Climate Change and Its Runoff Response in the Central Qilian Mountains over the Past 60 Years (Postprint)

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Abstract

Using hydrological and meteorological data from 1960–2017, this study investigates variation characteristics of climate and runoff in the central Qilian Mountains employing correlation analysis, Mann-Kendall test, and wavelet analysis methods. The results indicate: (1) Over the past 60 years, temperature, precipitation, and runoff in the central Qilian Mountains have generally exhibited trends of rising temperature, increasing precipitation, and growing runoff. The annual mean temperature has increased at a rate of 0.39 ℃ · $(10\ \mathrm{a})^{-1}$, with significant warming trends across all four seasons, and the most pronounced warming observed in annual mean minimum temperature and winter temperature. Precipitation has increased by approximately 19.2%, primarily attributed to enhanced summer precipitation. (2) The mean temperature experienced an abrupt change in 1993, earlier than in other regions of northwestern China. The dominant periods of temperature and precipitation are 8 a and 30 a, respectively. In the periodic response of runoff, the short-period component (8 a) shows strong consistency with temperature oscillations, while the long-period component (30 a) aligns well with annual precipitation variations. (3) Analysis demonstrates that both precipitation and temperature are major factors influencing runoff variation. The established runoff prediction model achieves a Nash-Sutcliffe efficiency coefficient of 0.68, demonstrating good capability in analyzing and predicting runoff. Changes in precipitation and temperature have increased runoff by 21.1% and 10.9%, respectively, with precipitation exerting a greater influence on runoff.

Full Text

Climate Change and Its Runoff Response in the Middle Section of the Qilian Mountains in the Past 60 Years

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Abstract

Based on hydrological and meteorological data from 1960 to 2017, the characteristics of climate and runoff variations in the middle section of the Qilian Mountains were studied using correlation analysis, Mann-Kendall mutation test, and wavelet analysis methods. The results show that over the past 60 years, temperature, precipitation, and runoff in the middle Qilian Mountains have generally exhibited increasing trends. The annual average temperature rose at a rate of $0.39°\text{C} \cdot (10\ \text{a})^{-1}$, with the annual minimum temperature increasing more significantly than both the maximum and average temperatures. Temperature increased across all seasons, particularly in winter. Precipitation increased by approximately 19.2%, with the increase mainly attributed to enhanced summer precipitation. The climate demonstrates a clear warming and humidifying trend, with winter warming and summer humidification being particularly pronounced. Mutation analysis revealed that the average temperature underwent an abrupt change in 1993, earlier than in other regions of northwestern China. The main periods for temperature and precipitation were 8 years and 30 years, respectively. In the runoff periodic response, the short period (8 years) aligns closely with average temperature oscillations, while the long period (30 years) aligns with annual precipitation variations. Further simulation results confirmed that both precipitation and temperature are key factors affecting runoff. The established runoff prediction model achieved a Nash efficiency coefficient of 0.68, demonstrating its capability for runoff analysis and prediction. Precipitation and temperature contributed to runoff increases of 21.1% and 10.9%, respectively, with precipitation exerting a greater influence on runoff.

Keywords: climate change; runoff; Mann-Kendall test; Heihe River; Qilian Mountains

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1. Study Area Overview

The Qilian Mountains, located on the northeastern edge of the Qinghai-Tibet Plateau, feature complex terrain and abundant cloud water resources, nurturing numerous high-altitude glaciers and snowpacks that serve as the headwaters for inland rivers such as the Heihe, Shiyang, and Shule Rivers. Previous studies have indicated that runoff changes in the Heihe River basin are representative of the response mechanisms to precipitation variations in the Qilian Mountains region. The Heihe River, spanning 102°06 E to 97°37 E and 42°40 N to 37°44 N with a main stream length of approximately 821 km, flows through Qinghai, Gansu, and Inner Mongolia provinces. The Heihe River basin is divided into three sections: the upper runoff generation area, the middle water consumption area, and the lower river-lake tail disappearance area. The Yingluoxia Hydrological Station serves as the boundary between the upper and middle reaches and provides representative measurements of Heihe River outflow. The basin exhibits complex topography and geomorphology with significant elevation differences, displaying pronounced climatic zonality and regional characteristics.

