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Original Research

Quantifying the Contribution of Climate Change and Human Activities to Runoff Changes in the Source Region of the Yellow River

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Abstract

Assessing the characteristics of runoff changes and quantifying the contribution of influencing factors to runoff changes are crucial for water resources management and sustainable development in the source region of the Yellow River (SRYR). The intra-annual distribution of runoff depicted a double-peak effect. The first runoff peak in July was primarily influenced by precipitation, which did not completely flow after falling to the ground. However, some water was stored in the active layer of permafrost and released in September resulting in the second runoff peak. The contributions of precipitation and temperature to the runoff changes were 74.2% and 25.8%, respectively. The runoff peaks advanced by 15 and 6 days for the first and second peaks, respectively, owing to the influence of the cryosphere change. Principal component analysis revealed that the contributions of climate change and human activity to runoff fluctuations were 72.9% and 27.1%, respectively, during 1961-2018, indicating that hydrological processes were mainly influenced by climate change in the SRYR. The combined effect of climate change created a warm and dry trend after 1990, indicating a spatial distribution of wetness in the northwest and aridity in the southeast of the SRYR.

Keywords: runoff effect, climate warming, human activity, the source region of the Yellow River

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Introduction

In the context of global warming, temperature trends are simply interannual variations in the climate system; however, global warming trends have not creased [1]. Since the 1950s, the warming trend has become more significant, resulting in many ecological problems that have put increasing pressure on water resources [2]. Since the 1990s, abrupt climate changes, accelerated warming and humidification have amplified the number of extreme events worldwide [3-5]. Runoff is an imperative component of the hydrological cycle and a specific vehicle for the presence of large quantities of water on the land surface of the Earth. Global runoff has not depicted substantial trend changes during the last few decades but has been clearly influenced by large-scale climate phenomena [6]. Rivers with noteworthy changes in runoff and downward trends outnumbered those with upward trends [7, 8]. The magnitude of warming is more pronounced in cold regions, which has an enormous impact on the hydrological processes of runoff [9-11]. However, there are still many gaps in the study owing to the challenge of observation and sampling in alpine regions and the lack of experimental data [12].

The source region of the Yellow River (SRYR) is located in the northeast of the Tibetan Plateau, at the Third Pole of the Earth [13], and is extremely sensitive to climate change [14]. It is a vital water conservation area in the upper reaches of the Yellow River and a crucial ecological hinterland area in China. For the lower reaches, SRYR water resources are not only related to the stability of the ecosystem but also have a socio-economic impact on drinking water, agriculture, water conservation and industry. This is directly or indirectly associated with the subsistence of the livelihood and civilization, and has an imperative ecological function and economic value. The economic and social development of China as well as ecological security are very important [15]. Average air temperature increased by 0.4°C×$(10a)^{-1}$ during 1961-2020 [16], and precipitation slightly increased by 3.6 mm×$(10a)^{-1}$ during 1960-2013 [17]. Climate change has also caused the SRYR to display continued permafrost degradation, with the area of permafrost declining from 2.4×10^4 km^2 in 1980 to 2.2×10^4 km^2 in 2016 [18] and demonstrating an accelerating trend after the 1990s [19, 20]. The annual runoff reduced significantly by 5.5×10^9 m^3 in 1960-2007 in the SRYR [21]. In recent years, studies have established that the timing of the runoff peak advances due to changes in the cryosphere [22, 23]. Bing et al. [24] noticed that the reduction in runoff was primarily due to the degradation of grassland, which is unable to store large amounts of water. Ji et al. [25] found that spring, summer and winter runoff fluctuations were mostly influenced by human factors, whereas autumn runoff changes were influenced by climatic factors using the Seasonal Budyko Hypothesis. In summary, climate change and variations in surface conditions due to human activities have become the most critical factors influencing runoff changes, which seriously endanger the stability of the watershed ecosystem and constrain high-quality development. Therefore, it is essential to investigate the mechanisms of their influence on runoff changes in the SRYR.

Currently, the SRYR is cold and lacks oxygen. The living and working conditions are challenging, the density of the observation station network is too sparse, the layout and structure are unreasonable, and the observation data cannot reflect the real situation of the entire region. Accurately evaluating the mechanisms of factors influencing runoff changes is arduous because the adverse natural conditions and complex terrain situations in the SRYR. Quantitative studies on the factors influencing runoff variations in these regions remain deficient. The objectives of this study were to: (1) evaluate the climate and runoff changes in the SRYR during 1961-2018; (2) investigate the association between runoff and climatic factors variables; and (3) quantify the contribution of climate change and human activity to runoff. The results of this study can provide valuable guidance for the rational allocation and scientific management of water resources and the implementation of ecological projects in the future.

Materials and Methods

Study Region

The SRYR (95.78°~103.43°E, 31.87°~36.24°N), with an area of 12.2×10^4 km^2, is located in the northeastern part of the Qinghai Tibet Plateau [26] (Fig. 1). The average elevation of the study area is approximately 3800 m above sea level, annual mean air temperature is less than 0ºC, and the annual mean precipitation ranges from 380 to 650 mm. The regional topography is tortuous, vegetation cover is high, terrain is high in the west and low in the east, and the river source area is distributed with permafrost and seasonal permafrost [27]. The SRYR has a highland semi-humid climate, predominantly influenced by westerly winds, the Indian monsoon and the East Asian monsoon [28]. The hydrological process is less affected by human activities, and is an essential flow-producing area in the Yellow River Basin and an ecological barrier in China [3]. The region encloses areas inhabited by the Han, Hui, Tibetan and Mongolian people, with a rich variety of natural resources, meadows, woodlands, farmlands, deserts and other ecosystems, as well as numerous rivers and lakes. SRYR is mainly based on animal husbandry, with a single industrial structure and underdeveloped productivity [29]. For a long time, the grasslands of SRYR have been used as conventional pastoral farmland for livestock grazing, the key livestock being yaks, sheep, goats and horses [30]. Recently, owing to changes in natural conditions

