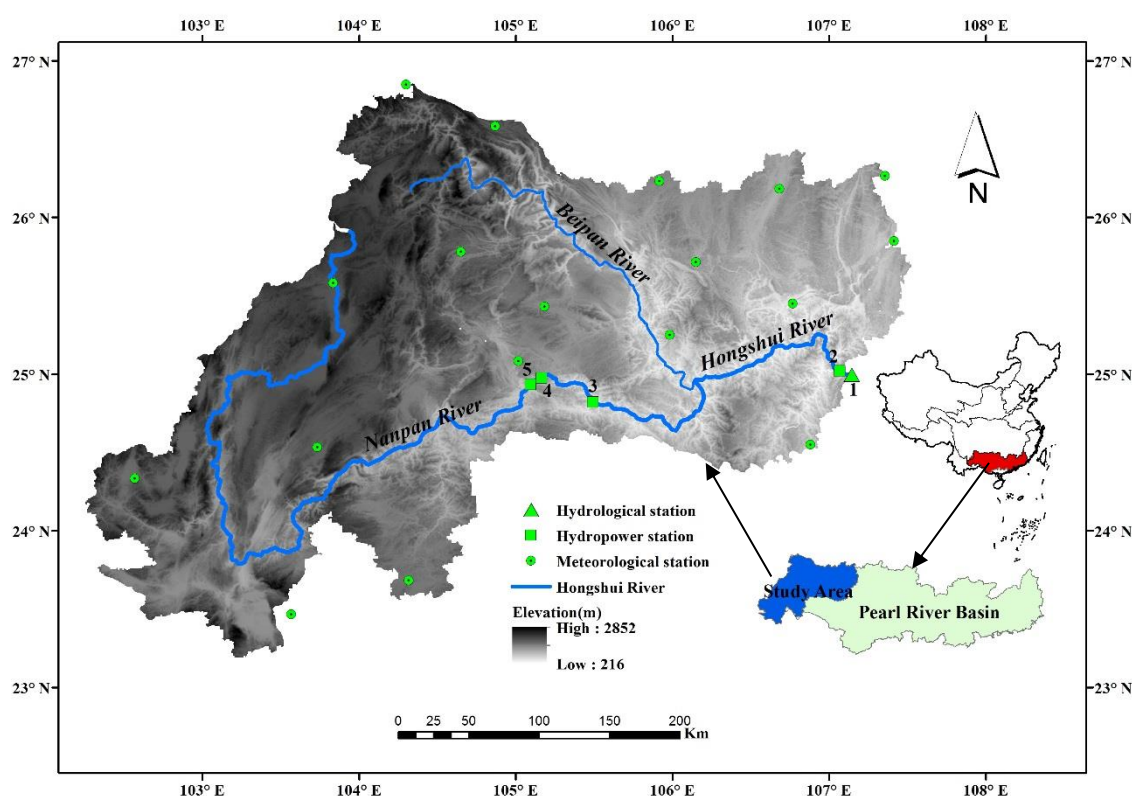


Figure 1. The geographic location map of the study area. 1: Tiane hydrological station; 2: Longtan hydropower station; 3: Pingtan hydropower station; 4: Tianshengqiao-II hydropower station; 5: Tianshengqiao-I hydropower station.

2.2. Data availability

In this study, meteorological data, hydrological data and spatially referenced data were used. The spatially referenced data include land use / land cover data, soil data, digital elevation model (DEM) data and vegetation cover data. Daily precipitation, temperature and wind speed data from 18 meteorological stations during 1959-2015 were provided by the National Climate Center (NCC) of the China Meteorological Administration (CMA). The meteorological forcing data were interpolated to the center of the grid with a resolution of $0.1^\circ \times 0.1^\circ$ by using the inverse distance weighting interpolation [29]. The meteorological data were used in the variable infiltration capacity (VIC) modelling to simulate monthly runoff from the Hongshui River basin. Potential evapotranspiration in the UHRB was obtained by the Penman-Monteith equation, as recommended by the FAO [30]. The runoff observation data for the Tianshengqiao-I and Tiane from 1959 to 2015 were obtained from local water resources department (figure 1).

