Impacts of climate change and human activities on runoff in Weihe Basin based on Budyko hypothesis

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Abstract. The Weihe River Basin (WRB) is the largest tributary of the Yellow River and plays an irreplaceable role in the Shaanxi-Gansu-Ningxia area. In recent years, owing to the human activities and climate change, the runoff of the WRB has reduced, wherefore, it is necessary to analyze the impact on runoff quantitatively. By using the data of Huaxian and Zhuangtou stations, we can respectively calculate the changes in runoff for climate change and human activities via Budyko hypothesis. The trend of runoff, precipitation, temperature, potential evapotranspiration and the break points are examined by Mann-Kendall test (M-K method), cumulative anomaly method and ordered cluster analysis. The results show that the break points of runoff series in WRB are 1970 and 1989, so that the runoff series can be divided into the baseline period and the changed period. Based on the data of potential evapotranspiration and Budyko formula, the contribution rates of climate change and human activities to runoff are 41% and 59% in 1970-1989. From 1990 to 2010, the contribution rates of climate change and human activities are 37% and 63%, respectively.

1. Introduction

Weihe River is one of the important rivers in the northwest region. It is the largest tributary of the Yellow River, flows through Shaanxi, Gansu and Ningxia provinces (autonomous regions). The WRB is located in the northwest of China, whose ecosystem is fragile and the occurrence of natural disaster is frequent. Among them, the frequency of drought is the highest, which is the main factor restricting the further development of the national economy. The WRB plays an important role in the production, living and ecology in the northwest area. The change of the runoff will directly affect the regional water resources and destroy the local water structure. In recent years, because of the dual role of climate change and human activities, the runoff in WRB has been decreasing year by year, and thus produces a series of problems [1, 2]. The main performances are as follows: (1) the water quantity in the watershed has been reducing; (2) the water quality has been polluted seriously; (3) water and sand balance has been destroyed, resulting in the sediment deposition, and the flood discharge capacity has been reducing.

The dramatic changes in climate and the increasing human activities have had a tremendous impact on the river basin in the world scope, and one such river basin is the WRB. However, this is also one of the areas where lacks water, water shortages have become a bottleneck restricting local economic development. During the last several decades, we have built a large number of water conservancy projects in the WRB, such as reservoir and hydropower station et al. Climate change surveys in the Yellow River basin suggested that trends at a rate of 1.28 ℃ over the past half century, while the

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average precipitation dropped by approximately 8.8 % over the second half of the 20th century [3]. The combination of these effects resulted in a reduction in runoff [4, 5]. Climate change affects runoff, chiefly through the variability of potential evapotranspiration and precipitation [6-9]. Human activities can cause changes in the underlying conditions. Moreover, unrestrained exploitation of surface water and groundwater will have an unpredictable impact on the runoff generation and confluence process. It is of great practical significance to quantitatively separate the impacts of climate change and human activities on runoff so that they can be applied to land management, water resource management and so on. Over the past few decades, hydrologists had been working to observe changes under the impact of climate change and human activities on runoff [10-13]. Based on the Budyko hypothesis [14], this study quantitatively analyzes the contribution rates of climate change and human activities to the reduction of runoff, which is of great reference value to watershed management and ecological sustainable development in the WRB.

2. Study area and data

2.1. Study area

The WRB (figure 1) is located in E 104° 25 '~ 110° 25', N 33° 75 '~ 37° 25', which originates in Gansu Province Weiyuan County NiaoShu mountain, and mainly follows through the Shaanxi-Gansu-Ningxia region, and finally through the Tongguan County, Shaanxi Province, into the Yellow River. The Weihe River flows across Shaanxi and Gansu provinces with a total length of 818 km and a total area of 134700 km^2. The average annual runoff is 72.7×10^8 m^3. Jinghe River, the largest tributary in the WRB, is located in the central Loess Plateau, and it has a total length of 455 km, and watershed area of 45400 km^2; the Beiluo River is the second largest tributary in Weihe, and it has a total length of 680 km, and watershed area of 26900 km^2.