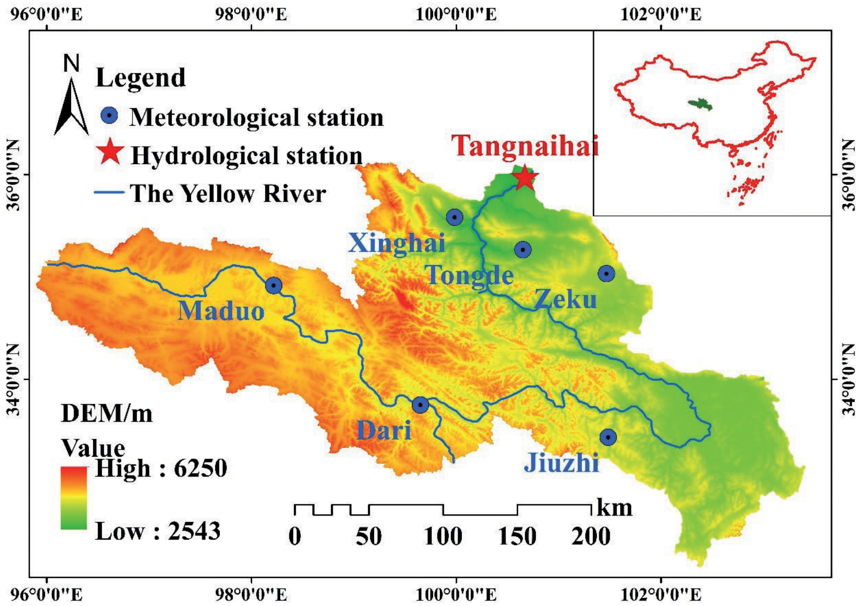

Fig. 1. The location of the SRYR.

and human activities, the ecological environment of the SRYR has undergone significant changes.

Data Source

In this study, monthly runoff data (1961-2018) were obtained from the Tangnaihai station. The Tangnaihai station is a critical national hydrological station and the main stream control station of the Yellow River that records water and sand changes. The daily temperature and precipitation data from of six meteorological stations (Table 1) in the SRYR from 1961 to 2018 were selected. Meteorological data were obtained from the National Meteorological Information Centre (http://data.cma.cn/), including Tongde, Mado, Dari, Jiuzhi, Zeku and Xinghai stations. Moreover, datasets of land use (1:100000), population density (1 km) and GDP density (1 km) were acquired from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (http://www.resdc.cn/) during 1995-2015.

Methods

Calculation of the Contribution of Climatic Factors to Runoff Changes

The runoff (Q) is mainly influenced by precipitation (P) and temperature (T), runoff changes are related to monthly precipitation and temperature to study their relationship [31], which can be calculated by:

$$Q = Q(P, T)$$

The relationship between runoff and precipitation and temperature can be determined by multiple regression. The changes in runoff can be explained by the changes in precipitation and temperature, which can be calculated by:

$$\triangle Q = \frac{\partial Q}{\partial P} \triangle P + \frac{\partial Q}{\partial T} \triangle T$$

Where $\frac{\partial Q}{\partial P}$, $\frac{\partial Q}{\partial T}$ are the multiple regression coefficients of the corresponding factors, which indicate the contribution of precipitation and temperature to the runoff rate, the contribution of each factor to the intra-annual variation in runoff can be approximated by multiplying the factor contribution by the standard deviation of each factor, the contribution of each factor to runoff changes over the years can be approximated by multiplying the factor contribution by the distance level [32].

ET0 Calculated with Penman-Monteith

The meteorological data obtained do not include evapotranspiration (ET_0), and we need to calculate ET_0 before we can analyze its effect on runoff changes. ET_0 is an important part of the hydrologic cycle and is a complex natural process, so the accuracy of ET_0 estimates is critical to the basin water balance [33]. Penman-Monteith equation was used for calculation of ET_0, as recommended by the FAO [34]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the daily reference evapotranspiration (mm d^{-1}), D is the slope of the saturation vapor pressure curve (kPa $°C^{-1}$), calculated from the air temperature, γ

Table 1. The selected weather stations in the SRYR.

Station	Longitude (°N)	Latitude (°E)	Altitude (m)	Mean annual precipitation (mm)	Mean annual temperature (ºC)	Mean annual evaporation (mm)
Tongde	100.65	35.27	3289.44	441.24	1.41	942.41
Maduo	98.22	34.92	4272.32	325.88	-3.51	770.07
Dari	99.65	33.75	3967.53	557.44	-0.65	773.28
Jiuzhi	101.48	33.43	3628.57	750.57	0.86	804.36
Zeku	101.47	35.03	3662.86	485.69	-1.55	786.93
Xinghai	99.98	35.58	3323.24	371.67	1.48	940.50

is the psychrometric constant (kPa $^{o}C^{-1}$), calculated from precipitation, R_n is net radiation (MJ $m^{-2}d^{-1}$), calculated from net solar radiation and net thermal radiation from the ground, G is the ground heat flux density at the soil surface (MJ $m^{-2}d^{-1}$), T is the mean air temperature at 2 m height (ºC), u_2 is the wind speed 2 m above the ground (m s^{-1}), converted from 10 m wind speed, e_s is the saturation vapor pressure (kPa), calculated from the maximum and minimum daily air temperature, e_a is the actual vapor pressure (kPa), calculated by the ratio of specific humidity, precipitation and water vapor molecular mass to the molecular mass of dry air. All the intermediate parameters were computed following [34].

Principal Component Analysis

This paper uses principal component analysis (PCA) to quantify the contributions of climate change and human activities to runoff changes in the SRYR. PCA is a statistical analysis method that classifies multiple original variables into a few composite indicators [35]. In multi-indicator variable studies, there is often a degree of information overlap due to the large number of variables and their correlation with each other. PCA takes a dimensionality reduction approach to find several composite factors to represent the original multitude of variables. These composite factors reflect the information of the original variables as much as possible, and are not correlated with each other, so as to achieve the purpose of simplification [36]. Assuming that the original variable indicators are x_1, x_2, …, x_n, and the data are standardized to obtain the composite indicators z_1, z_2, …, z_m($m \le n$), then the model of PCA can be calculated by:

$$\begin{cases} z_1 = l_{11}x_1 + l_{12}x_2 + \cdots + l_{1p}x_p \\ z_2 = l_{21}x_1 + l_{21}x_2 + \cdots + l_{2p}x_p \\ \cdots\cdots\cdots\cdots \\ z_m = l_{m1}x_1 + l_{m1}x_2 + \cdots + l_{mp}x_p \end{cases}$$

Where l_{ij} is the principal component loading value can be calculated by:

$$l_{ij} = p(zi, xj) = \sqrt{\lambda_i} e_{ij} (i, j = 1,2, \ldots, p)$$

Where e_{ij} is the jth component of the vector e_i, which is required that e_{ij} satisfies $\sum_{j=1}^{p} e_{\text{ij}}^2 = 1$.