The vegetation data used in this study were developed by the University of Maryland

(<http://glcfapp.glcf.umd.edu:8080/esdi/index.jsp>). The digital elevation model (DEM) of the UHRB was clipped from the Shuttle Radar Topography Mission (SRTM) 90 m digital elevation data provided by the Geospatial Data Cloud (<http://www.gscloud.cn/>). The soil texture data in the catchment were produced according to China Soil Map (<http://westdc.westgis.ac.cn>). The land use/cover data for land use/cover change analysis provided by the Chinese Academy of Sciences (<http://www.resdc.cn>).

3. Methodology

3.1. Quantitative assessment of the impacts of anthropogenic activities and climate change on runoff

3.1.1. General framework. The study period was divided into two parts: the baseline and the variation period. A change in the mean annual runoff can be calculated as equation (1):

$$\Delta\bar{R}_{total} = \Delta\bar{R}_{variation} - \Delta\bar{R}_{baseline} \quad (1)$$

where $\Delta\bar{R}_{total}$ represents the total change in the annual mean runoff due to anthropogenic activities and climate change; and $\Delta\bar{R}_{baseline}$ and $\Delta\bar{R}_{variation}$ represent the annual average runoff of the baseline and variation periods, respectively. For a designated study basin, the overall change in average annual runoff can be estimated as equation (2).

$$\Delta\bar{R}_{total} = \Delta\bar{R}_{clim} + \Delta\bar{R}_{hum} \quad (2)$$

Where $\Delta\bar{R}_{clim}$ represents the changes in the mean annual runoff caused by climate change; and $\Delta\bar{R}_{hum}$ is the changes in the mean annual runoff caused by anthropogenic activities. When $\Delta\bar{R}_{clim}$ is obtained, $\Delta\bar{R}_{hum}$ can be calculated by equation (2). Consequently, the levels of anthropogenic activities (η_{hum}) and climate change (η_{clim}) on runoff are obtained by the following formula:

$$\eta_{hum} = \frac{\Delta\bar{R}_{hum}}{|\Delta\bar{R}_{clim}| + |\Delta\bar{R}_{hum}|} \times 100\%, \text{ and} \quad (3)$$

$$\eta_{clim} = \frac{\Delta\bar{R}_{clim}}{|\Delta\bar{R}_{clim}| + |\Delta\bar{R}_{hum}|} \times 100\% \quad (4)$$

Sections 3.1.2 and 3.1.3 enumerate how $\Delta\bar{R}_{clim}$ can be distinguished from $\Delta\bar{R}_{hum}$ using hydrological sensitivity method and hydrological modelling.

3.1.2. The hydrological sensitivity method. The hydrological sensitivity method was used to estimate the impact of climate on streamflow using the long-term water balance [31]. The water balance can be estimate by the following formula:

$$P = AET + R + \Delta S \quad (5)$$

where P , AET and R represent the precipitation (mm), actual evapotranspiration (mm) and the runoff depth (mm), respectively. And ΔS represents the change of water storage in the study area, which is considered to be zero over a long period, at least 10 years [9]. The evapotranspiration can be calculated as follows [32]:

$$\frac{AET}{P} = \frac{1 + w(PET/P)}{1 + w(PET/P) + (PET/P)^{-1}} \quad (6)$$

where PET represents the potential evapotranspiration (mm); and w represents a model parameter. w can be calculated by the following formula:

$$w = \frac{AET(1 + P / PET) - P}{PET(1 - AET / P)} \quad (7)$$

The change in annual runoff due to climate variation (ΔR_{clim}) can be estimated as equation (8) [33,34].

$$\Delta \bar{R}_{clim} = \beta \cdot \Delta P + \gamma \cdot \Delta PET \quad (8)$$

where ΔP is the change in the mean annual precipitation; and ΔPET is the change in the potential evapotranspiration. The sensitivity coefficient β and γ are calculated by equations (9) and (10), respectively [13].

$$\beta = \frac{1 + 2x + 3wx}{(1 + x + wx^2)^2}, \text{ and} \quad (9)$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2} \quad (10)$$

Where w is the same as in the equations of (6) and (7), and x is equal to PET/P , which represents the drying index.