2. Data and Methods

2.1 Data

Based on the distribution of the Heihe River’ s upper source region, this study selected six meteorological stations (Tuole, Yeniugou, Qilian, Menyuan, Sunan, and Minle) and the Yingluoxia Hydrological Station as representative sites (Table 1). Monthly temperature, precipitation, and runoff data from 1960 to 2017 were used as the research dataset. Following seasonal division standards (March-May for spring, June-August for summer, September-November for autumn, and December-February for winter), monthly, seasonal, annual, and annual average values and anomalies were calculated to analyze variation characteristics. The six meteorological stations are distributed across the northern and southern slopes of the mountain range (Figure 1), providing a comprehensive representation of the climate conditions in the middle Qilian Mountains. Runoff data from Yingluoxia Hydrological Station for corresponding monthly, seasonal, and annual periods were used to represent upstream runoff in the Heihe River.

[Figure 1: see original paper]

2.2 Analysis Methods

This study employed the least squares method, Mann-Kendall (M-K) rank correlation analysis, and wavelet analysis to examine linear trends, mutation points, and periodic variations in runoff, precipitation, and temperature. In recent years, Mann-Kendall rank correlation analysis and wavelet analysis have been widely applied to periodic analysis of climatic and hydrological time series. The Mann-Kendall method analyzes temporal trends (increasing or decreasing) and identifies mutation points in data series. Through significance testing at confidence levels, it determines variation trends and mutation points for runoff, precipitation, and temperature. Wavelet analysis accurately reveals variation characteristics of analytical objects along temporal sequences and identifies primary time scales (periods) for each variable.

3. Results and Discussion

3.1 Temperature Variation Characteristics

Over the past 60 years, the temperature in the middle Qilian Mountains has shown an overall increasing trend (Figure 2). From the perspective of decadal average changes, temperatures have continuously risen since the 1960s. After 1997, the annual average temperature anomaly turned positive and continued to increase, consistent with global trends. The average temperature in the middle Qilian Mountains increased by 0.81°C since the 1960s, significantly exceeding the global average warming magnitude. The warming rates for annual average, maximum, and minimum temperatures were $0.39°\text{C} \cdot (10\ \text{a})^{-1}$, $0.32°\text{C} \cdot (10\ \text{a})^{-1}$, and $0.46°\text{C} \cdot (10\ \text{a})^{-1}$, respectively, with the minimum temperature showing the highest rate. Domestic research on temperature changes in China indicates that against the backdrop of global warming, the national average warming rate over the past 120 years was $0.25°\text{C} \cdot (10\ \text{a})^{-1}$, while the northwestern region' s average warming rate was $0.32°\text{C} \cdot (10\ \text{a})^{-1}$, with western China temperatures rising approximately 1.2°C over the past 100 years. The warming rate in the middle Qilian Mountains is significantly higher than in other northwestern regions, demonstrating pronounced climate warming characteristics.

The annual average temperature anomaly percentage variation curve reveals that during the 1960s-1970s, temperatures in the middle Qilian Mountains were generally low, particularly in the 1960s when the average temperature anomaly reached -0.71°C, representing the coldest period in the basin over the past 60 years (Table 2). The temperature anomaly shifted from negative to positive in the mid-1990s and has remained positive since, indicating continuous warming. Mann-Kendall test results (Figure 4) show that annual average, maximum, and minimum temperatures all exhibited fluctuating upward trends, though with slightly different mutation times. The 1990s represented a turning point for temperature, after which temperature anomalies became positive and continued increasing. All three temperature variables passed significance tests at the 0.05 level, with the annual minimum temperature mutation occurring slightly earlier, indicating greater sensitivity to global warming. The temperature mutation in the middle Qilian Mountains preceded that in other northwestern regions of China. Wavelet analysis (Figure 5) reveals that the annual average temperature series exhibits periodic oscillations of 8 years and 30 years, with the 8-year period being most significant as the primary period and 30 years as the secondary period.