Results

Background Conditions for Runoff Changes

Climate Change

According to available studies, 1990 was the abrupt change point in climate and runoff changes in the SRYR [3, 4, 37]. The annual precipitation increased by 9.63 mm×(10 a)$^{-1}$ during 1961-2018, and the rate of the increase in precipitation increased from east to west, with a larger increase in higher altitude areas (Fig. 2a and 3a). The rate of increase in precipitation was 9.46 mm×(10 a)$^{-1}$ and 41.10 mm×(10 a)$^{-1}$ during 1961-1990 and 1991-2018, respectively, with the latter being 4.3 times greater than the former (Fig. 2a). The annual temperature increased by 0.46ºC×(10 a)$^{-1}$ during 1961-2018, with larger increase in the central part of the SRYR (Fig. 2b and 3b). The rate of increase of temperature were 0.27ºC×(10 a)$^{-1}$ and 0.72ºC×(10 a)$^{-1}$ during 1961-1990 and 1991-2018, respectively, with the latter being 2.7 times greater than the former (Fig. 2b). The annual evaporation increased by 13.4 mm×(10 a)$^{-1}$ during 1961-2018, with a surge in the central part of the SRYR (Fig. 2c and 3c). The rate of increase of evaporation were 13.2 mm×(10 a)$^{-1}$ and 21.0 mm×(10 a)$^{-1}$ during 1961-1990 and 1991-2018, respectively, with the latter being 1.6 times greater than the former (Fig. 2c). The spatial patterns of evaporation were similar to those of the annual temperature (Fig. 3).

Land Use, Population and GDP Change

Fig. 4 illustrated the changes in land-use types, population and GDP in the SRYR during 1995-2015. The major land types were grassland and unused land, which accounted for 75.22% and 14.94% of the study region, respectively, followed by forest land, which

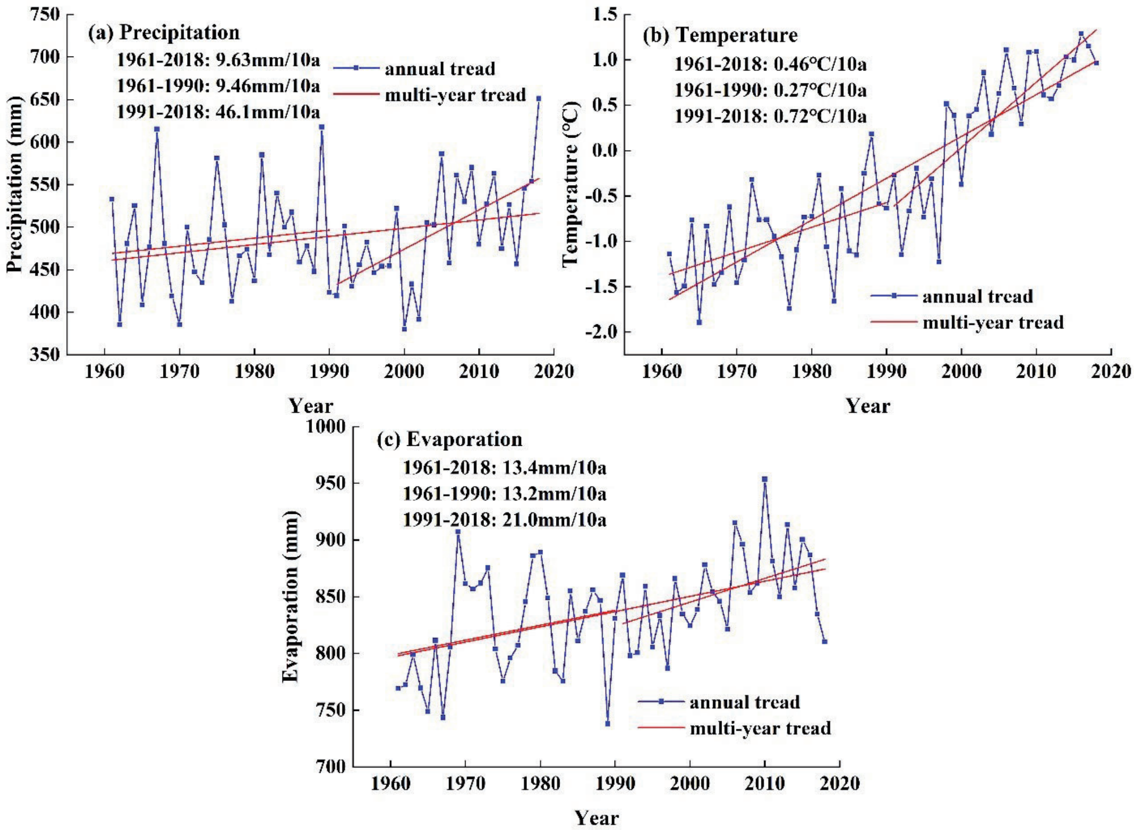

Fig. 2. Interannual variation of precipitation a), temperature b), and evaporation c).