3.1.3. Hydrological modelling. The VIC model was used to simulate streamflow. This model has been widely used in many basins all over the world [35-44]. The results of those studies indicated that VIC model was able to adequately reproduce the water cycle. The VIC model is calibrated and validated by using runoff data in the baseline period. Next, the model is run to reconstruct the runoff in the natural state of the variation period. Thus, the differences between the simulated streamflow for the variation period and the streamflow from the baseline period are caused by climate. The contribution of climate variability on streamflow changes can be calculated by the following formula:

$$\Delta \bar{R}_{clim} = \Delta \bar{R}_{variation}^{simulation} - \Delta \bar{R}_{baseline}^{simulation} \quad (11)$$

where $\Delta \bar{R}_{baseline}^{simulation}$ is the simulated annual runoff for the baseline period; $\Delta \bar{R}_{variation}^{simulation}$ is the reconstructed annual runoff estimated by the VIC model for the the variation period simulated. $\Delta \bar{R}_{hum}$ can then be calculated as shown in equation (2) above.

3.2. Evaluation of the VIC model performance

Before the runoff reconstruction, seven parameters such as the infiltration shape parameter (b), the fraction of Ds_{max} where nonlinear baseflow begins (Ds), the maximum velocity of the baseflow (Ds_{max}), the fraction of the maximum soil moisture where nonlinear baseflow occurs (Ws), the thickness of top soil moisture layer (d_1), the thickness of second soil moisture layer (d_2) and the thickness of bottom soil moisture layer (d_3) should be calibrated. The preheating, calibration and validation periods were 1959, 1960-1969 and 1970-1979, respectively. The validity and goodness of fit of the VIC model were evaluated by the relative error (RE) and the Nash-Sutcliffe model efficiency coefficient (NSE), respectively [45,46].

3.3. Analysing the hydroclimatic trend and change point

The nonparametric Mann-Kendall method [47,48] was used to analyse the trends of the temporal variations of hydrometeorological parameters. This method has been considered to be a simple and effective means for climate change analysis and has been widely used for analysis of hydrologic time series data [12,49-51].

The Mann-Kendall mutation method was further utilized to investigate the homogeneity of the hydroclimatic data by detecting the break points in the means of time series. These methods have been

proven to be very useful tools for quantifying the significance and magnitude of the changes in hydroclimatic data. At the same time, to accurately determine the mutation point, this study introduced the moving T-test to find the change point in the streamflow time series data. The details of the mathematics and the associated parameters were described by Lu *et al* [52] and Li *et al* [53].

4. Results

4.1. Hydroclimatic trend and change point in the UHRB from 1959 to 2015

In this study, the change point for streamflow in the UHRB during 1959-2015 was detected by moving T-test and Mann Kendall test. The detection results of these two methods show that 2003 is a change point ($P < 0.01$) (figure 2); therefore, we divided the whole series into two sub-periods: the baseline period (1970-2003) and the variation period (2004-2015). Figure 3(d) shows that during 1959-2015, runoff increased at a rate of 2.29 mm/year ($P < 0.01$). The annual mean runoff depth of the baseline and the variation period is 481.05 mm and 383.89 mm, respectively (table 1).

However, a significant downward trend ($Z_c = -1.96$; $P < 0.05$) was detected in the precipitation series from 1959 to 2015 (figure 3(b)). The average annual precipitation is 1166.08 mm in the variation period, which is 107 mm less than the baseline period (table 1). Figure 3(c) shows a downward trend of PET, but the trend does not pass the significance test ($P = 0.39$). The mean values of PET in the baseline period and variation periods were 1082.94 mm and 1099.49 mm, respectively.

