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Response of runoff to climate change in the area of runoff yield in upstream Shiyang River Basin, Northwest China: A case study of the Xiying River

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Abstract: The objective of this study was to analyze the response of runoff in the area of runoff yield of the upstream Shiyang River basin to climate change and to promote sustainable development of regional water resources and ecological environment. As the biggest tributary of the Shiyang River, Xiying River is the only hydrological station (Jiutiaoling) that has provincial natural river and can achieve long time series monitoring data in the basin. The data obtained from this station is representative of natural conditions because it has little human activites. This study built a regression model through identifying the characteristics of runoff and climate change by using Mann-Kendall nonparametric statistical test, cumulative anomaly, and correlation analysis. The results show that the average annual runoff is 320.6 million m^3/a with the coefficient of variation of 0.18 and shows slightly decrease during 1956–2020. It has a significant positive correlation the average annual precipitation ($P<0.01$). Runoff is sensitive to climate change, and the climate has becoming warm and wet and annual runoff has entering wet period from 2003. Compared to the earlier period (1955–2000), the increases of average annual temperature, precipitation and runoff in recent two decades were 15%, 9.3%, and 7.8%, respectively. Runoff in the Shiyang River is affected by temperature and precipitation among climate factors, and the simulation results of the runoff-climate response model ($R = 0.0052P - 0.1589T + 2.373$) indicate that higher temperature leads to a weakening of the ecological regulation of surface runoff in the flow-producing area.

Keywords: Runoff; Heating and wetting; Mann-Kendall test; Regression model; Ecological function

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Introduction

The response of surface runoff to climate change is sensitive because surface runoff is an important factor in the hydrological cycle (Shen et al. 1998). Global warming is an indisputable fact (Bongaarts, 2019; IPCC, 2021), and it will accelerate the regional water cycle, driving changes in glacial meltwater and atmospheric precipitation and causing regional and temporal redistribution and changes in water resources (Ren et al. 2007; Blue Book, 2020; Song et al. 2022). The Shiyang River Basin located in the intersection of the northwestern inland arid zone and the East Asian monsoon zone in China is sensitive to global climate change (Shi et al. 2007; Xu et al. 2007; Zhou et al. 2020). The warming rate in this area is far higher than the world average in the past two decades (Jiang et al. 2006; Ji et al. 2014; Liu et al. 2021). As a typical water shortage and ecologically fragile area, the response characteristics of runoff from the area of runoff yield in the upstream the Shiyang River to climate change have received much attention.

The eastern section of the Qilian Mountains, the origin of the Shiyang River, is located on the northeastern edge of the Tibetan Plateau. 95% of the water resources in the basin originate from precipitation in the upper mountains and glacial meltwater, and surface runoff from the area of runoff yield is key to safe water of the oasis areas in the

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middle and lower reaches. Temperature and precipitation are representative indicators of climate change and play an important role in changing regional ecosystems. Surface runoff in the upper reaches of the study area originates from mountain precipitation (Ding et al. 2007), and the two have a strong positive correlation (Ma et al. 2010; Lan et al. 2014; Guo et al. 2016); the typical small subcontinental glaciers in the study area (glacier area is mainly <1 km^2) were melting at an unprecedented rate in the past 50 years with the increase of temperature (Sun et al. 2018; Pan et al. 2021), and the glacier reserves were decreasing sharply (Gao et al. 2019; Song et al. 2022), and the glacier meltwater reached a peak in 2008 (Zhang et al. 2015), with the contribution to runoff was continuously decreasing (Matin et al. 2015; Li et al. 2017); in mountainous areas, oasis plains and desert, where climate was widely divergent, the complex topography of the upper mountainous areas can be influenced by continental desert climate and alpine landforms, and the changing trend in temperature and humidity of the basin (Xu et al. 2007; Zhang et al. 2017) was no longer representative. In addition, in the context of global warming, more specific and representative upstream mountain climate data are needed to evaluate the response of surface runoff to climate in the area of runoff yield.

In the context of glacier ablation, this paper analyzed data monitored by the meteorological stations in the upper reaches of Shiyang River and Jiutiaoling (the only provincial natural river hydrological monitoring station in the watershed) by trend analysis, Mann-Kendall non-parametric test, correlation analysis, differential product curve method, multiple regression and other methods to discover the multi-scale and long time series variation pattern of surface runoff in the area of runoff yield. The objective of this paper is to explore its relationship with the climate (temperature and precipitation) in the upper mountainous areas, so as to provide scientific basis for optimizing regional water resources allocation and realizing sustainable water resources utilization.