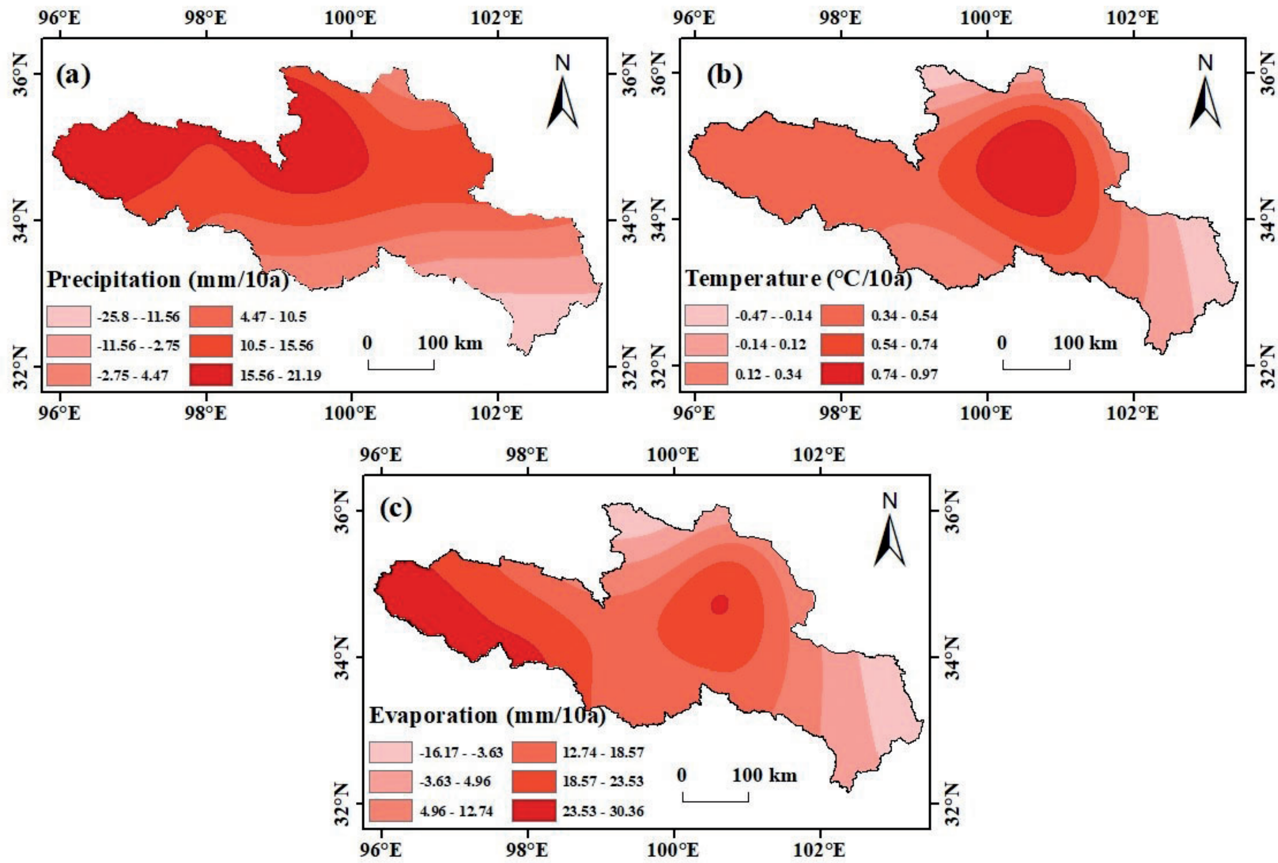

Fig. 3. Spatial pattern for variation rates of precipitation a), temperature b), and evaporation c).

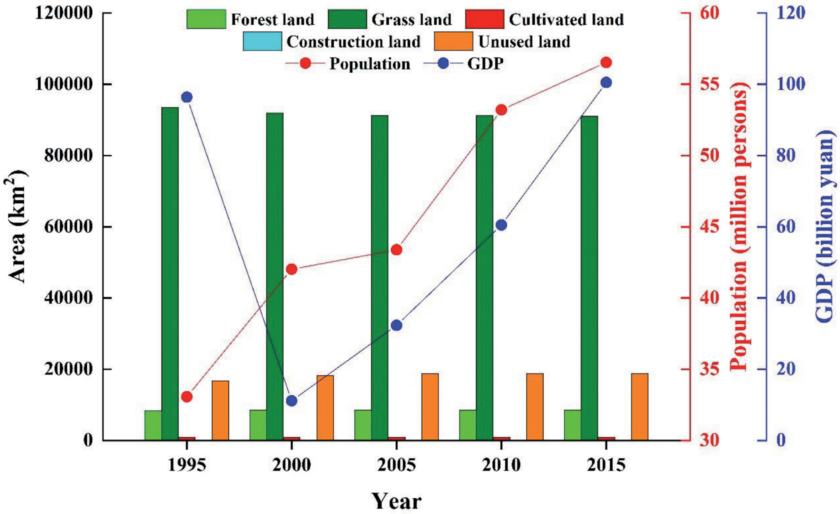

Fig. 4. Interannual variation of land use types, population and GDP in the SRYR.

accounted for 6.92% of the study region, and cultivated land and construction land for only 0.76% and 0.05% of the study region, respectively. During 1995-2015, forest, cultivated, construction and unused land increased at the rate of 26.77 km^2/a, 6.06 km^2/a, 9.27 km^2/a and 461.64 km^2/a, respectively. In 2015, forest, construction and unused land area increased by 135.87 km^2, 40.95 km^2 and 1995.52 km^2, respectively, compared with 1995. Grassland depicted a decreasing trend with a rate of -551.71 km^2/a, and the area decreased by 2386.95 km^2 in 2015 as compared to 1995. The rate of increase in population was 58,100 people/year, which was 234,600 greater in 2015 than 1995, and the rate of increase in GDP was 576 million yuan/year, which was 413 million greater in 2015 than in 1995.

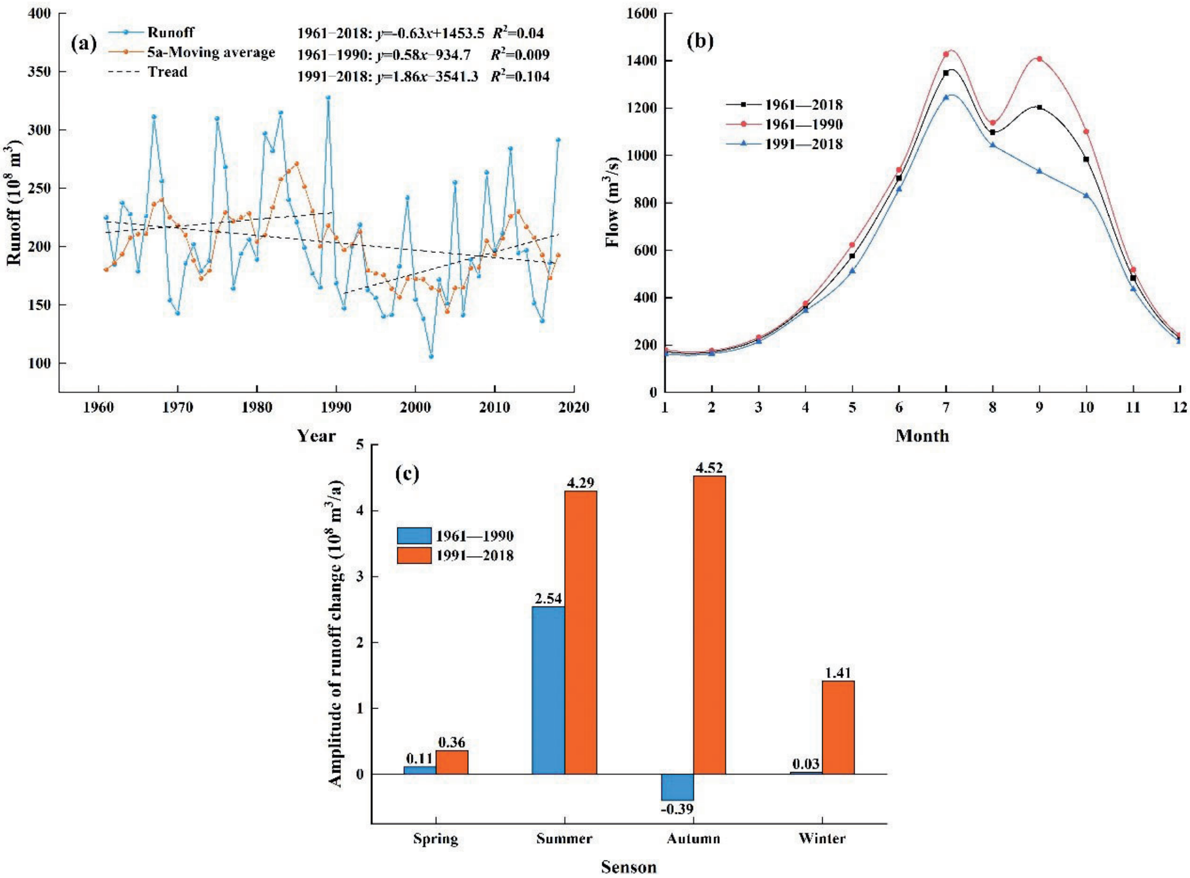

Fig. 5. Annual variation of runoff a); intra-annual variation of runoff b); seasonal variation amplitudes of runoff c).