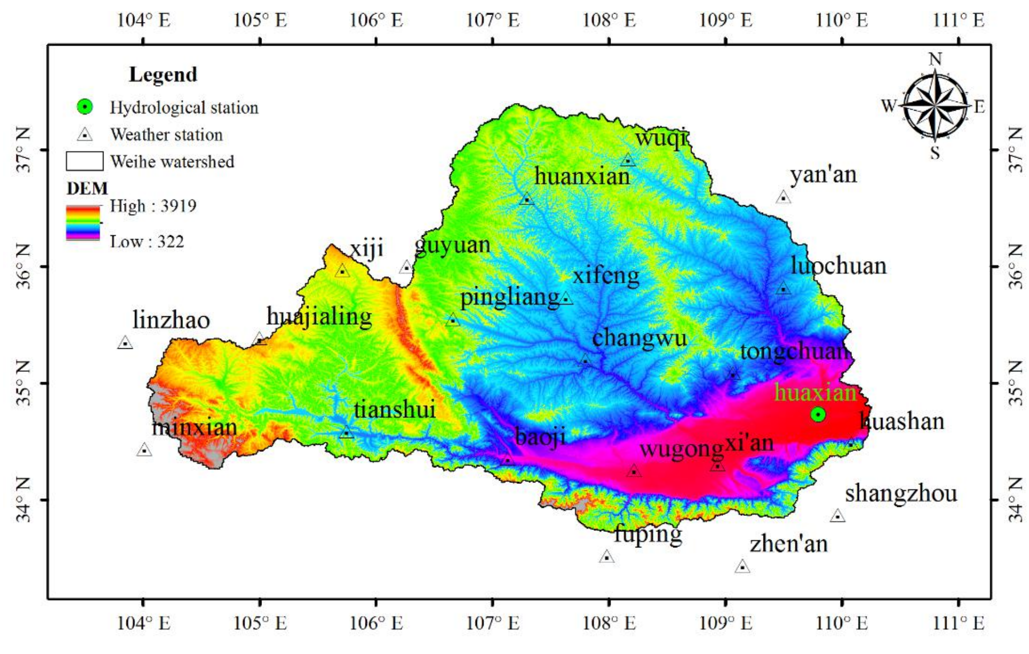

Figure 1. Meteorological stations and their control basins in WRB.

The WRB belongs to the typical temperate continental monsoon climate. The local climate is dry in winter and hot in summer, and the precipitation is concentrated in the July to September. The average annual precipitation is 636 mm, and the average annual temperature is 9.42℃. In addition, the extreme maximum and minimum temperatures are 42.8℃ and -28.1℃. The average annual evapotranspiration is 848.78 mm, and gradually increased from south to north. The eastern part of Guanzhong is a high evapotranspiration area, where the annual evapotranspiration is more than 1200 mm. The western part of Guanzhong and Qinling Mountains are the areas with low evapotranspiration, which are less than 800 mm. The minimum monthly evapotranspiration usually occurs in January or December, and the maximum one appears in July.

2.2. Data

The meteorological data of the 21 meteorological stations of the WRB in this study are provided by the China Meteorological Data Sharing Network. The measured runoff data is selected from the Huaxian and Zhuangtou station, which control the study area [15]. The Penman-Menteith formula is used to calculate the potential evapotranspiration [16]. For the missing precipitation and meteorological data, we use the linear interpolation method of adjacent meteorological stations to interpolate the extension. By Utilizing ArcGIS 9.3, we can convert precipitation and potential evapotranspiration into watershed data.

3. Study methods

3.1. Budyko hypothesis

Based on the global water and energy balance, Budyko pointed out that the watershed evapotranspiration was controlled by both the ability of precipitation and evaporation. The precipitation P is used to express the moisture supply condition, and the potential evapotranspiration E_0 is used to denote the energy supply condition. Thus, in the calculation of land surface evapotranspiration, there are the following boundary conditions [17]:

In extreme arid regions, all of the precipitation will be converted into evapotranspiration:

$$\frac{E_0}{P} \to \infty,\ \frac{E}{P} \to 1 \tag{1}$$

In extremely humid regions, all of the evapotranspiration energy will be converted to latent heat:

$$\frac{E_0}{P} \to 0, \frac{E}{E_0} \to 1 \tag{2}$$

Thus, we can obtain the coupled equilibrium equation of water and heat:

$$\frac{E}{P} = \mathrm{f}(\frac{E_0}{P}) = \mathrm{f}(\emptyset) \tag{3}$$

$$\mathrm{f}(\emptyset) = [\emptyset \tan h\,(\frac{1}{\emptyset})(1 - e^{-\emptyset})]^{1/2} \tag{4}$$