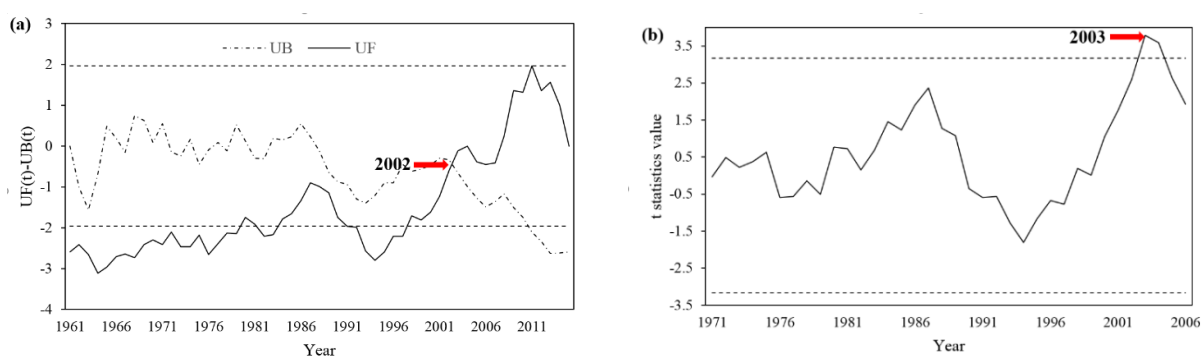
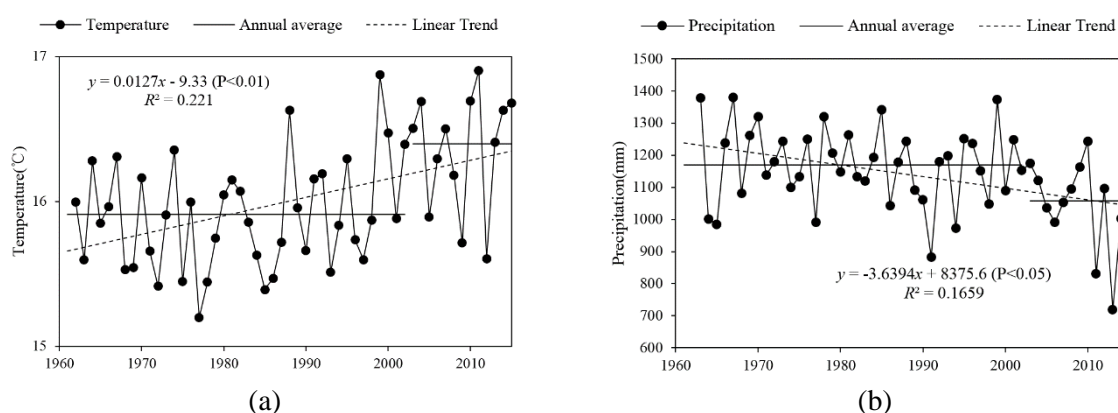


Figure 2. The UF (forward trend-solid line) and UB (backward trend-dash dotted line) curves as determined by the Mann-Kendall test and the 95% confidence intervals (dashed horizontal line) (a). Moving T-test curve (solid line) and the 99% confidence level line (dashed horizontal line) (b).



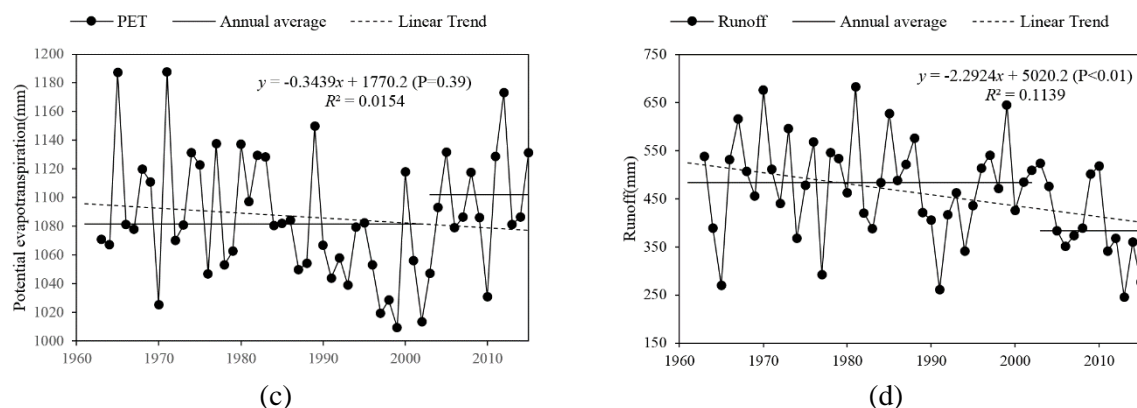


Figure 3. Annual mean values and variation trend of temperature (a), precipitation (b), potential evapotranspiration (PET; (c)), and runoff (d) in the UHRB from 1959 to 2015.

Table 1. Change rates, the Mann-Kendall statistics (Z_c) and change points for temperature, precipitation, PET and runoff.

