Postprint of Runoff Variation and Attribution Analysis in the Zuli River Mainstream over the Past 65 Years

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Abstract

Based on monthly and annual runoff data measured from 1957 to 2021 at three national basic hydrological stations (Huining, Guochengyi, and Jingyuan) on the main stream of the Zuli River, this study employed methods such as linear trend estimation, Mann-Kendall test, and wavelet analysis to investigate runoff variation patterns at different time scales in the Zuli River basin and conducted attribution analysis of runoff reduction. The results show that: (1) During the period 1957–2021, the runoff of the Zuli River main stream exhibited a decreasing trend, with a 52.9% reduction in runoff over the past 30 years. (2) The measured annual runoff at the three hydrological stations of Huining, Guochengyi, and Jingyuan experienced abrupt changes in 1992, 1984, and 1994, respectively. (3) The runoff at the three stations on the Zuli River main stream and precipitation displayed similar wet-dry cycles. The analysis results indicate that the reduction in measured annual runoff of the Zuli River main stream was primarily influenced by human activities such as soil and water conservation measures, followed by climatic factors such as precipitation reduction, with human activities and climate change contributing 74.47% and 25.53% to the runoff reduction, respectively.

Full Text

Analysis of Runoff Variation and Attribution in the Main Stream of Zuli River over the Past 65 Years

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Abstract

Based on monthly and annual runoff data measured from 1957 to 2021 at three national basic hydrological stations (Huining, Guochengyi, and Jingyuan) in the main stream of the Zuli River, this study employed linear trend estimation, Mann-Kendall test, and wavelet analysis to investigate runoff variation patterns at different time scales in the Zuli River Basin and conducted attribution analysis of runoff reduction. The results show that: (1) Runoff in the main stream of the Zuli River exhibited a decreasing trend during 1957-2021, with a 52.9% reduction over the past 30 years. (2) The measured annual runoff at Huining, Guochengyi, and Jingyuan stations underwent abrupt changes in 1992, 1984, and 1994, respectively. (3) Runoff and precipitation showed similar wet-dry cycles at the three stations. The analysis indicates that the reduction in measured annual runoff in the main stream of the Zuli River is mainly influenced by human activities such as soil and water conservation measures, followed by climatic factors like precipitation reduction. The contribution rates of human activities and climate change to runoff reduction are 74.47% and 25.53%, respectively.

Keywords: human activities; climate change; runoff; attribution analysis; main stream of Zuli River

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Introduction

River runoff is not only an important component of the hydrological cycle but also a crucial factor affecting ecological environment changes and socio-economic development. In recent years, against the backdrop of intensified climate change and human activities, watershed water cycle processes and spatiotemporal distribution patterns of water resources have undergone significant changes, making river hydrological characteristics more complex. Northwest China is an arid region with scarce water resources and fragile ecological environment, which severely restricts regional sustainable economic development. The Zuli River, as a first-level tributary of the Yellow River's upper reaches, is located in the semi-arid region of the Loess Plateau. Over the past 65 years, human activities such as soil and water conservation measures have altered the underlying surface, increased the watershed's water retention capacity, and caused a sharp reduction in river runoff with frequent drying phenomena. Understanding the runoff evolution characteristics of the Zuli River Basin over recent decades is crucial for rational water resource utilization. Therefore, research on runoff variation characteristics in the main stream of the Zuli River is urgently needed.

Although numerous scholars have conducted research on runoff variation in the Zuli River Basin, previous studies have mostly focused on limited aspects such as trend and abrupt change analysis, and have concentrated on either the upstream Huining station or downstream Jingyuan station. Few scholars have conducted comprehensive attribution analysis from both climate change and human activity perspectives. With global warming and intensified human activities, the

Zuli River Basin faces the threat of flow interruption. Comprehensive analysis of runoff evolution patterns in the main stream of the Zuli River over the past 65 years under changing environmental conditions is of great significance. Therefore, this study selected Huining, Jingyuan, and Guochengyi stations in the main stream of the Zuli River, used long-series monthly and annual runoff data, and employed linear trend estimation, Mann-Kendall test, wavelet analysis, and other methods to scientifically analyze interannual and seasonal runoff variation patterns in the main stream. The study also discussed the comprehensive impacts of climate change factors (precipitation, temperature, evaporation) and human activities (water conservancy and soil conservation measures) on runoff variation in the main stream, and analyzed the causes of abrupt change points, aiming to provide scientific basis for watershed water resource management and ecological environment governance.