Variable Characteristics of Runoff

Temporal Variation of Runoff

The runoff reduced at a rate of 6.3×10^8 $m^3\times(10a)^{-1}$ during 1961-2018, increased at a rate of 5.8×10^8 m^3 $\times(10a)^{-1}$ during 1961-1990, and at a rate of 18.6×10^8 m^3 $\times(10a)^{-1}$ during 1991-2018 in the SRYR. This increasing trend during 1991-2018 was 3.2 times higher than that of 1961-1990 (Fig. 5a). The overall trend of the runoff change depicted an increase during (1961-1990), decrease (1991-2005) and increase (2006-2018).

The monthly runoff indicated double peaks during the year and showed a downward trend, with the most significant decrease in runoff in July, September and October; the overall difference in the monthly runoff of the SRYR was 16.8 % (Fig. 5b). The runoff increased consistently from January to July, majorly due to the increased precipitation. There was a low peak in the reduction of runoff in August, due to melting of the active layer of permafrost, which had more space to store rainfall. The rainfall did not immediately recharge the river to generate direct runoff, but first entered the active layer of permafrost and was stored. Precipitation decreased by 13.7 mm and evaporation by 2 mm in August compared with July, and decreased precipitation was also one of the reasons. The second peak of runoff befell in September, primarily because the previously stored permafrost water started to be discharged to recharge the runoff. The precipitation decreased by 13.3 mm and evaporation decreased by 20.5 mm in September compared with August, and the increase in recharge and evaporation augmented the runoff. Runoff decreased consistently from September to December, due to decreased precipitation. The growing trends of spring, summer, and winter runoff during 1991-2018 were 3.3, 1.7 and 47 times higher than those of 1961-1990, and winter runoff depicted an intense rising trend after 1990 (Fig. 5c). The sharp diminution in water resources in the 1990s led to an overall decrease in the runoff in the SRYR.

Runoff Peaks Advance After 1990

The first runoff peak mainly occurred in July; some years may also advance to May or June; before 1990 the peak occurred four times in June, and thrice in May and four times in June after 1990. The probability that the first runoff peak during 1991-2018 compared with 1961-1990 occurred in May is from 0% to 20%, June from 17% to 27%, and July from 83% to 53% (Fig. 6a). The second runoff peak largely occurred in September, with some years in August and some in October. It has transpired thrice in August and 11 times in October over a total of 58 years during 1961-2018. The probability that the second runoff peak during 1991-2018 compared with 1961-1990 occurred in August is from 0% to 20% and in September from 67% to 47% (Fig. 6b). The timing of runoff peak occurrence indicated an overall trend of advancement, with the first peak and second peak during 1991-2018 being 15 and 6 days earlier, respectively, compared with 1961-1990 in the SRYR. This is predominantly due to global warming, melting glaciers, shorter snowpack periods and fewer snow days, resulting in earlier snowmelt runoff [22]. The augmented runoff recharge from snow and ice melting makes it easier for runoff to reach peak conditions compared to previous conditions with the same precipitation.

Contribution of Climate Change and Human Activities to Runoff Changes

The "Double Peak" effect of the intra-annual distribution of runoff in the SRYR was influenced by the key meteorological factors of precipitation and temperature. The contribution of precipitation to runoff changes was always positive and augmented from

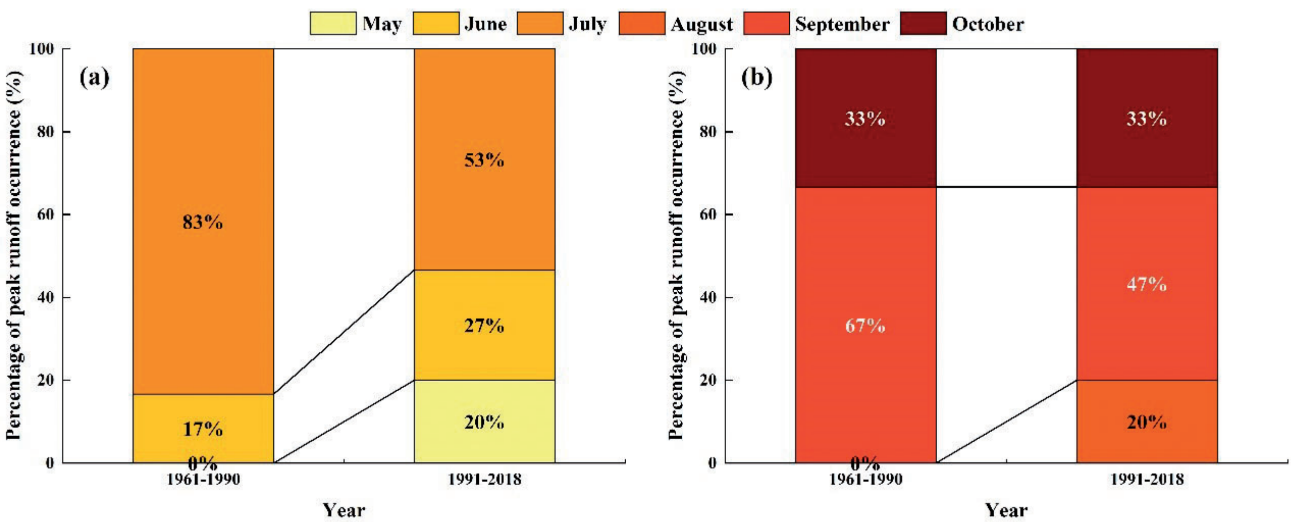

Fig. 6. Percentage of months with runoff peaks.

January to May annually, fluctuated steadily from June to October, and began to regress after October (Fig. 7). The contribution of temperature to runoff changes was also consistently positive, which indicates that there is a relationship between temperature and runoff and that temperature indirectly affects runoff changes. Overall, temperature and precipitation jointly influenced runoff changes from November to March each year, and the contribution of temperature cannot be ignored; from April to October each year, the influence of precipitation on runoff was dominant. The contribution of precipitation to runoff changes was 74.2% and temperature was 25.8% during 1961-2018. The overall temperature contribution to runoff changes boosted by 7.5% from 1991 to 2018 compared to 1961-1990, with larger intensifications in February, April, November, and December of 25.9%, 11.0%, 8.2%, and 8.5%, respectively.

