Variation Characteristics of Runoff in the Hotan River Headwaters, 1957-2018 (Postprint)

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Date: 2021-04-23T00:00:00+00:00

Abstract

Runoff evolution characteristics are of great significance to watershed water resources management and development and utilization. Based on 62-year long-term observed runoff data from 1957 to 2018 at the Uluwati and Tongguziluoke stations in the source region of the Hotan River, and using linear trend analysis, Mann-Kendall trend test, and rescaled range analysis (R/S analysis) methods, the runoff evolution characteristics in the source region of the Hotan River were analyzed from four temporal scales: interdecadal, interannual, seasonal, and monthly. The results show that the interdecadal variation characteristics of runoff at the Uluwati and Tongguziluoke stations are consistent, both experiencing "normal water year to relatively abundant water year"; both stations exhibit an insignificant increasing trend in annual runoff, with the abrupt change point of the runoff series being 2009, and the annual runoff continues to increase for a certain period; at the Uluwati station, changes in summer and autumn runoff have the greatest impact on annual runoff, while at the Tongguziluoke station, summer runoff has the greatest impact on annual runoff; the intra-annual distribution of runoff is uneven, mainly concentrated from May to September, accounting for 86.11%-90.86%, showing a pattern of "dry winter and flood summer".

Full Text

Evolution Characteristics of Runoff in the Headstream of the Hotan River from 1957 to 2018

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Abstract: The evolution characteristics of river runoff are of great significance for watershed water resource management and development. Based on 62 years (1957-2018) of measured monthly runoff data from Wuluwati station and Tongguziluoke station in the headstream area of the Hotan River, this study analyzed the runoff evolution characteristics using linear trend analysis, Mann-Kendall trend tests, and rescaled range analysis across four temporal scales: interdecadal, annual, seasonal, and monthly. The results indicate that the interdecadal variation patterns at both stations were consistent, showing a transition from "normal water years" to "preferential wet years." Both stations exhibited nonsignificant increasing trends in annual runoff, with mutation points identified in 2009, after which runoff continued to increase for a period. At Wuluwati station, summer and autumn runoff changes had the greatest impact on annual runoff, while at Tongguziluoke station, summer runoff had the greatest impact. Runoff distribution within the year was highly uneven, concentrated mainly in May–September, accounting for 86.11%-90.86% of the total, showing a "dry winter and flood summer" pattern.

Keywords: Hotan River; linear trend; runoff change; Mann-Kendall test; rescaled range analysis

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1.1 Study Area Overview

The Hotan River basin is located in southern Xinjiang, at the northern foothills of the Kunlun Mountains on the southern edge of the Tarim Basin, with a total catchment area of 2.6×10^{4} km^2. The Hotan River consists of two major tributaries: the western Karakash River and the eastern Yurungkash River, forming the second largest river system on the northern slope of the Kunlun Mountains. Both tributaries flow northward into the Tarim Basin, cross the Taklamakan Desert, and eventually converge into the Tarim River. The Yurungkash River has a total length of 504 km, with the Tongguziluoke hydrological station (hereinafter referred to as Tongguziluoke station) located at its mountain pass. The Karakash River extends 808 km, with the Wuluwati hydrological station (hereinafter referred to as Wuluwati station) at its outlet. The section from the confluence at Koshlash to Xiaojieke is called the main stream, spanning 319 km as a seasonal river. The primary sources of water supply for the Hotan River are glacier and snow meltwater, supplemented by minor summer precipitation. The combined multi-year average runoff of the two tributaries is approximately 43×10^{8} m^3, with 4.29×10^{8} m^3 of plain area groundwater resources. Summer runoff accounts for over 80% of the total annual flow, showing substantial intra-annual variation. The basin features an arid climate with scarce precipitation (multi-year average of 39.6 mm) and high evaporation (multi-year average of 2648.7 mm measured with a 20 cm evaporation pan).

1.2 Data Sources and Methods

Wuluwati station and Tongguziluoke station were selected as representative stations for analysis, using monthly runoff data from 1957 to 2018. Tongguziluoke station provides multi-year measured records, while Wuluwati station required restoration of natural runoff data because the Wuluwati Water Control Project (an incomplete annual regulation reservoir), constructed in 1995, altered the natural runoff characteristics. Using the itemized investigation method, the monthly runoff was restored. Located at the mountain pass with minimal industrial, agricultural, or domestic water consumption, Wuluwati station only required restoration for reservoir evaporation and seepage losses based on hydrological yearbooks and interpolation from adjacent hydrological stations.