1.1 Study Area Overview

The Zuli River, formed by the confluence of the Zu River and Li River, is a first-level tributary in the upper reaches of the Yellow River Basin. Originating from the northern foothills of Huajia Ridge in southern Huining County, the Zuli River flows through six counties (districts) in Gansu Province (Huining, Anding, Tongwei, Longxi, Yuzhong, and Jingyuan) and parts of Ningxia, before joining the Yellow River at Hongzuizi in Jingyuan County. The basin is located between 104°13 ~105°35 E and 35°16 ~36°34 N, with a main stream length of 220 km and a drainage area of 1.041 $\times 10^4$ km^{2}. The multi-year average runoff is 1.22×10^8 m^{3}, and the multi-year average sediment load is 3.03×10^6 t, of which 10056 km^{2} lies within Gansu Province. Situated at the edge of the maritime monsoon region, the basin features a temperate semi-arid climate with continental monsoon characteristics. The annual average temperature ranges from 3.60~8.80 ℃, annual sunshine hours range from 2430~2680 h, and precipitation is scarce and unevenly distributed. The basin-wide annual average precipitation is 314.70 mm, with 68.50% of rainfall concentrated in June-August. Annual evaporation ranges from 1407~1736 mm.

1.2 Data Sources

The basic data used in this study include long-term series (1957-2021) of measured monthly and annual runoff data and precipitation observation data from three hydrological stations (Huining, Guochengyi, and Jingyuan) in the main stream of the Zuli River. All runoff and precipitation data were measured by Gansu Provincial Hydrological Stations, with reliable sources meeting the 'three characteristics' requirements (reliability, consistency, and representativeness).

1.3 Research Methods

This study divides the year into four seasons: spring (March-May), summer (June-August), autumn (September-November), and winter (December-

February). Linear trend estimation and moving average methods were employed to analyze annual runoff variation trends and wet-dry conditions, with significance levels tested. The Mann-Kendall mutation test was used to identify abrupt change years in annual runoff, a widely applied method for detecting temporal mutation points in hydrological analysis. Wavelet analysis was adopted to investigate periodic variation characteristics of runoff. The double mass curve method was utilized to quantitatively estimate the contribution rates of climate change and human activities to runoff variation.

2 Results and Analysis

2.1 Trend Analysis

The annual runoff at Huining, Guochengyi, and Jingyuan stations decreased significantly at rates of -0.03$\times 10^8 m^{3}\cdot(10a)^{-1}$, $-0.06\times 10^8 m^{3}\cdot(10a)^{-1}$, and $-0.15\times 10^8 m^{3}\cdot(10a)^{-1}$, respectively. At Huining station, the maximum runoff was $0.67\times 10^8 m^{3}$ (1967) and the minimum was $0.003\times 10^8 m^{3}$ (1997), with a difference of $0.667\times 10^8 m^{3}$; the maximum was 223 times the minimum. At Guochengyi station, the average annual runoff was $0.447\times 10^8 m^{3}$, wi
(1978) and a minimum of $0.17\times 10^8 m^{3}$ (2002), differing by $1.72\times 10^8 m^{3}$; the maximum was 11.1 times the minim
(1967) and a minimum of $0.39\times 10^8 m^{3}$ (2002), differing by $2.64\times 10^8 m^{3}$; the maximum was 7.8 times the minimum.

According to the cumulative anomaly curves of annual runoff, Huining station showed an upward trend during 1957-1967 (wet period), 1968-1992 (normal-dry period), and a downward trend during 1993-2021 (dry period). Guochengyi station exhibited an upward trend during 1957-1978 (wet period) and a downward trend during 1979-2021 (dry period). Jingyuan station displayed an upward trend during 1957-1967 (wet period), a downward trend during 1968-1994 (dry period), an upward trend during 1995-2004 (wet period), and a downward trend during 2005-2021 (dry period).

Trend and significance analysis of seasonal runoff at the three stations revealed that Huining station showed significant decreasing trends in all four seasons, with the decreasing rate ranking as: summer > spring > autumn > winter. Guochengyi and Jingyuan stations showed decreasing trends in spring, summer, and autumn (non-significant in spring and autumn), while both exhibited significant increasing trends in winter.

2.2 Abrupt Change Analysis

The Mann-Kendall mutation test was applied to annual runoff time series at Huining, Guochengyi, and Jingyuan stations. For Huining station, the UF and UB curves intersected in 1992 within the 0.05 confidence interval, indicating an abrupt change in 1992. Using this mutation point, the series was divided into two periods: 1957-1992 (pre-mutation) and 1993-2021 (post-mutation). Results showed that the average runoff before mutation exceeded the multi-year average, while the average runoff after mutation was below the multi-year average. The total runoff before and after mutation accounted for 79.01% and 20.99% of the multi-year total runoff, respectively. The post-mutation average annual runoff was approximately one-quarter of the pre-mutation value, demonstrating a significant reduction.