Seasonal temperatures in the middle Qilian Mountains all show fluctuating upward trends, though with considerable seasonal differences (Figure 3). The interannual variation rates for spring, summer, autumn, and winter temperatures were $0.35°\text{C} \cdot (10\ \text{a})^{-1}$, $0.31°\text{C} \cdot (10\ \text{a})^{-1}$, $0.33°\text{C} \cdot (10\ \text{a})^{-1}$, and $0.50°\text{C} \cdot (10\ \text{a})^{-1}$, respectively, with winter showing the most significant increase, followed by summer, autumn, and spring. Winter demonstrates a more pronounced response to global warming compared to other seasons.

3.2 Precipitation Variation Characteristics

Over the past 60 years, precipitation in the middle Qilian Mountains has shown a significant increasing trend, with the multi-year average precipitation being 376 mm. Precipitation increased by 19.2% after the 1960s, at a rate of 13.2 mm $\cdot$ $(10\ \mathrm{a})^{-1}$, slightly higher than the increase in northwestern China. Precipitation increased by approximately 72 mm over the 60-year period. From a decadal perspective (Figure 2), precipitation was relatively low in all decades except the 1980s, with the 1970s being the driest. After the 21st century, precipitation increased significantly. Combined with temperature analysis, the middle Qilian Mountains experienced alternating periods of cold-dry, cold-wet, warm-dry, and warm-wet conditions. Since 2000, characterized by high temperatures and abundant precipitation, the region has shown clear warm-humidification features.

Mann-Kendall test results (Figure 6) indicate that precipitation has shown an increasing trend since 1970, with multiple intersection points between UF and UB curves, though no clear mutation time is evident, reflecting the random and discontinuous nature of precipitation. Periodic analysis (Figure 5) reveals precipitation cycles of 8 years and 30 years, with the 30-year cycle being dominant and 8 years secondary. Due to complex topographic conditions and significant seasonal differences in water vapor conditions across the four seasons, precipitation distribution varies considerably. Summer precipitation accounts for the largest proportion at 61.2% of annual total, while winter precipitation is the smallest at only 3.2%. All four seasons show increasing precipitation trends at rates of 1.5 mm $\cdot$ $(10\ \mathrm{a})^{-1}$, 8.2 mm $\cdot$ $(10\ \mathrm{a})^{-1}$, 2.0 mm $\cdot$ $(10\ \mathrm{a})^{-1}$, and 1.0 mm $\cdot$ $(10\ \mathrm{a})^{-1}$ for spring, summer, autumn, and winter, respectively. The increase in annual precipitation is primarily caused by increased summer precipitation. Monthly precipitation varies significantly, with June, July, and August each exceeding 63 mm, while other months have relatively small amounts. The interannual change tendency rate shows increases across all months, with July showing the largest increase, followed by August and June.

3.3 Runoff Variation Characteristics

Runoff in the Heihe River shows an overall increasing trend (Figure 7). Summer runoff accounts for the largest proportion at 52.8% of annual total, followed by autumn and spring, with winter being the smallest at only 13.5%. All four seasons show increasing runoff trends. Runoff was lowest in the 1970s, 21.2% below the multi-year average, and reached its maximum in the 2000s, 13.5% above average. After entering the 21st century, runoff increased significantly. Monthly runoff distribution shows a clear "single-peak" pattern, concentrated in June-October with a peak in August. All months show increasing interannual change tendency rates, with August having the highest rate at 0.21 $\mathrm{m}^3 \cdot (10\ \mathrm{a})^{-1}$, followed by July and September, consistent with precipitation patterns, indicating that runoff increase is closely related to summer precipitation increase.

Mann-Kendall test results (Figure 6) show that annual runoff mutation occurred in 1993. After 1993, UF values exceeded 1.96, indicating a significant increasing trend. Periodic analysis (Figure 5) reveals runoff oscillations with periods of 8 years and 30 years, with 8 years as the primary period and 30 years as secondary. The short period aligns with temperature, while the long period aligns with precipitation.