1 Study area

Xiying River is the largest tributary in the Shiyang River system, with a total length of 124 km and a catchment area of 2 495.4 km^2 and a area of runoff yield 1 441.8 km^2. The average annual runoff from precipitation as well as glacier meltwater out of the mountain accounts for 27% of the that of Shiyang River. Located in the alpine semi-arid climate zone, the main peak of the mountain is 4 874 m, with the average annual temperature at 4.79℃ and the precipitation of 312.6 mm, which is mainly concentrated in the summer. Precipitation from June to September accounted for 76% of the annual precipitation. The main upstream tributaries of Xiying River are the water pipes and the Ningchang river and its surface runoff control station is the Jiutiaoling hydrological station, which is located 19 km upstream of the Xiying reservoir (Fig. 1), with an altitude of 2 270 m and catchment area of 1 077 km^2.

2 Data sources and methods

2.1 Data sources

The runoff data of Xiyang River were measured by Jiutiaoling hydrological station from 1956 to 2020,

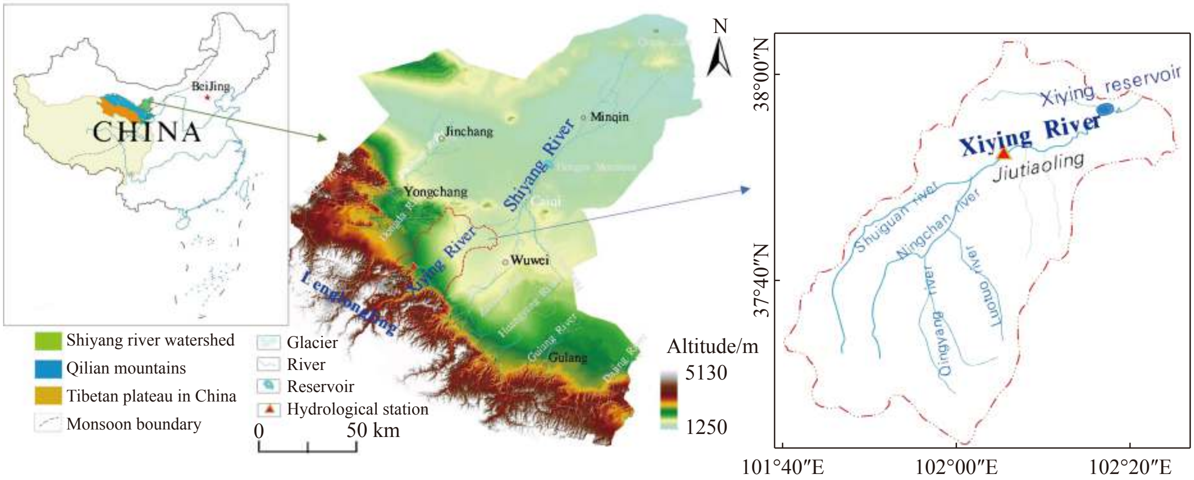

Fig. 1 Schematic map of the study area

of which the data from 1956 to 2012 were obtained from Shiyang River Basin Hydrology and Water Resources Bureau, and the others were quoted from Gansu Province Water Resources Bulletin.

The glacier remote sensing monitoring data was selected from 16 the Landsat series of images from 1975 to 2018, with a spatial resolution of 30 m. To minimize the influence of seasonal snow accumulation on the glacier interpretation results, this paper used Landsat TM/ETM/ETM+ images from June to August in summer as the data source to collect glacier change information.

The meteorological stations consist of Wuqiaoling, Menyuan and Jiutiaoling, with temperature and precipitation data is provided by the National Meteorological Information Center of the China Meteorological Administration and local monitoring stations.

2.2 Methods

Many statistical methods, such as linear regression, Mann-kendall (M-k) test, cumulative anomaly, and correlation analysis, were used to analyze meteorological, surface runoff, and glacier data. This section will explain Mann-kendall (M-k) test and cumulative anomaly in detail.