Climate change and human activities are the focal driving factors affecting the evolution of water resources in basin [38]. The most significant meteorological factors affecting runoff changes are precipitation, temperature and evaporation, which directly and indirectly affect runoff changes. Herein, precipitation, temperature and evaporation were chosen as meteorological factors to evaluate changes in runoff. Industry, agriculture, production, and living organisms directly or indirectly affects water resources in the basin. Here, GDP, cultivated area, and construction land area were selected as human activity factors to investigate runoff changes. Six parameters were chosen as the core factors for analyzing runoff changes in the SRYR employing PCA: precipitation (x_1), temperature (x_2), evaporation (x_3), GDP (x_4), cultivated area (x_5), and construction land area (x_6). An Eigenvalue greater than one was considered a significant component [39] (Fig. 8). The PCA results depicted that approximately 90.68% of the total variance was clarified by the principal components PC1 and PC2. To interpret PCA weightings, the magnitude of the values verified the strength of the

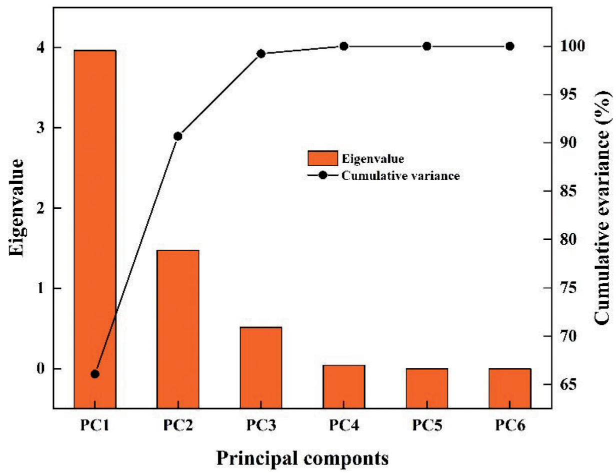

Fig. 8. Eigenvalues and proportions of principle components.

correlation, with positive and negative values signifying positive and negative correlations, respectively. The coefficients corresponding to each indicator in the principal components were estimated by dividing the parameter loading values in the principal component loading matrix by the square root of the corresponding principal component eigenvalues and building an integrated model of the two principal components. The model can be defined as:

$$F_1 = 0.476x_1 + 0.408x_2 + 0.461x_3 + 0.312x_4 + 0.373x_5 + 0.398x_6$$

$$F_2 = -0.235x_1 - 0.467x_2 - 0.276x_3 + 0.644x_4 + 0.466x_5 + 0.138x_6$$

The integrated model was weighted by the variance contribution of PC1 and PC2, which can be defined as:

$$R = 0.661F_1 + 0.246F_2$$

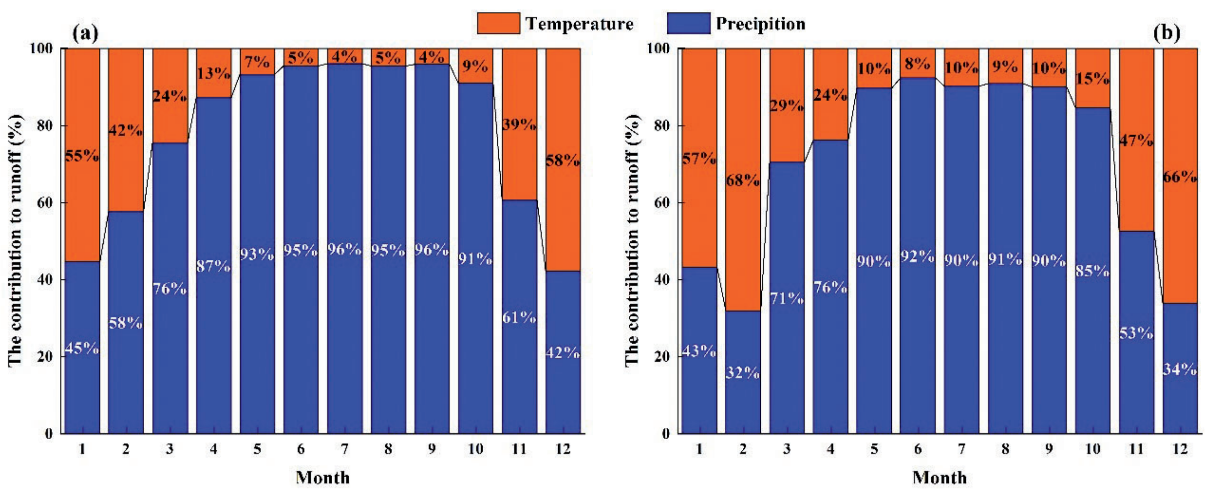

Fig. 7. Intra-annual percent contribution of precipitation and temperature to runoff.

Table 2. Results of the PCA for parameter loading matrix.

Factors	Parameter loading values	
	PC1	PC2
Precipitation	0.948	-0.285
Temperature	0.812	-0.567
Evaporation	0.918	-0.335
GDP	0.621	0.782
Cultivated area	0.742	0.566
Construction land area	0.792	0.168

The loading values of the first principal component with precipitation (x_1), temperature (x_2), and evaporation (x_3) were 0.948, 0.812, and 0.918, respectively, implying that the first principal component was ascertained by climatic factors. The loading values of the second principal component with GDP (x_4), cultivated area (x_5), and construction land area (x_6) reached 0.782, 0.566, and 0.168, respectively, indicating that the second principal component was determined by human activity factors (Table 2). The variance of the effect of the climate change factor was 3.965, and the variance of effect of the human activity was 1.475. If the effects of other components are ignored, the proportion of variance of climate change and human activity to the total variance (5.44) signifies that the contributions of climate change and human activity to runoff changes are 72.9% and 27.1%, respectively, demonstrating that climate change is the chief factor influencing runoff changes. Human activities have influenced runoff changes by altering land use, substrate cover. and the amount of water abstraction, which influences the hydrological cycle processes in the watershed. The ecological and pasture degradation caused by the development of SRYR modified the runoff infiltration conditions. However, with increasing awareness of environmental protection and the implementation of government policies, the ecological environment of the SRYR has substantially improved.