For analysis purposes, annual runoff anomaly values (K) were classified into five categories: K $>$ 20% (wet year), 10% $\leq$ K $<$ 20% (preferential wet year), -10% $\leq$ K $<$ 10% (normal year), -20% $\leq$ K $<$ -10% (preferential dry year), and K $<$ -20% (dry year).

1.2.1 Mann-Kendall Trend Test The Mann-Kendall test is a non-parametric method recommended by the World Meteorological Organization for analyzing long-term hydrological and climatic time series. It offers robustness against interference from outliers and can identify significant trends and mutations, making it widely applicable in hydrology. The test uses the statistical value Z for significance testing of surface runoff trends. Under the null hypothesis of no trend, if the test passes a two-tailed test at a given significance level, the critical value is obtained from the normal distribution table. If $|Z| > Z_1\ \alpha/_2$, the null hypothesis is rejected, indicating a significant trend. $Z > 0$ indicates an increasing trend, $Z < 0$ indicates a decreasing trend, and larger absolute values of Z suggest stronger trends. By analyzing the statistical sequences UF and UB , the method reveals trend changes and mutation characteristics. If UF $>$ 0, runoff shows an increasing trend; if UF exceeds the critical value, the trend is significant. Intersection points between UF and UB within the critical lines indicate potential mutation points where the sequence begins to change.

1.2.2 Rescaled Range Analysis (R/S) The Hurst exponent effectively describes time series dependence and is commonly used to determine the degree to which future trends vary from past trends. This study employed rescaled range analysis (R/S) to obtain the Hurst exponent. The method divides the time series into intervals and standardizes the data within each interval. Assuming the interval length is N, with log(N) as the independent variable and log(R/S) as the dependent variable, linear regression yields a slope representing the Hurst exponent H. When $H = 0.5$, the time series changes randomly; when $0.5 < H <$

1, future trends persist as past trends; when $0 < H < 0.5$, future trends reverse from past trends. The V statistic determines periodic cycles: if the V curve transitions abruptly from rising to flat or declining, the influence of past trends on future trends disappears at that point. The V statistic is calculated as $V = (R/S) /\sqrt{n}$, where n is the variable sub-interval and N is the interval length.

2.1 Interdecadal Variation Characteristics of Annual Runoff

The annual runoff data from 1957 to 2018 at Wuluwati and Tongguziluoke stations were divided into six periods (Tables 1 and 2). At Wuluwati station, the mean runoff in the 1960s, 1970s, and 1980s was below the multi-year average, with the 1970s showing the lowest value. The mean runoff in other periods exceeded the multi-year average, with the 2010s showing a preferential wet year at 2.98$\times10^{8}$ m^3, 4.44% above the multi-year average. At Tongguziluoke station, the mean runoff in the 1960s, 1970s, and 1980s was also below the multi-year average, while the 1990s marked the beginning of a wet period, exceeding the multi-year average by 4.44%. Overall, the interdecadal variation trends at both stations were consistent: below the multi-year average from the 1960s to 1980s, and above from the 1990s to 2010s, experiencing a "normal water year-preferential wet year" transition with clear demarcation points. This pattern aligns with Wang' s finding of increased runoff in western Xinjiang showing a "U-shaped" change.

2.2 Annual Runoff Evolution Characteristics

The annual runoff at both stations from 1957 to 2018 showed increasing rates of 0.46$\times10^{8}$ m^3/(10a) at Wuluwati station and 0.52$\times10^{8}$ m^3/(10a) at Tongguziluoke station (Figure 2). The Mann-Kendall test yielded Z values of 1.42 and 1.37, respectively, indicating nonsignificant increasing trends. At Wuluwati station, the maximum and minimum annual runoff values were 31.85$\times10^{8}$ m^3 and 12.28$\times10^{8}$ m^3, respectively, with an extreme ratio of 2.59 and a variation coefficient of 0.26. At Tongguziluoke station, the maximum and minimum values were 37.12$\times10^{8}$ m^3 and 12.25$\times10^{8}$ m^3, respectively, with an extreme ratio of 3.03 and a variation coefficient of 0.29. The moving average trend lines show that Wuluwati station experienced slow fluctuations with a "wet-dry-wet" pattern, while Tongguziluoke station showed larger fluctuations with a "sawtooth" pattern but overall persistent wet years.