The Mann-Kendall test was recommended by the World Meteorological Organization and was widely used in the analysis of trends in time series of hydrological and climatic elements and abrupt change points (Kendall, 1990; Kahya, 2004). This method was used to achieve mutation tests analysis (Wei, 2007). The Mann-Kendall mutation test does not require samples to follow a certain distribution and is not disturbed by outliers, therefore it is very effective for testing changes from one stable state to another. For the time variable X (containing n samples), a sequence (S_k) is established:

$$s_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \cdots, n)$$

$$r_i = \begin{cases} \pm 1 & x_i > x_j \\ 0 & \end{cases} \quad (j = 1, 2, \cdots, i)$$

S_k equals the accumulation of the number of values when x in the i-th moment is greater than that in the j-th moment.

Define the statistics UF_k and UB_k, which are the positive and inverse statistical series of the time variable X, respectively, both with standard normal distribution.

$$UF_k = \frac{[s_k - E(s_k)]}{\sqrt{\mathrm{Var}(s_k)}} (k = 1, 2, \cdots, n)$$

$$UF_k = -UB_k$$

Where: $UF_1=0$, $UB_1=0$； and $\mathrm{Var}(S_k)$ are the average and variance of S_k.

Given the significance level α=0.05, sketch the critical (confidence reliability) line ($U_{\alpha/2}=\pm1.96$) and the positive and negative series (UF_k, UB_k) curves. If the UF_k value is greater than 0, it indicates an upward trend of X series; if that number is less than 0, it indicates a downward trend; when the number exceeds the critical line, it indicates a significant upward or downward trend, and the range beyond the critical line is determined as the time region where the mutation occurs; if there is an intersection of the two curves UF_k and UB_k within the critical line, then the intersection point corresponds to the moment when the mutation starts.

Cumulative anomaly curve is used to analyze the evolution of river or meteorological elements by the direction of curve changes. The evolution of precipitation and runoff are often characterized by cumulative anomaly curves of annual precipitation and average annual runoff (Zhang et al. 2012), where a complete ascending segment represents wet season and a complete descending segment represents dry season.

The correlation coefficients were used to characterize the interdependence between hydrological and meteorological variables and to quantitatively reflect the degree of interdependence between the elements. SPSS24 software was applied to analyze the correlations between runoff and temperature and precipitation.

3 Results and discussion

3.1 Runoff characteristics

From 1956 to 2020, the average annual runoff volume in the Xiying River area of runoff yield (Jiutiaoling) was 320.6 million m^3, remaining stable with little interannual variation. In addition, the coefficient of variation Cv value was 0.18. The overall runoff process showed a weak decreasing, and the variation trend (Fig. 2a and Fig. 2b) changed significantly in the early 21st century:

From 1956–2000, there was a significant trend ($P<0.05$) of decreasing average annual runoff, with a tendency rate of −14.3 million m^3/10a;

From 2001 to 2020, there was a non-significant increasing trend ($P>0.05$), with a tendency rate of change of 14.3 million m^3/10a, which was 7.45% higher than the multi-year average runoff from 1956 to 2000.

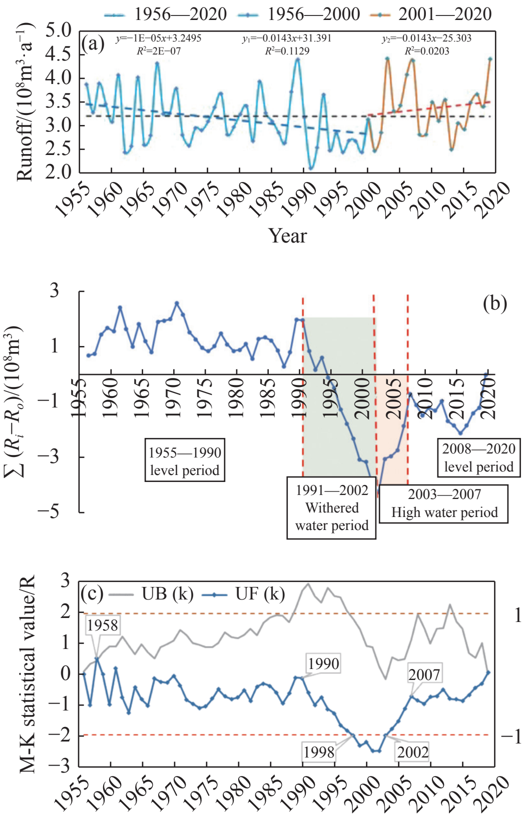

Fig. 2 (a) Runoff variation in the Xiying River runoff yield area; (b) Cumulative anomaly; (c) M-k characteristics curve (1956–2020)

The runoff decreased sharply from 1991 to 2002, which was a typical dry season, and the contraction was especially significant from 1998 to 2002, exceeding the lower limit value (Fig. 2c); the runoff increased sharply from 2003 to 2007, which was wet season; and then entered a period when a river is at its normal level from 2008 to 2020. The runoff in the study area included two normal-water periods, one dry season and one wet season during 1956-2020, which was representative and consistent with the statistical requirements of river hydrological data.