Factor	Trend Rate	Unit	Annual average		Trend analysis	
			baseline	variation	Z_c	Significance level
Temperature	0.01	$^{\circ}\text{C year}^{-1}$	15.93	16.38	3.62	**
Precipitation	-3.63	mm year^{-1}	1166.08	1059.04	-1.96	*
PET	-0.34	mm year^{-1}	1082.94	1099.49	-0.28	-
Runoff	-2.29	mm year^{-1}	481.05	383.89	-2.58	**

*indicates significance at the 0.01 confidence level;

*indicates significance at the 0.05 confidence level;

- indicates that the significance level exceeds 0.05.

4.2. VIC model parameter calibration and validation

In this study, 1960-1969 is the calibration period, whereas 1970-1979 is the validation period. Figure 4 shows the simulated and observed streamflow for the calibration and validation periods on a monthly basis. During the whole study period, the simulation runoff and the observation runoff fit well. The NSE of the two sites, Tiane and Tianshengqiao, are more than 0.8, whereas RE is less than 10% (table 2). Overall, the calibration and verification results of the VIC model can meet the needs of runoff analysis. After the parameters of the VIC model have been set up, runoff in the natural state from 1980 to 2015 will be reconstructed by using a long series of meteorological data.

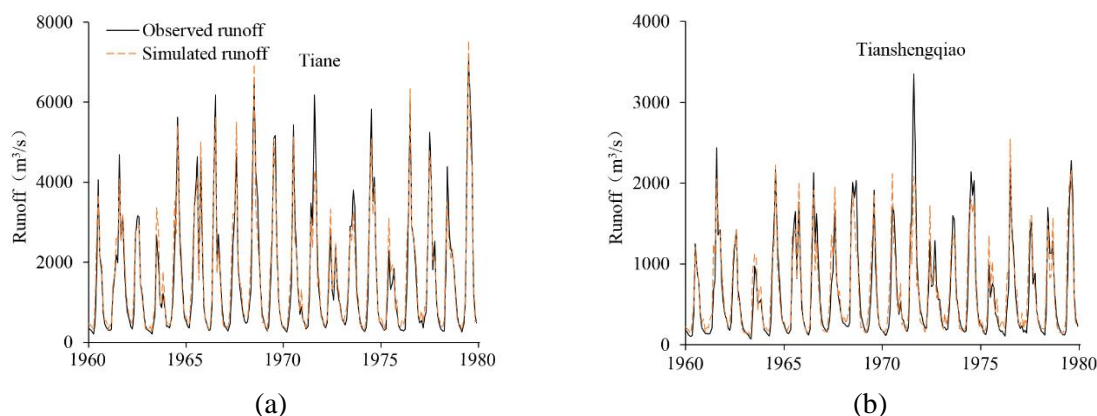


Figure 4. Hydrological stations observed and simulated monthly streamflow during calibration period (1960-1969) and validation period (1970-1979).

Table 2. Performance of the VIC model for monthly runoff simulation in the UHRB.

Station	Calibration period		Validation period	
	NSE	RE(%)	NSE	RE(%)
TSQ	0.87	6.5	0.82	3.2
Tiane	0.92	4.6	0.93	1.1

4.3. Individual impacts of climate variability and anthropogenic activities on streamflow

In this study, hydrologic sensitivity analysis and a hydrological model were applied to quantitatively calculate streamflow reduction in response to anthropogenic activities and climate. Because the results of these two methods are more consistent, the average of the two methods is analyzed in order to facilitate the follow-up analysis. The results of the two methods are shown in table 3. Generally, climate played a decisive role in basin streamflow reduction during the period 1970-2015. The contribution of climate change to streamflow was 97.9% during the baseline period (1970-2003) and 81.4% during the variation period (2004-2015). In addition, the intensity of anthropogenic activity in the baseline period was very small, but it had a strong negative effect during the variation period. The intensity of anthropogenic activities was much greater after than before the period of mutation. However, during 2004-2015, the negative impact of climate change on runoff increased from approximately 33 mm to 94 mm, and the direct effects of climate change were far more than that of anthropogenic activities. Thus, the contribution of anthropogenic activities to streamflow was weakened during this period.

Table 3. Influence of anthropogenic activities and climate on streamflow in the UHRB before (1970-2003) and after (2004-2015) the abrupt change in the impacted period (1970-2015).