The Mann-Kendall mutation test results show that UF and UB curves intersected within the $\pm$1.96 critical lines in 2009 at Wuluwati station, indicating a potential mutation point after which persistent wet years occurred (Figure 3). Similarly, the UF and UB curves for Tongguziluoke station intersected within the critical lines in 2009, suggesting a mutation point for annual runoff (Figure 3). To further verify the mutation timing, cumulative anomaly analysis was applied, revealing that after brief wet-dry alternations, both stations showed sharp declines entering dry years. Influenced by climate change, they experienced a 30-year dry period (1979–2009) before entering a wet period after the 2009 mutation, confirming the Mann-Kendall test results.

Rescaled range analysis can predict future trends and durations. The Hurst exponent for Wuluwati station is 0.65, indicating positive weak persistence—annual runoff will continue increasing for a period. The V statistic shows the first inflection point at n = 1.94, indicating continued increase. Tongguziluoke station has a Hurst exponent of 0.68 with the first inflection at n = 2.19, also indicating continued increase. Both stations will experience increasing annual runoff in the near future.

2.3 Seasonal Runoff Variation Characteristics

Seasonal runoff variation is crucial for water resource allocation and utilization. All four seasons at both stations showed increasing trends, though with different magnitudes. At Wuluwati station, the increasing rates were 0.16$×10^{8}$ m^3/(10a) in spring, 0.13$×10^{8}$ m^3/(10a) in summer, 0.08$×10^{8}$ m^3/(10a) in autumn, and 0.08$×10^{8}$ m^3/(10a) in winter. Autumn showed the largest increase, while summer and winter showed the smallest. From 1957 to 2018, spring, summer, autumn, and winter runoff increased by 0.99$×10^{8}$ m^3, 0.81$×10^{8}$ m^3, 0.99$×10^{8}$ m^3, and 0.50$×10^{8}$ m^3, respectively, indicating that autumn runoff had the greatest impact on annual runoff. In terms of interannual anomaly percentages, spring runoff at Wuluwati station was lowest in 1985 (23.8% below mean) and highest in 2010 (21.6% above mean); summer runoff was lowest in 1979 (20.2% below mean) and highest in 2010 (18.4% above mean); autumn runoff was lowest in 1985 (17.2% below mean) and highest in 2009 (21.6% above mean); winter runoff was lowest in 1967 (40.0% below mean) and highest in 2009 (44.0% above mean).

At Tongguziluoke station, all seasons also showed increasing trends, with the largest increase in summer at 0.20$×10^{8}$ m^3/(10a), followed by spring and autumn at 0.16$×10^{8}$ m^3/(10a), and winter at 0.08$×10^{8}$ m^3/(10a). From 1957 to 2018, spring, summer, autumn, and winter runoff increased by 0.99$×10^{8}$ m^3, 1.24$×10^{8}$ m^3, 0.99$×10^{8}$ m^3, and 0.50$×10^{8}$ m^3, respectively, indicating summer had the greatest impact on annual runoff. Seasonal interannual anomaly percentages varied across decades, with summer and autumn showing larger variations while spring and winter showed clear "dry-wet" stage changes consistent with annual runoff trends. Research indicates that the warming and wetting trend in Northwest China' s arid regions is evident, with spring and autumn contributing 21.6% and 18.4% to annual precipitation changes, respectively, explaining why spring and autumn runoff showed the largest increases.

2.4 Monthly Runoff Evolution Characteristics

The multi-year average monthly runoff distribution shows that both stations have a "single-peak" pattern with extremely uneven intra-annual allocation, concentrated in May–September (Figure 7). At Wuluwati station, August had the maximum monthly runoff, while at Tongguziluoke station, July was the peak month, accounting for 33.37% and 28.18% of annual runoff, respectively. The combined runoff from May to September accounted for 86.25% at Wuluwati station and 90.86% at Tongguziluoke station. Under global climate change, both stations exhibited a "dry season increase, wet season decrease" pattern. The Mann-Kendall trend test for monthly runoff (Figure 8) shows increasing trends in most months, though the increasing trend during flood season was significantly smaller than in dry season. The significant increasing trends in dry season months are a major factor contributing to the overall increasing annual runoff trends at both stations.