Guochengyi station experienced an abrupt change in 1984. Analysis of pre- and post-mutation periods revealed that the average runoff before mutation exceeded the multi-year average, while the post-mutation average was below it. The total runoff before and after mutation represented 53.85% and 46.15% of the multi-year total, respectively. The pre-mutation average annual runoff was approximately 1.2 times the post-mutation value.

Jingyuan station underwent an abrupt change in 1994. Analysis showed that the pre-mutation average runoff exceeded the multi-year average, while the post-mutation average was below it. The total runoff before and after mutation accounted for 70.32% and 29.68% of the multi-year total, respectively. The pre-mutation average annual runoff was approximately 2.4 times the post-mutation value.

2.3 Wavelet Analysis

Huining station's annual runoff exhibits three main periodicities: 8-12 years, 1-7 years, and 24-32 years, with 8-12 years being the first principal period. Runoff shows periodic variations at the 8-12 year time scale with multiple wet-dry oscillations. Before 1992, the periodicity was more pronounced, featuring three distinct wet-period centers (1960, 1967, 1979) and two dry-period centers (1964, 1973).

Guochengyi station's annual runoff shows three main periodicities: 13-26 years, 3-6 years, and 7-12 years, with 13-26 years as the first principal period. Runoff demonstrates periodic variations at the 13-26 year scale with four wet-dry cycles. The wavelet variance diagram reveals a prominent peak corresponding to the 13-26 year characteristic time scale. Before 1984, the periodicity was more evident. The first principal period featured particularly frequent wet-dry alternations, with the maximum wet-center corresponding to 1978 and the minimum dry-center to 1993.

Jingyuan station's annual runoff exhibits three main periodicities: 7-18 years, 1-6 years, and 19-32 years, with 7-18 years as the first principal period. Runoff shows periodic variations at the 7-18 year scale with multiple wet-dry oscillations. Before 1994, the periodicity was more pronounced. The first principal period contained three wet-period centers and two dry-period centers with frequent alternations. The maximum wet-center corresponded to 1967, while the minimum dry-center corresponded to 2002.

2.4 Driving Factor Analysis

2.4.1 Precipitation Trends The annual precipitation at Huining, Guochengyi, and Jingyuan stations in the main stream of the Zuli River all showed decreasing trends, with the decreasing rates (from largest to smallest) being: Guochengyi station -7.24 mm·(10a)^-1, Jingyuan station -7.08 mm·(10a)^-1, and Huining station -6.02 mm·(10a)^-1. During 1957-2021, precipitation decreased by 27.1 mm, 17.1 mm, and 12.5 mm at Huining, Guochengyi, and Jingyuan stations, respectively. According to the cumulative anomaly curves of annual precipitation, Huining station showed an upward trend during 1957-1967 (wet period) and a downward trend during 1968-2021 (dry period). Guochengyi and Jingyuan stations showed similar patterns, both exhibiting upward trends during 1957-1967 (wet period) and downward trends during 1968-2021 (dry period). Comparative analysis reveals that precipitation abundance generally corresponds to runoff wet-dry conditions, though runoff variations lag behind precipitation changes, indicating that runoff in the main stream of the Zuli River decreases with precipitation reduction.

2.4.2 Soil and Water Conservation Measures As shown in [Figure 8: see original paper], the area of various soil and water conservation measures in the Zuli River Basin changed significantly during 1957-2021. Beginning in the 1960s, extensive farmland capital construction was implemented, including slope terracing and gully dam system engineering, with terraced land area increasing notably from 2.27 $\times 10^4 hm^2$ in 1957 to 8.42 $\times 10^4 hm^2$ in 2021. Starting in the 1970s, all types of soil and water conservation measures began to increase, particularly terraced land, forestland, and grass planting areas. In the 1980s, 57 silt dams were constructed, while the 1990s represented the peak period of dam construction (64 key dams and 131 medium-small dams). In the 2000s, numerous medium-small silt dams were built, reaching 276 dams. By 2021, the basin's terraced land, closed restoration area, forestland, and grassland reached 298.59 $\times 10^4 hm^2$, 83.03 $\times 10^4 hm^2$, 71.97 $\times 10^4 hm^2$, and 83.49 $\times 10^4 hm^2$, respectively. Dam land area decreased sl in 1957 to 0.47 $\times 10^4 hm^2$ in the late 1990s, then increased to 4.87 $\times 10^4 hm^2$ by 2021. The closed restoration area showed a particularly significant increasing trend, rising from 23.31 $\times 10^4 hm^2$ in 1957 to 195.31 $\times 10^4 hm^2$ in 2021.