$\emptyset$ (the degree of dryness), which can be used as an indicator of water and heat to divide climate and vegetation zones. $\tan h$ is a hyperbolic tangent function [17]. f is a universal function [18]. Based on the hypothesis of Budyko, Fu, a meteorologist in China, put forward the analytical expression of the actual evapotranspiration [19]:

$$\mathrm{E} = \mathrm{P} + E_0 - [P^{\omega} + E_0^{\omega}]^{1/\omega} \tag{5}$$

ω is a parameter that indicates the efficiency of evapotranspiration, and its range is (1,+∞). ω mainly reflects the underlying surface conditions, such as topography, vegetation and other conditions. According to Fubao Sun, Dawen Yang and other data calculated in 2007, in this study ω take 3.22 [20].

For a certain closure area, the expression of its multi-year water balance is:

$$\mathrm{P} = \mathrm{E} + \mathrm{Q} + \Delta \mathrm{S} \tag{6}$$

The Δ S is the watershed storage variables, in the years of average scale, it can be neglected [21].

The changes in runoff caused by climate change are quantitatively calculated according to the method proposed by Milly and Dunne *et al* [22]:

$$\triangle Q_c = \frac{\partial Q}{\partial P} \triangle P + \frac{\partial Q}{\partial E_0} \triangle E_0 \tag{7}$$

Where $\triangle P$ and $\triangle E_0$ represent the changes of precipitation and potential evapotranspiration, $\frac{\partial Q}{\partial P}$ and $\frac{\partial Q}{\partial E_0}$ respectively represent the sensitive coefficient of runoff to precipitation and potential evapotranspiration. Based on Fu's formula, the sensitive coefficient can be expressed as:

$$\frac{\partial Q}{\partial P} = (1 + x^{\omega})^{\left(\frac{1}{\omega}\right)} - x^{\omega}(1 + x^{\omega})^{\left(\frac{1}{\omega}-1\right)} \tag{8}$$

$$\frac{\partial Q}{\partial E_0} = x^{(\omega-1)} (1 + x^{\omega})^{\left(\frac{1}{\omega}-1\right)} - 1 \tag{9}$$

3.2. Cumulative anomaly method [23]

The cumulative anomaly method is also a widely used method to judge the trend of series change from the curve. It can reflect the trend of the change of the elements. The cumulative anomaly curve shows an upward trend, which indicates that the anomaly value increases, otherwise the anomaly value decreases. Through the ups and downs of the curve can also determine the break points of the series.

For a given sequence X, the cumulative anomaly value at a given moment is expressed as

$$\mathrm{X} = \sum_{i=1}^{t} x_i - x (\mathrm{t}=1,\ 2,\ \ldots,\ \mathrm{n}) \tag{10}$$

Among $x = \frac{1}{n} * \sum_{i=1}^{t} x_i$

3.3. Mann-Kendall Test (M-K) [24]

Mann-Kendall nonparametric test method is widely used for its advantages that it is not affected by sample value and the type of distribution. So it is commonly used in hydrological, meteorological and other non-normal distribution of the sequence .The basic principles are as follows:

- Given a time sequence X (X_1, X_2, ... X_n), construct a rank sequence M_i, which indicates the cumulative number of samples($X_i > X_j$ ($1 \le j \le i$)). Define d_k as:

$$d_k = \sum_1^k M_i \quad (2 \le \mathrm{k} \le \mathrm{n}) \tag{11}$$

- The mean and variance of d_k:

$$\mathrm{E}(d_k) = \frac{k(\mathrm{k}-1)}{4} \tag{12}$$

$$\mathrm{var}(d_k) = \frac{k(\mathrm{k}-1)(2\mathrm{k}+5)}{72} (2 \le \mathrm{k} \le \mathrm{n}) \tag{13}$$