3.2 Response of runoff to climate

3.2.1 Main influencing factors of runoff

Surface runoff is influenced by both human activities and natural factors. The influence of human activities on runoff from the Xiying River area of runoff yield is mainly manifested in the types of land use in the upstream mountainous area. Woodland, grassland and unused land were the main resources, accounting for about 95% of the total area in the upper reaches. Remote sensing monitoring data in the study area showed (Fig. 3) that cropland, grassland and unused land had changed little over the years, which increased in the 1980s and decreased in the 21st century, remaining stable afterwards. The change is mainly due to the conversion of the ablation and retreating glacier area into unused land; arable land and urban industrial and mining residential land account for less than 1% and 0.2% of total lands, with little change over the years. It could be seen that the mountainous area in the upper reaches of Xiying River was rare influenced by human causes and therefore the surface runoff was mainly affected by climate.

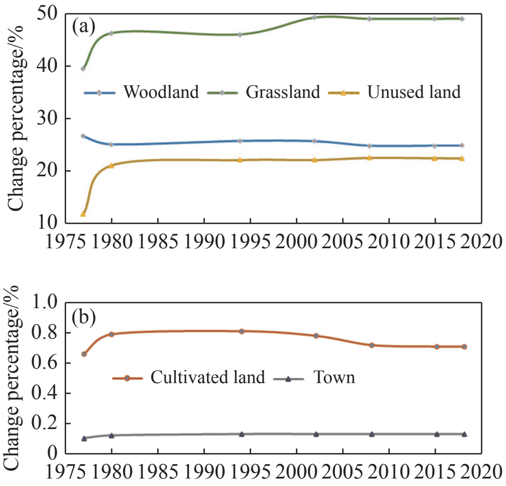

Fig. 3 The types of land uses in the Xiying River runoff yield area (1975–2018)

Surface runoff in the area of runoff yield originated from atmospheric precipitation and seasonal meltwater from glaciers and permafrost active layers, and the direct contribution of precipitation to the runoff out of the Xiyang River was 78% (Li et al. 2017). As a result of global warming, the cryosphere was shrinking, and glacier remote sensing monitoring showed that the glacier area of Xiying River ablated 51.54 km^2 from 1975 to 2018, with a cumulative retreat rate of 89.48%, and glacier meltwater contributed little to outflow runoff; permafrost degradation led to the thickening of the permafrost active layer and increasing permafrost water storage capacity and then significantly affected the hydrological process in cold areas.

Climate determines the magnitude and spatial and temporal distribution characteristics of surface runoff, where precipitation and temperature are the main drivers of runoff variability (Liu et al. 2010). Runoff was positively correlated with precipitation, with a correlation coefficient of 0.552 ($P<0.01$); in terms of temperature, the number was −0.114 ($P>0.05$); temperature was not directly correlated with either precipitation or runoff (as shown in Table 1). Based on the previous (Lan et al. 2000;

Table 1 Correlation between runoff and meteorological elements in Jiutiaoling (Pearson)

Feature item	Correlation coefficient	Sample size
R-P	0.552^{**}	65
R-T	−0.114 4	
T-P	0.042 9	

Note: R-unoff, P-Precipitation, T-Temperature;** means significance at 0.05level； * means significance at 0.01 level.