Discussion

Response of Runoff to Climate Factors

Simple linear relationships were employed to evaluate the effects of annual temperature, precipitation and evaporation on runoff during different periods (Fig. 9). The years 1961-1990 and 1991-2018 are defined

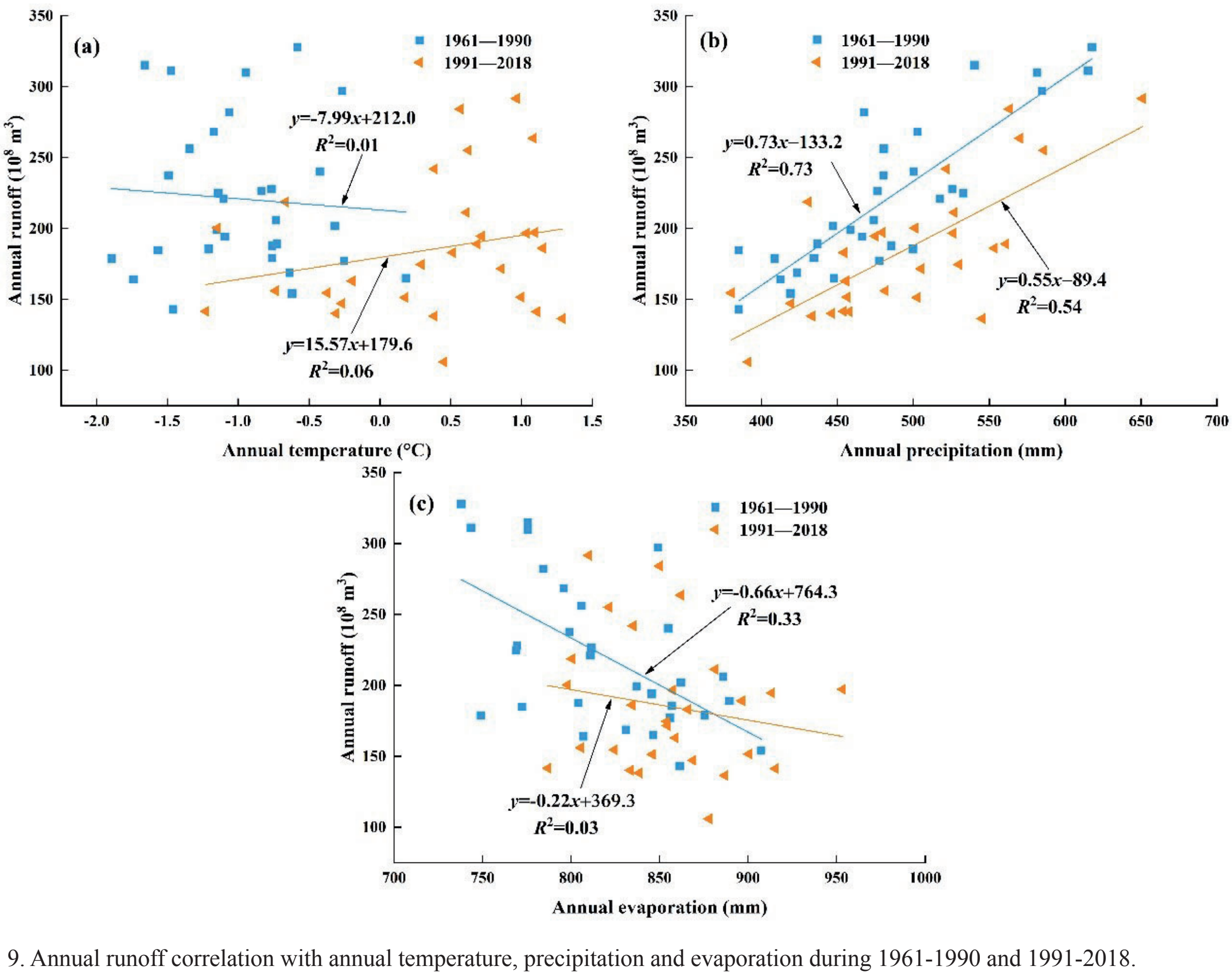

Fig. 9. Annual runoff correlation with annual temperature, precipitation and evaporation during 1961-1990 and 1991-2018.

Table 3. Annual runoff correlation coefficients with annual temperature, precipitation and evaporation during 1961-1990 and 1991-2018.

Correlation coefficients	Temperature	Precipitation	Evaporation
Runoff (1961-1990)	-0.074 (P>0.05)	0.855 (P<0.01)	-0.578 (P<0.01)
Runoff (1991-2018)	0.235 (P>0.05)	0.732 (P<0.01)	-0.18 (P>0.05)

Note: P is the significance level.

as T0 and T1, respectively; temperature and runoff were negatively correlated at T0 but became positively correlated at T1. This implies a change in the effect of temperature on runoff changes, and the significance levels were below 95%. Precipitation and runoff were significantly positively correlated at T0 and T1, with correlation coefficients of 0.855 and 0.732, respectively. This signifies that the contribution of precipitation to runoff becomes smaller at T1, with significance levels above 99% in both cases. Evaporation and runoff were negatively correlated at T0 and T1, with a correlation coefficient of -0.578 and a significance level above 99% during T0, and a correlation coefficient of -0.18 and a significance level below 95% during T1 (Table 3).

Accelerative Warming and Drying after 1990

Table 2 indicates that runoff change was primarily caused by climate change in the SRYR. The spatial distribution of relative moisture index ($\frac{P-ET_0}{ET_0}$) in various periods was attained based on daily meteorological data from meteorological stations utilizing the inverse distance interpolation method [40] in the SRYR (Fig. 10). The minimum relative moisture index was -0.61, the maximum was -0.02, and the average was -0.39 during 1961-1990. The distribution increased from northwest to southeast, with being more arid in the northwest and more humid in the southeast. The minimum relative moisture index was -0.59, the maximum was -0.11, and the average was -0.4 during 1991-2018, and the distribution characteristics were the same as in 1961-1990. The average value of the relative wetness index during 1991-2018 was lesser than that of 1961-1990, indicating that the SRYR was more arid. In recent decades, although precipitation has depicted an increasing trend, the collective effect of climate change due to rising temperatures has revealed a significant increase in evaporation, leading to meteorological drought, which triggers hydrological drought and displays an overall decreasing trend in runoff [41-43]. Meteorological drought triggers diverse many ecological problems, including enhanced desertification, mainly in the east and south of the study region, which verifies our result that the southeast was more arid [26, 44]. Climate change has also led to dramatic changes in the cryosphere, making hydrological processes more complex, with glacier retreat and permafrost degradation leading to a greater proportion of runoff recharge from snow and ice melt water and an earlier runoff peak [3, 4, 45]. Precipitation and temperature will increase in the future, evaporation will also be enhanced, and surface water resources may be reduced in the SRYR [16, 43, 46].