- In time sequence, the statistics are defined independently:

$$\mathrm{UF}_K = \frac{d_k - \mathrm{E}(d_k)}{\sqrt{\mathrm{var}(d_k)}} (\mathrm{k} = 1,2,\ldots,\mathrm{n}) \tag{14}$$

Firstly, given the confidence level α, if the $|\mathrm{UF}_K| > \mathrm{UF}\alpha/2$, indicates that the sequence has significant trend. Then, the time sequence is arranged in reverse order. According to the equation (14) calculation, while making

$$\mathrm{UB}_k = -UF_k \tag{15}$$

$$\mathrm{K}=\mathrm{n}+1-\mathrm{k} \tag{16}$$

Finally, UB_k and UF_k are drawn as UB and UF curve. If there is an intersection between the two curves, the intersection is the beginning of the mutation.

3.4. Ordered cluster analysis [25]

With the "like attracts like" to describe the cluster analysis, it can express the idea of cluster analysis vividly. If the order of classification cannot be disrupted, such a classification is called ordered classification. In order to estimate the most likely break point τ in orderly classification, the essence is to find the optimal segmentation point which make the same classes ' sum of deviation square is smaller, while the different classes is larger. For the hydrological sequence X_1, X_2 ..., X_n, the optimal two-segment method is as follows:

Suppose that the possible break point is τ, then the square sum of the deviations before and after the mutation is

$$V_\tau = \sum_{i=1}^{\tau}(x_i - x_\tau)^2 \quad (17)$$

$$V_{n-\tau} = \sum_{i=\tau+1}^{n}(x_i - x_{n-\tau})^2 \quad (18)$$

In this equation, x_τ and $x_{n-\tau}$ are the mean of the two parts before and after the τ.
The sum of squared deviations

$$S_n(\tau) = V_\tau + V_{n-\tau} \quad (19)$$

Then, when the $S = \min_{2\le\tau\le n-1}\{S_n(\tau)\}$, τ is the optimal two-segment point and it can be speculated as a break point.

4. Calculation results and analysis

4.1. The analysis of variability and trend

The break points of the precipitation, temperature and runoff in the WRB were determined by the M-K method. The break points of precipitation appeared in the range from 1971 to 1985, and further through the cumulative anomaly and ordered cluster analysis to determine the break point was 1985 (figure 2). At the same time, the break point of temperature was determined in 1991 (figure 3). In addition, with the M-K test of runoff, the break point was determined in 1989, further through the cumulative anomaly to determine the break points were 1970 and 1989 (figure 4). The results of the break point test are shown in figures 2-4:

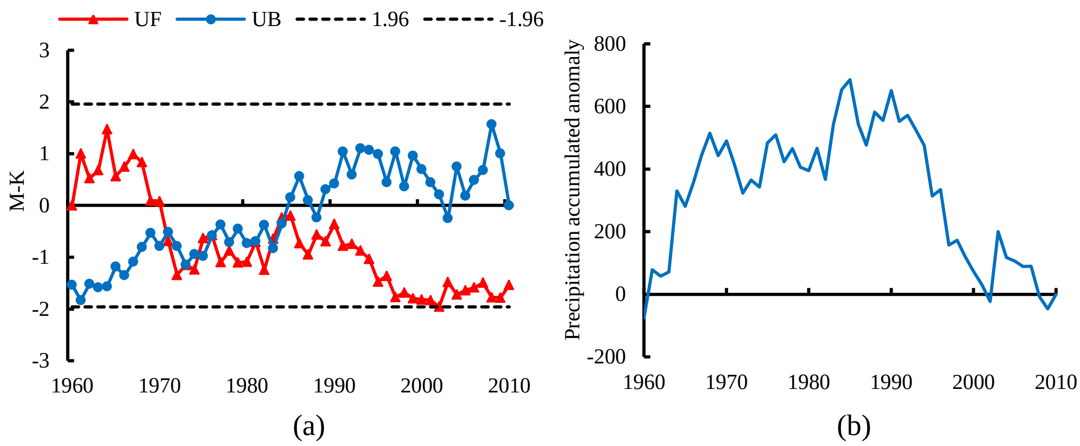

Figure 2. The break point test of annual precipitation with M-K (a) and cumulative anomaly (b).