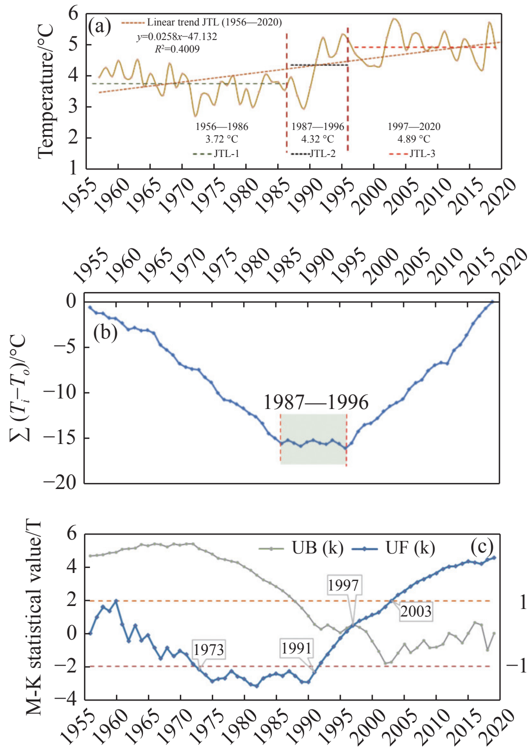

Fig. 4 Xiying River runoff yield area: (a) Temperature change process; (b) cumulative anomaly; (c) M-k characteristics (1956–2020) curve

Zhou et al. 2012; Sun et al. 2018) results, this study focuses on analyzing the main influencing factors of temperature and precipitation.

3.2.2 Climate change

（1）Temperature

Fig. 4 shows annual average temperature change in the Xiying River area of runoff yield. It revealed that the annual average temperature from 1956 to 2020 in the study area had a significant increasing trend ($P<0.05$), with a tendency rate of 0.258℃/10a, the warming rate was much higher than that of 0.064℃/10a in the Northern Hemisphere land and 0.076℃/10a in the whole country (Zuo et al. 2004). The warming rate in the last 20 years (2001–2020) was 0.285℃/10a, which was 15% higher than that in 1956–2000; the temperature had gone through three periods of "decline (1956–1986) — stabilization(1987–1996)—increase((1997–2020)" (Fig. 4a and Fig. 4b); 1973–1991 was a statistically significant cold period, during which temperature had witnessed a significant decline ($P<0.01$), from 2003 to 2020, the temperature increased significantly ($P<0.01$). 1997 was a year of sudden temperature change, since then the climate of the study area had entered a period of significant warming (Fig. 4c), which coincided with the rare record of high temperatures in northern China under the influence of the East Asian monsoon.

（2）Precipitation

The average annual precipitation in the study area showed an overall increasing trend from 1956 to 2020 (Fig. 5a), with a tendency rate of 10.65 mm/10a; the tendency rate of change of annual precipitation during 2001–2020 was 28.72 mm/10a, which was 9.3% higher than that of 1956–2000.

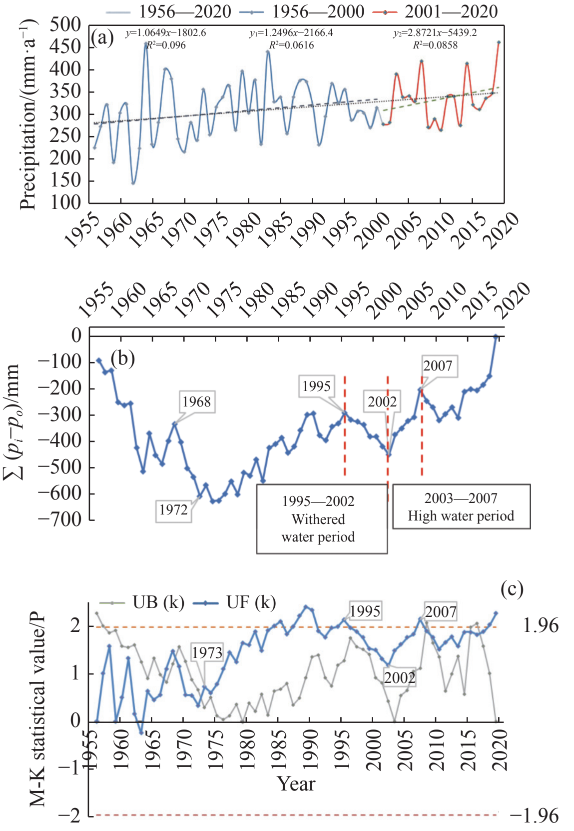

Fig. 5 Xiying River runoff yield area: (a) Precipitation change process; (b) Cumulative anomaly; (c) M-k characteristics (1956–2020) curve

Precipitation in the area of runoff yield is influenced by many factors, including typical mountain climate of the Qilian Mountains region, the distribution of water vapor conveyor belt of the East Asian summer wind. Resulting in complex average annual precipitation changes. The interannual variation was more in line with the surface runoff characteristics, as shown in Fig. 5b, 1968 to 1972, and

1995 to 2002 were drought years with reduced precipitation; 2002–2007 and 2016–2020 were increased rainfall of abundant water years; the precipitation M-k variation process curve (Fig. 5c) showed several anomalous years (1968, 1973, 2007, 2016, etc.). According to that curve, the sliding t-test method and the differential product curve, 1973 was a variation year, and the average annual precipitation had increased significantly since then.