Environmental and Social Effects of Runoff Changes

Human demand for water resources has augmented, and water resources pressure has become a major threat to the sustainable development of human society, due to rapid global population growth, economic development, and enriched living standards [47-49]. In recent years, the population, farmland area, and construction land area have continued to increase, and surface conditions have drastically changed [50-52]. Especially since 1990, the study region has undergone a strong climate transition in the context of climate warming, making

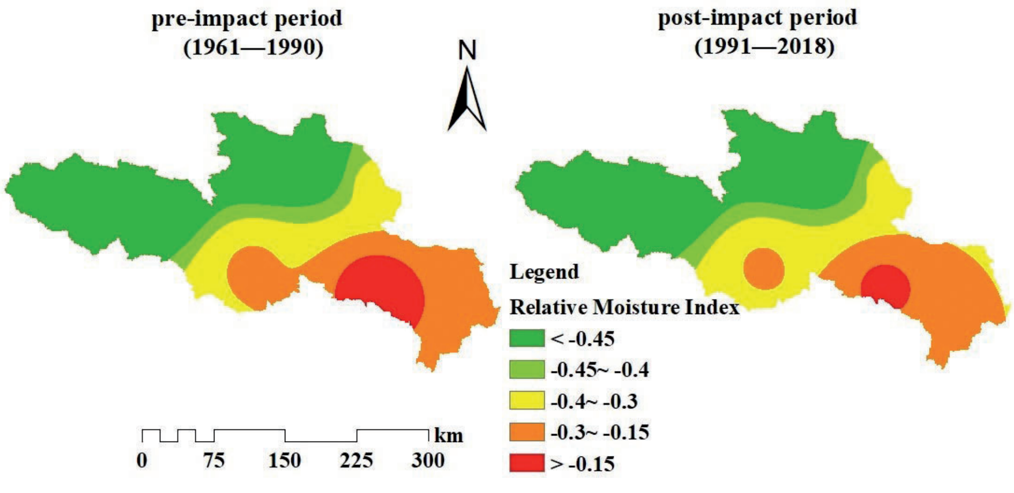

Fig. 10. Spatial distribution of relative moisture index in the SRYR in different period.

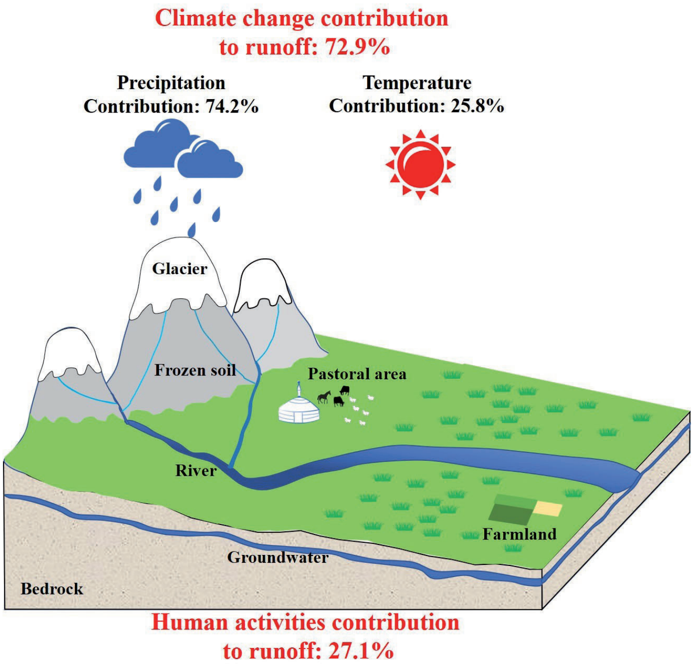

Fig. 11. Conceptual model map of the contribution of climate change and human activities to runoff.

the hydrological response process in the region more volatile and recurrent, and the impact of human activities on hydrological cycle processes can no longer be overlooked [53-55].

Yan et al. [56] noticed that climate change and human activities contributed 75.3% and 24.7%, respectively, to runoff changes in the SRYR using the Budyko hypothesis, which was mostly consistent with the results of our study (Fig. 11). In comparison, we evaluated the change patterns of influencing factors not only in terms of time change but also in terms of spatial change. Further, we also explored the specific situation of land use, population, and GDP change, and the time series was longer.

The completion of Sanjiangyuan National Park resolutely guarantees the enhancement of the ecological environment [57]. Reversing conflict between humans and the environment requires not only the self-regulation of the natural environment but also the rational use of natural resources [49].

Conclusions

Based on runoff data from Tangnaihai station, meteorological data, land-use data, population data and GDP data, this study evaluated the temporal variation characteristics of runoff. We also inspected the response of runoff to climate change and quantified the contributions of climate change and human activities to runoff changes in the SRYR, and the following conclusions were drawn. Annual average temperature, precipitation and evaporation increased by 0.46ºC×(10 a)$^{-1}$, 9.63 mm×(10 a)$^{-1}$ and 13.4 mm×(10 a)$^{-1}$ during 1961-2018. Annual runoff depicted an overall decreasing trend with a rate of 6.3×10^{8} m^{3}×(10a)$^{-1}$ during 1961-2018, but with 1990 as the boundary, annual runoff indicated increasing trends with rates of 5.8×10^{8} m^{3}×(10a)$^{-1}$ and 18.6×10^{8} m^{3}×(10a)$^{-1}$ during 1961-1990 and 1991-2018, respectively, the latter being 3.2 times higher than the former. The overall trend of the runoff change indicated an increase during (1961-1990), decrease during (1991-2005), and again an increase during (2006-2018).

The intra-annual distribution of runoff depicted the "Double Peak" effect, with the two peaks of runoff advancing by 15 and 6 days, respectively, due to the influence of freeze-thaw processes in cold regions. The impact of precipitation and evaporation on runoff reduced, whereas the influence of temperature on runoff increased after 1990. Temperature and runoff demonstrated a negative correlation in 1961-1990 and a positive correlation in 1991-2018, indicating a change in the effect of temperature on runoff changes. The contribution of precipitation to runoff was 74.2% and the temperature was 25.8 % during 1961-2018. The overall temperature contribution to runoff amplified by 7.5% from 1991 to 2018 compared to 1961-1990, with larger increases in February, April, November, and December of 25.9%, 11.0 %, 8.2%, and 8.5%, respectively.

The contributions of climate change and human activities to runoff changes were 72.9 % and 27.1 %, respectively, using PCA during 1961-2018, implying that runoff processes were predominantly influenced by climate change in the SRYR. The relative moisture index was -0.39 during 1961-1990 and -0.4 during 1991-2018, and the combined effect of climate change showed a warm and dry trend, with a spatial distribution of wetness in the northwest and aridity in the southeast of the SRYR. The changes in present study area provided evidence of accelerated global warming post 1990.

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Conflict of Interest

The authors declare no conflict of interest.

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