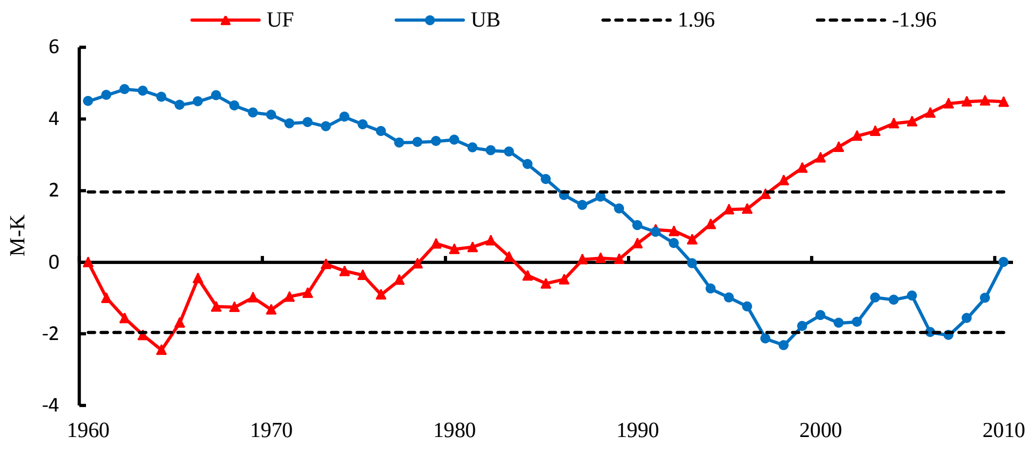

Figure 3. The break point test of annual temperature with M-K.

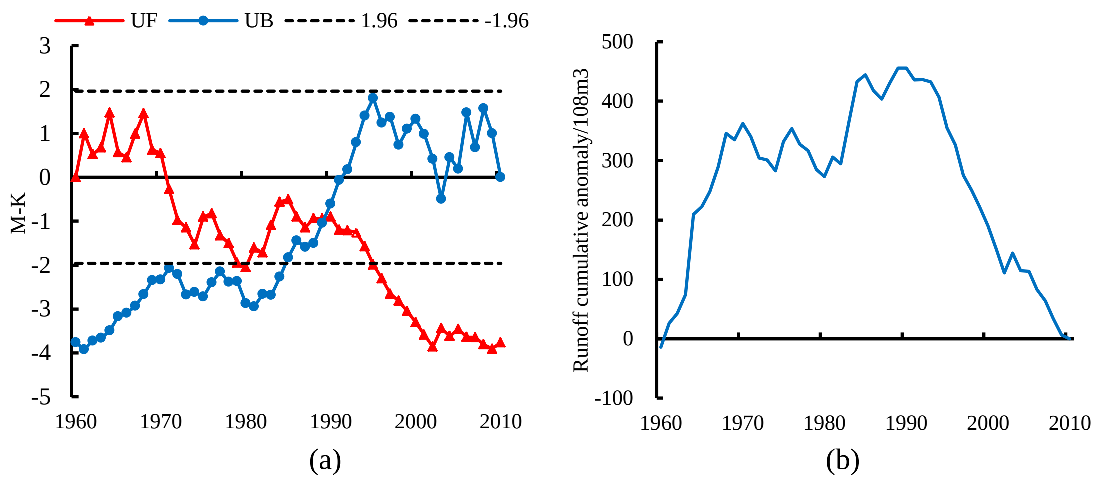

Figure 4. The break point test of annual runoff with M-K (a) and cumulative anomaly (b).

Figure 5 shows that the annual runoff and precipitation of the WRB have a decreasing trend, while the temperature and potential evapotranspiration are increasing. The maximum annual precipitation appears in 1964 (808.7 mm), and the minimum annual precipitation occurs in 1997 (372.4 mm), the precipitation series decreased by 12.7% (figure 5 (a)). In addition, the maximum annual runoff appears in 1964 (207.8×10^8 m^3), and the minimum annual runoff occurs in 1995 (21×10^8 m^3), and the runoff series decreased by 58.9% (figure 5 (b)). The maximum annual temperature appears in 1998 (10.6℃), and the minimum annual temperature occurs in 1967 (8.2℃), the temperature series increased by 14.4% (figure 5 (c)). Besides, the maximum potential evapotranspiration occurs in 1997 (934.8 mm), and the minimum potential evapotranspiration appears in 1964 (721.7 mm), the evapotranspiration series increased by only 1.2% (figure 5 (d)).