3.2.3 Model of runoff response to climate change

The Xiying River area of runoff yield was less affected by human activities, and climate change (temperature and precipitation) affected hydrological processes in the basin. Based on the principle of regional multi-year water balance, this study improved the linear regression equation ($R = b_0 + b_1P + b_2T$, with b_0, b_1, and b_2 as model parameters to be determined) for surface runoff (R), precipitation (P), and air temperature (T) established by Roger and Waggoner (Savabi M R et al. 2001). With data on surface runoff and meteorological elements (air temperature and precipitation) in the Xiying River area of runoff yield from 1956 to 2020, this paper conducted a regression analysis and established the regression model of runoff R on climate change in the Xiying River area of runoff yield as follows.

$$R = 0.0052P - 0.1589T + 2.3731 \qquad (1)$$

Where: R is the annual runoff (in billions of m^3) from the flow-producing area Jiutiaoling; T is the average annual temperature (℃); P is the annual precipitation (mm).

The complex correlation coefficient of the model was 0.753, the standard deviation was 0.38, and the Significance F value was 0.66×10^{-6} ($<<0.05$), which passed the F test of $\alpha=0.05$. This indicates that the model has a significant regression and can predict the response of annual average runoff to future climate change in the Xiying River area of runoff yield.

The average annual temperature variation of 2℃ ($T\pm2$) and change of annual precipitation range from 50 mm to 100 mm ($P\pm50$; $P\pm100$) were selected as the simulated climate to predict the annual runoff changes under different temperature and precipitation (Table 2).

According to Table 2, when the annual average temperature of the Xiying River area of runoff yield rises (≤0.5℃), the annual runoff increases with the increase of precipitation, for example, when the temperature rises 0.5℃, the annual average precipitation will increase or decrease 100–50 mm, and the annual average runoff will increase 19.7% or decrease 21.7%; when the temperature rises more than 0.5℃, the annual precipitation will increase 50 mm, and the runoff will still decrease; when the temperature rises by 2℃, if the annual average precipitation decreases by 100 mm, the runoff will be reduced by 28.73%, even if that number increases by 100 mm, the runoff will only increase by 1.94%; with higher temperature, more equivalent precipitation will lead to a smaller runoff increase, while the decrease in the equivalent precipitation will lead to a larger runoff decrease.

Table 2 Annual runoff R variation (%) under different climate (temperature T, precipitation P)

T(℃)	P(mm)			
	R(%)			
	100	**50**	**−50**	**−100**
2	1.94	−5.73	−21.06	−28.73
1.5	15.02	−3.39	−18.72	−26.39
1	17.37	−1.04	−16.38	−24.05
0.5	19.71	1.30	−14.03	−21.70
−0.5	24.40	5.99	−9.35	−17.02
−1.0	26.74	8.33	−7.01	−14.67
−1.5	29.08	10.67	−4.66	−12.33
−2.0	31.43	13.01	−2.32	−9.99

4 Conclusions

(1) In the area of runoff yield in the upstream Shiyang River basin, where human activities was little, the change of runoff was controlled by climate. Precipitation and temperature were two major driving factors for the change of surface runoff, which jointly influence the spatial and temporal distribution of runoff; the runoff had a significant positive correlation with the precipitation ($P<0.01$), and both had similar change characteristics.

(2) Runoff in the study area was sensitive to climate change, and the climate had becoming warm and wet and annual runoff had entering wet period from 2003 (2002). Compared to the earlier period (1955–2000), the increases of average annual temperature, precipitation and runoff in recent two decades were 15%, 9.3%, and 7.8%, respectively.

(3) In the context of global warming, when the precipitation increased, the runoff would increased less than in the period between 1956–2020, and especially, it decreased more when the precipitation decreased. In addition, the ecological regulation function of surface runoff in the area of runoff yield was weakening due to the global warming.

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