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3 Discussion

This study systematically analyzed interdecadal, annual, seasonal, and monthly runoff variations at Wuluwati and Tongguziluoke stations in the Hotan River headstream area using restored natural runoff data over a relatively long time series. Compared with previous studies, Huang Lingmei et al. used 1957–2007 data, while Dong Diwen et al. used 1957-2015 data, both concluding that annual runoff showed nonsignificant decreasing trends. However, this study found a nonsignificant increasing trend due to the different time series selected, though it validates Dong Diwen' s conclusion that runoff will increase in the near future. The differences in trend and mutation timing from previous studies are partly attributable to the different periods analyzed.

Both stations are located at mountain passes where climate is the primary factor influencing runoff changes, with temperature and precipitation jointly determining annual surface runoff. Research indicates that temperature serves as the "barometer" of runoff changes in the Hotan River. The headstream area contains extensive modern glaciers that regulate runoff, evidenced by low variation coefficients (0.26–0.29), indicating glacier and snow melt are the primary water sources. The interannual runoff variation shows a clear transition from dry to wet periods. After 1993, Northwest China experienced a temperature "mutation-type" increase, but the cumulative anomaly curve shows a declining trend entering a dry period after 1979. Most scholars attribute this dry period to the 0.17 $m \cdot a^{-1}$ decrease in 0°C level height, which inhibited mountain ice and snow melting, combined with scarce precipitation. After 2009, increased temperatures accelerated glacier melting and enhanced warm-wet conditions, with increased mountain precipitation and heavy rainfall events driving the runoff transition from dry to wet.

Seasonal evolution shows that all four seasons at both stations exhibited increasing trends. At Wuluwati station, autumn runoff increase contributed most to annual runoff, while at Tongguziluoke station, summer runoff increase was the dominant contributor. Spring and autumn runoff changes are influenced by both temperature and seasonal precipitation. The Hotan River headstream runoff is supplied by glacier meltwater (59.50%), precipitation (20.95%), and groundwater (19.55%). Although the underlying surface and climate factors are similar across the headstream area, their distribution to the Karakash and Yurungkash Rivers differs. Wuluwati station' s annual runoff increase rate [0.46$\times10^{8}$ m^3/(10a)] is smaller than Tongguziluoke station' s [0.52$\times10^{8}$ m^3/(10a)], primarily due to different proportions of glacier/snow meltwater and groundwater contributions, with the Karakash River showing better stability than the Yurungkash River in interannual variation.

Rescaled range analysis indicates that annual runoff will continue in a wet period for some time, though with considerable uncertainty in intra-annual variations. Given the Hotan River basin' s unique geographical environment and complex climate changes, the amplitude of water resource variations caused by climate change will intensify conflicts between water resource development management and ecological sustainability. Future research should scientifically and rationally allocate water resources quantitatively under climate and human activity influences to actively respond and adapt to potential climate change impacts, ensuring ecological security and sustainable economic development in the "Hotan Oasis."

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4 Conclusions

Using natural runoff data from Wuluwati and Tongguziluoke stations in the Hotan River headstream, this study analyzed the runoff evolution process from 1957 to 2018 across interannual, seasonal, and monthly scales. The main conclusions are:

1) Both Wuluwati and Tongguziluoke stations showed mean runoff below the multi-year average during the 1960s–1980s (normal water years) and above the multi-year average during the 1990s–2010s (preferential wet years), demonstrating an interdecadal "normal water year–preferential wet year" evolution pattern.

2) Annual runoff in the Hotan River headstream area is extremely unevenly distributed, concentrated in the flood season (May–September), accounting for over 86% of annual runoff. The intra-annual pattern shows "dry winters and flood summers," making the basin prone to flood and drought disasters. This highlights the importance of increased water conservancy investment and construction of storage projects for efficient water resource utilization.

3) Both stations exhibited nonsignificant increasing trends in annual runoff,

with mutation points in 2009 marking a transition from dry to wet periods. Hurst exponents greater than 0.5 indicate that runoff will continue increasing for a period.

4) Seasonal runoff at both stations showed increasing trends, with autumn runoff having the greatest impact on annual runoff at Wuluwati station and summer runoff having the greatest impact at Tongguziluoke station. Monthly runoff showed increasing trends in most months, with more pronounced increases in dry season months.

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Note: Figure translations are in progress. See original paper for figures.