4.2. Calculation of contribution rate of climate change and human activities on runoff

According to the above results, the break points of the runoff are determined in 1970 and 1989, so the measured runoff series can be divided into three time periods. The baseline period is from 1960 to 1970, and the 1971-1989, 1990-2010 are the changed periods. The information for each parameter of each period can be seen from table 1, moreover, the results are shown in table 2.

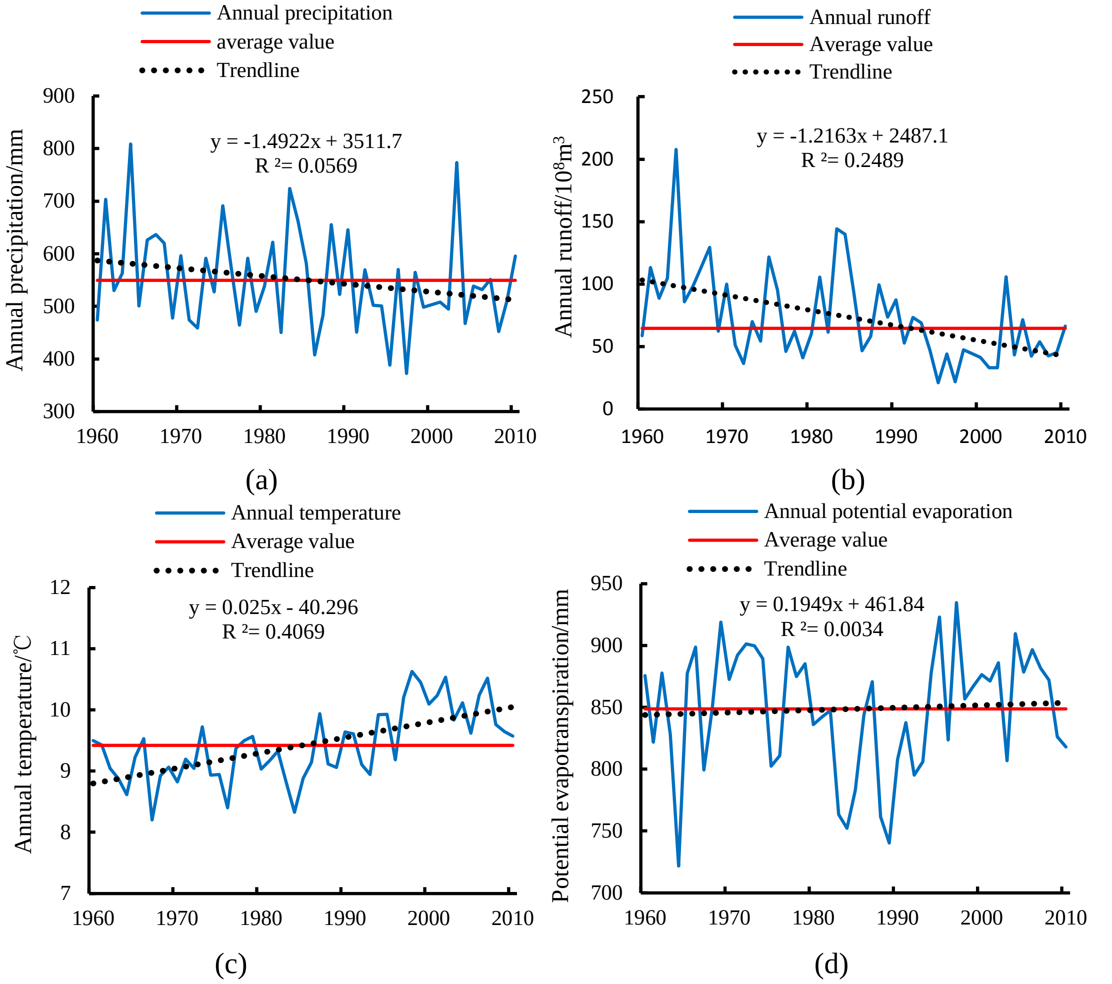

Figure 5. Trend test for precipitation (a), runoff (b), temperature (c) and evapotranspiration (d).