Methods	Period	R	ΔR_{clim}		ΔR_{hum}	
		mm	mm	%	mm	%
Hydrologic sensitivity method	1970-2003	476.2	-43.1	98.9	-0.5	1.1
	2004-2015	383.9	-93.5	80.9	-22.0	19.1
	1970-2015	452.1	-43.1	91.1	-4.2	8.9
Hydrological modelling	1970-2003	476.2	-22.5	96.9	-0.7	3.1
	2004-2015	383.9	-94.6	81.9	-20.9	18.1
	1970-2015	452.1	-41.3	87.3	-6.0	12.7

Table 4. Influence of anthropogenic activities and climate on streamflow of the UHRB by using hydrological modelling and hydrologic sensitivity analysis in different periods.

Methods	Period	R	ΔR_{clim}		ΔR_{hum}	
		mm	mm	%	mm	%
Hydrologic sensitivity method	1960-1969	499.4	—	—	—	—
	1970-1979	496.8	-8.4	59.0	5.8	41.0
	1980-1989	459.2	-46.6	87.9	6.4	12.1
	1990-1999	473.8	-1.2	4.7	-24.4	95.3
	2000-2015	406.2	-95.1	90.8	-9.6	9.2
Hydrological modelling	1960-1969	499.4	—	—	—	—
	1970-1979	496.8	-8.0	59.5	5.4	40.5
	1980-1989	459.2	-44.5	91.2	4.3	8.8
	1990-1999	473.8	-0.7	2.6	-24.9	97.4
	2000-2015	406.2	-85.5	91.7	-7.7	8.3

To further analyse the impact of anthropogenic activities and climate in different periods, we also analysed the contributions of anthropogenic activities and climate in four different periods: 1970-1979

(1970s), 1980-1989 (1980s), 1990-1999 (1990s), and 2000-2015 (2000s). The intensities of the influence of anthropogenic activities on changes in streamflow in the 1970s, 1980s, 1990s and 2000s were 40.7%, 10.5%, 96.4% and 8.8%, respectively. During 1970-1989 and 1990-2015, the impact of anthropogenic activities on runoff was reflected not only in the intensity changes but also in the changes in the means of influence. In the two periods of 1970-1989 and 1990-2015, climate change had a negative impact on runoff. However, the factors of anthropogenic activities had a completely opposite effect on the change of runoff in those two periods. We can see from table 4 that anthropogenic activities have a positive impact on runoff in the previous period, but the latter period is mainly negative, and the impact intensity was also far greater than that in the previous period. The contribution of anthropogenic activities reached up to 96.4%, and the impact on runoff varied from positive to negative.

5. Discussion

5.1. Impact of climate on streamflow

Runoff changes were closely related to precipitation and PET. The precipitation and PET of the UHRB were reduced during 1970-2015 (table 5). Therefore, precipitation had a negative effect on streamflow, while PET had a positive effect on streamflow in the UHRB. In addition, based on the calculations of β and γ , the response of runoff to the change of precipitation was more sensitive than PET. There is no doubt that the combination of these two causes result in the negative impact of climate on streamflow in the UHRB during 1970-2015. The ΔP was approximately 3 times higher during 2004-2015 (139.23 mm) than during 1970-2003 (40.72 mm) (table 5). During 2004-2015, the precipitation decreased obviously (table 1). At the same time, the ΔPET changed from -25.54 mm to -3.65 mm, indicating that there was an increase in PET in the UHRB during 2004-2015. However, the weak change in PET would not have had a significant impact on runoff. In addition, the ΔR during 2004-2015 was 5 times higher than that during 1970-2003. Compared with the baseline period (1960-1969), ΔR changed by -23.13%, which was much higher than the change in ΔP (-11.62%). Most of the changes in runoff resulted from the direct effect of precipitation reduction, but there were still other factors that contributed to the decrease in runoff that were closely related to anthropogenic activities.