3.4 Hydrological Effects of Climate Change

Climate is the primary factor influencing runoff variation. Basin runoff is affected by precipitation, temperature, evaporation, glacier and snowmelt, groundwater, and other factors, with precipitation and temperature changes directly impacting runoff recharge. Analysis shows that over the past 60 years, the middle Qilian Mountains have experienced increased precipitation and rising temperatures, which inevitably affect Heihe River runoff. Correlation coefficients between monthly runoff at Yingluoxia and upstream precipitation, average temperature, minimum temperature, and maximum temperature (Table 3) show significant positive correlations, all passing α=0.01 significance tests. Runoff increase is closely related to increased basin precipitation and rising temperatures, with higher temperatures causing more glacier and snowmelt, thereby increasing runoff recharge.

To quantify the impacts of precipitation and temperature changes on runoff, we established correlation models using stepwise regression analysis. Model 1 used monthly average precipitation and monthly average temperature as climatic parameters; Model 2 used annual precipitation, annual average temperature, annual maximum and minimum temperatures, and seasonal precipitation and temperature as climatic parameters. Model 2 performed better based on correlation coefficients, single-tailed significance probabilities, and model fit. The established model is:

$$Ra = 0.046 \times Pa + 0.801 \times Ta$$

where Ra is runoff, Pa is annual precipitation, and Ta is annual average temperature. The correlation coefficients are 0.801 and 0.046, respectively, with small single-tailed significance probabilities. Figure 8 compares measured and model-calculated annual runoff, with the Nash efficiency coefficient reaching 0.68, indicating good agreement between simulated and observed runoff and validating the model for runoff prediction and impact factor analysis.

Using the established model, we calculated the impacts of precipitation and temperature changes on runoff. Taking 1993 as the mutation year, we analyzed the differences before and after this point. Before 1993, runoff was positively correlated with precipitation but negatively correlated with temperature; after 1993, runoff showed positive correlations with both, with the correlation coefficient with precipitation further increasing, indicating that warming and humidification effects on runoff enhancement gradually intensified.

To further analyze the contribution of each factor, we calculated the actual linear increase rates of the two factors over the past 60 years. Compared to the multi-year average runoff, increased precipitation and rising temperature contributed to runoff increases of 5.33\$×10^{8}\$ m^{3} and 2.76\$×10^{8}\$ m^{3}, respectively, corresponding to 21.1% and 10.9% increases. Precipitation exerts a greater influence on runoff. Using 1993 as a boundary, the impacts of annual precipitation and temperature on runoff both increased significantly after this year. As upstream precipitation continues to increase, Heihe River runoff will continue to rise; meanwhile, temperature increases will enhance ice and snowmelt, further augmenting runoff.

4. Conclusions

1) Over the past 60 years, temperature in the middle Qilian Mountains has shown a significant increasing trend, with annual average, maximum, and minimum temperatures rising at rates of 0.39°C · (10 a)$^{-1}$, 0.32°C · (10 a)$^{-1}$, and 0.46°C · (10 a)$^{-1}$, respectively. The warming rate exceeds that of other northwestern regions, with minimum temperature showing the largest increase. Temperature increased across all seasons, with winter warming being most pronounced.

2) Precipitation in the middle Qilian Mountains shows a significant increasing trend, with a 19.2% increase over the past 60 years, higher than the northwestern regional average. Seasonally, summer precipitation increased at the highest rate, making the increase in annual precipitation primarily attributable to enhanced summer precipitation. The climate warming and humidification trend is more pronounced in the middle Qilian Mountains than elsewhere in the northwestern region, characterized by winter warming and summer humidification.

3) Mutation analysis indicates that while precipitation mutation time is not obvious, annual average, minimum, and maximum temperatures mutated in 1993, 1989, and 1997, respectively, with temperature mutation preceding that of other northwestern regions.

4) Both precipitation and temperature affect runoff. Under the influence of increased precipitation and rising temperatures, runoff in the upper Heihe River shows a clear increasing trend. The correlation model established through analysis effectively simulates runoff and its influencing factors, enabling runoff prediction. Model results confirm that precipitation and temperature increased runoff by 21.1% and 10.9%, respectively, with precipitation having a greater impact. After the temperature mutation, the effects of both precipitation and temperature on runoff increased significantly.

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