Table 1. Parameter information for each period.

Time periods	Multi-year average runoff Q (10^8m^3)	Multi-year average evapotranspiration E_0 (mm)	Multi-year average precipitation P (mm)	$x=E_0/P$	Amount of runoff change ΔQ (10^8m^3)
1960-1970	105.71	849.15	594.25	1.43	
1971-1989	76.92	836.60	563.18	1.49	-28.79
1990-2010	51.78	859.61	553.32	1.55	-53.93

Table 2. Contribution of climate change and human activities on runoff based on Budyko hypothesis.

Time periods	∂Q/∂P	$\partial Q/\partial E_0$	ΔQc (mm)	Climate change		Human activities	
				Qc (10^8m^3)	ηc	Q_H (10^8m^3)	η_H
1960-1970							
1971-1989	0.35	-0.16	-8.99	11.84	0.41	16.95	0.59
1990-2010	0.33	-0.14	-14.97	19.71	0.37	34.22	0.63

Compared with the baseline period, the annual runoff decreased by 28.79×10^8 m^3 in 1971-1989, accounting for about 27.2% of the baseline period. In addition, the annual precipitation decreased by 31.07 mm (5.2%) compared with the baseline period. The potential evapotranspiration decreased by 12.55 mm (1.5%). According to equation (7), the contribution rate of climate change to runoff is 41%, and the human activity is 59%. In 1990-2010, the annual runoff decreased by 53.93×10^8 m^3 compared with the baseline period, accounting for about 51% of the baseline period. The annual precipitation decreased by 40.93 mm (6.9%). But the annual potential evapotranspiration is 10.46mm higher than the baseline period, accounting for 1.2% of the baseline period. The contribution rate of climate change to runoff change is 37%, and the human activity is 63%.

The results show that the runoff demonstrates a significant reduction from 1960 to 2010, and the 1970 and 1989 are the break points. At the same time, the descending trend of the precipitation series after 1985 is not obvious. It is shown that human activities rather than climate change are the main reason for the reduction of runoff. Human activities change the underlying conditions of the basin, directly or indirectly affecting the quality, quantity and processes of runoff. Human activities have both positive and negative effects on runoff. Human beings can build water conservancy projects such as reservoirs, silt dams and water tanks, which can reduce the peak flow, adjust the runoff process. The principle of the soil conservation measures is to reduce the slope of the original ground, truncate slope length, and increases the roughness of the ground, thereby increasing the amount of infiltration, extending the confluence time and reducing the peak, so that the flow process line becomes flat. In addition, humans can also play a role in regulating runoff by planting trees and increasing the forest coverage.

However, unreasonable human activities, such as excessive deforestation, uncontrolled exploitation can cause serious soil erosion. Besides, factory waste and chemical pesticides, not only undermine the regulation of soil runoff, but also pollute the water seriously. Meanwhile, the acceleration of the urbanization process is also one of the factors affecting the reduction of runoff [26-28].

5. Conclusion

Based on the Budyko hypothesis, this study analyzes the impact of climate change and human activities on runoff of Weihe River from 1960 to 2010. And the conclusions are as follows:

- With the analysis of the runoff, precipitation, potential evapotranspiration and temperature in the WRB, the results show that: the annual precipitation and runoff both show a decreasing trend, while the decreasing trend of runoff is more obvious. Conversely, the potential evapotranspiration and temperature present an increasing trend, but the increasing trend of the former is not significant.
- Compared with the baseline period, the runoff in the WRB has greatly reduced over the past 20 years, and the annual runoff (51.78×10^8 m^3) is 51% lower than the baseline period (105.71×10^8 m^3).
- Utilizing the M-K method and the cumulative anomaly method, we can determine the break points of runoff in WRB are 1970 and 1989, and the break point of the precipitation is 1985. From 1971 to 1989, the contribution rates of climate change and human activities to runoff are 41% and 59% respectively. And the contribution rates of climate change and human activities to runoff are 37% and 63% in 1990-2010. The results that the impact of human activities on runoff is increasing are in agreement with the findings of other scholars [29-32].

Acknowledgments

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