Table 5. Changes in precipitation (ΔP), PET (ΔPET) and streamflow (ΔR) in the UHRB before (1970-2003) and after (2004-2015) the abrupt change during the impacted period (1970-2015).

period	ΔP		ΔPET		ΔR	
	mm	%	mm	%	mm	%
1970-2003	-40.72	-3.40	-25.54	-2.32	-23.20	-4.65
2004-2015	-139.23	-11.62	-3.65	-0.33	-115.50	-23.13
1970-2015	-66.42	-5.54	-19.83	-1.80	-47.28	-9.47

Similarly, we also analyse the effects of climate on streamflow in four different periods. The maximum effects of anthropogenic activity and climate on runoff occurred in the 1990s and 2000s, respectively (table 4). Compared with climate change, anthropogenic activity played a leading role in the decrease of runoff during 1990~1999, and the impact was greater than that of other periods. The dramatic change in runoff can be explained in terms of climate change: compared to the periods of 1980-1989 and 2000-2015, the decrease in precipitation was lower during 1990-1999 than during the other periods, whereas the PET was reduced more than during the other periods, which may have led to a smaller decrease in streamflow due to climate change (table 6). At the same time, the effects of anthropogenic activities on runoff during 1990-1999 significantly differed from those during 1980-1989 (table 4). The influence of anthropogenic activities on runoff changed from positive to negative. During 2000-2015, the precipitation decreased by 123.68 mm, which was much higher than during other periods, whereas the PET of the same period was not obvious. The great contribution of

precipitation reduction caused the runoff to decrease in this period far more than other periods.

Table 6. Changes in precipitation (ΔP), PET (ΔPET) and streamflow (ΔR) during different periods in the UHRB.

period	ΔP		ΔPET		ΔR	
	mm	%	mm	%	mm	%
1970-1979	-14.82	-1.24	-9.16	-0.83	-2.56	-0.51
1980-1989	-69.48	-5.80	-16.14	-1.46	-40.19	-8.05
1990-1999	-23.33	-1.95	-48.81	-4.42	-25.61	-5.13
2000-2015	-123.68	-10.32	-10.69	-0.97	-93.20	-18.66

5.2. Impacts of anthropogenic activities on runoff

In general, there are two types of human activity affecting runoff, the first of which is land use/change caused by the development of urbanization, afforestation and reservoir operation activities. Another type is transferrals of water such as agricultural irrigation, artificial water use, and water diversion projects. These anthropogenic activities mentioned above may directly or indirectly alter the hydrological cycle, resulting in spatial and temporal changes in regional water resources. Anthropogenic activities are complex. Some anthropogenic activities will lead to positive changes in runoff, whereas others will lead to negative changes. These anthropogenic activities usually occur at the same time, and it is difficult to consider a particular human activity alone. We tried to understand the impacts of land use/cover change from 1959 to 2015 using a long-term (from the late 1980s to 2015) land use/cover data. In the 1980s, forest, grassland, dry land and paddy land were the most widely distributed land cover types in the UHRB, with proportions of 50.57%, 25.97%, 13.88% and 8.15%, respectively. Cultivated land, forest and grassland account for more than 98% of the entire drainage area, whereas urban and industry account for less than 1% of the total area. Moreover, the water area was only 0.71%, with a total area of only 702 km².

Table 7. The change rates in land use types in different periods compared with those in the 1980s.

Time Stage	Paddy Land	Dry Land	Forest	Grass Land	Water	Urban & Industry	Bared Land
1990	-0.44	-0.07	0.07	-0.23	0.80	7.22	0.83
1995	-0.08	-5.78	0.95	0.47	-2.31	30.42	11.82
2000	-0.50	-2.08	-0.41	1.51	4.68	17.79	0.28
2005	-1.50	-2.16	0.08	0.69	5.29	25.85	0.28
2010	-2.02	-2.54	-0.10	0.86	18.22	33.61	0.28
2015	-3.41	-2.96	-0.32	0.50	19.78	87.38	22.81

When compared with the situation in the 1980s, the areas of forest, paddy land and dry land in 2015 had decreased by 0.32%, 3.41% and 2.96%, respectively (table 7). However, there were increases in the areas of grassland, water, bare land and residential land, especially in 2015, when the areas increased by 0.5%, 19.78%, 22.72% and 87.37%, respectively. Of all land types, the urban and industry areas increased most rapidly. When compared to 1980, the urban and industrial areas increased by 17.79%, 25.83%, 33.60% and 87.37% in 2000, 2005, 2010 and 2015, respectively (table 7). Although the proportion of urban and industry in the entire basin was relatively low, the degree of its change was obvious. By 2015, the urban and industrial areas increased by 628.17 km² (87.37%) compared to the 1980s, and the amount of change was much higher than that of other land types during the same period. On the one hand, the rapid development of urbanization may reduce runoff by increasing demand for agricultural, industrial and domestic. On the other hand, urbanization will lead to increases in streamflow through increases in impervious area.

However, returning farmlands to lakes, returning farmlands to forests and water and soil

conservation projects may cause decreases in streamflow. Since 1999, the policy of the conversion of degraded croplands into woodlands and grasslands has been implemented in most areas of China [54]. Since 2000, the area of cultivated land has been decreasing continuously. By 2015, paddy and dry lands have been reduced by 3.41% and 2.96%, respectively (table 7).

The operation of large-scale water conservancy projects such as dams and reservoirs has also hydrological process in the catchment, especially the increase of evaporation intensity due to water storage. In order to meet the requirements of UHRB's energy, industrial, agricultural and domestic water demands, a lot of water conservancy projects (e.g., the Tianshengqiao-I hydropower station, Tianshengqiao-II hydropower station, Pingban hydropower station and Longtan hydropower station) have been constructed. A large amount of land was submerged because of the rising water level. Table 7 shows that the water bodies of the 2000s had increased by 19.78% compared with those of the 1980s. There were ever increasing water bodies after 2000, which may be an important reason for streamflow decreases in the UHRB.

5.3. Uncertainty analysis

There may be some uncertainty in the hydrological sensitivity analysis used to assess the impact of anthropogenic activities and climate on streamflow. The limited number of hydrometeorological stations may reduce the reliability and accuracy of the hydroclimatic variables such as AET, PET and streamflow simulated by hydrological sensitivity method. In addition, the method is based on the assumption that anthropogenic activities and climate are independent of each other [55]. However, anthropogenic activities such as forestation, urbanization may cause changes in climate, and climate change may influence anthropogenic activities such as agriculture. In addition, although the VIC model has good applicability in the study area, simulation error is still inevitable. At the same time, the accuracy of the observations may also have an impact on the credibility of the results. Nevertheless, the conclusion about the contribution trend of anthropogenic activities and climate to streamflow changes is reasonable.

In addition, the impacts of anthropogenic activities and climate on hydrological processes are complex, and different types of anthropogenic activities may have positive or negative effects. When many different positive or negative effects are mixed together, it is usually difficult to distinguish. In addition, the interactions between anthropogenic activities and climate is inseparable. Both anthropogenic activities and climate contribute to changes in land use/land cover and vice versa. Although there are some uncertainties and limitations, our study reveals the sensitivity of UHRB's streamflow response anthropogenic activities and to climate. In addition, future research will focus on those uncertainties to improve the results of the quantification. Further studies must be conducted to fully understand the responses of water systems to anthropogenic activities and climate in the UHRB.

6. Conclusions

The results show that the effects of anthropogenic activities and climate on the long-term trend in streamflow over the past 55 years in the UHRB, Southwest China. The factors that influence runoff change in the UHRB were quantitatively identified using hydrological simulation and hydrologic sensitivity analysis methods. Although the two methods have different principles and scales, their similar calculation results show that climate is the main cause of streamflow reduction. The Mann-Kendall mutation detection method and moving T-test were used to detect the time of the streamflow mutation. The results of the two methods show that the abrupt change occurred in 2003. The reduction in runoff was more obvious during 2004-2015 and was mainly affected by the reduction in precipitation. Anthropogenic activities also had an indirect influence on runoff reduction. Generally, the contribution of climate to streamflow accounted for 89.2% during the whole study period of 1970-2015.

In general, anthropogenic activities have a relatively small influence on runoff of the UHRB. Overall, however, the influence of anthropogenic activities on streamflow variation was obviously enhanced, especially since the 1980s. In addition, the impact of anthropogenic activities on streamflow

is mainly negative in the UHRB. There are primary types of anthropogenic activities, including land use, agricultural water and the operation of water conservancy projects, that affected the UHRB in different periods, and these activities therefore should be managed effectively according to the attributes of each period. The results are not only helpful to understand the variation process of hydrological cycle and factors affecting streamflow in the catchments across southwest China, but also can be used as a reference for water resource planning and management in the UHRB.

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