2.4.3 Contribution Rates of Climate Change and Human Activities The double mass curve method was used to attribute runoff reduction to precipitation and human activities. As shown in [Figure 10: see original paper], the multi-year average precipitation during the variation period (post-mutation) decreased by 30.05 mm compared to the baseline period (pre-mutation), while runoff decreased by 0.35 $\times 10^8 m^3$. The runoff reduction caused by human activities was 0.12 $\times 10^8 m^3$, indicating that precipitation and human activities contributed 25.53% and 74.47%, respectively, to runoff reduction in the main stream of the Zuli River. Human activities represent the dominant factor driving the sharp decline in watershed runoff.

3 Discussion

Precipitation, evaporation, and temperature are the main meteorological factors affecting runoff variation. Previous studies have shown that precipitation change is the primary cause of runoff variation in most Chinese rivers. This study found that annual precipitation in the main stream of the Zuli River showed a decreasing trend, and precipitation reduction led to runoff decrease. Research indicates that since the 1980s, the Zuli River's upper source region has experienced significant regional climate change, with notably rising temperatures and increased evaporation, causing runoff reduction. With the increase in soil and water conservation measures, vegetation coverage has expanded, and the corresponding water consumption for vegetation physiology and environmental support has created an inhibitory effect on runoff formation, indirectly contributing to runoff reduction in the Zuli River Basin. The runoff mutations at Huining, Guochengyi, and Jingyuan stations all occurred after the 1980s, likely related to the extensive soil and water conservation measures implemented during the 1970s-1990s.

Additionally, the inter-basin water diversion irrigation project—the Jinghui Yellow River Electric Pumping Irrigation Project—has been particularly influential. Since the Jinghui irrigation district began operation in 1974, annual water diversion has reached over 10^8 m^3. However, due to rapid population growth and significant land use changes in the middle and lower reaches, this surface water transfer has not increased river runoff in the region. The Jinghui irrigation district is located in the middle and lower reaches of the Zuli River, and studies have shown that irrigation return flow can recharge runoff in the middle and lower reaches, affecting annual runoff at Guochengyi and Jingyuan stations, while the upstream Huining and above remain unaffected. This indicates that the earlier runoff mutation at Guochengyi station is closely related to the Jinghui Project.

In summary, human activities dominated by soil and water conservation measures and the Jinghui Project represent the primary factors, while climate change characterized by precipitation reduction plays a secondary role; their combined effects have caused runoff reduction in the main stream of the Zuli River. The Zuli River Basin is located in an arid and semi-arid region, and its runoff variation plays a vital role in ecological environment changes and socio-economic development in the watershed. Continued attention to the current runoff reduction situation is needed. Moreover, the Zuli River is one of the main sediment sources for the upper Yellow River. Due to climate change and human activities, watershed sediment load has sharply decreased in recent decades, altering the water-sediment relationship. Future research should strengthen investigations into water-sediment changes and their driving factors to provide scientific support for watershed ecological restoration.

4 Conclusions

This study focused on the main stream of the Zuli River, comprehensively analyzing the trend, abrupt change, and periodicity of runoff variation, discussing the main causes affecting Zuli River runoff changes, and quantitatively estimating the contribution rates of climate change and human activities to runoff variation. The main conclusions are as follows:

(1) Runoff in the main stream of the Zuli River showed an overall decreasing trend over the past 65 years, with the decreasing rates (from largest to smallest) being: Jingyuan [-0.15$\times10^8m^{\{3\}\$\cdot(10\mathrm{a})}$-1] > Guochengyi [-0.06$\times10^8m^{\{3\}\$\cdot(10\mathrm{a})}$-1] > Huining [-0.03$\times10^8m^{\{3\}\$\cdot(10\mathrm{a})}$-1]. The intra-annual runoff distribution is extremely uneven, concentrated mainly in June-August, accounting for 68.50% of the annual total.

(2) The measured annual runoff at Huining and Jingyuan stations underwent abrupt changes in 1992 and 1994, respectively, related to extensive soil and water conservation measures during the 1970s-1990s and precipitation reduction. The abrupt change at Guochengyi station in 1984 resulted from the construction of the Jinghui Yellow River Electric Pumping Irrigation Project. Since these mutations occurred, the total annual runoff at the three stations decreased by 73.43%, 57.80%, and 38.62% in the post-mutation periods compared to pre-mutation periods.

(3) Huining, Guochengyi, and Jingyuan stations all exhibit multi-scale characteristic periods. The wavelet periodograms of annual runoff at the three main stream stations show reduced fluctuation amplitude or even stabilization over the past 30 years, reflecting relatively decreased frequency of wet-dry cycles and reduced occurrence of drought-flood disasters in the Zuli River.

(4) The wet-dry cycles of runoff at the three hydrological stations in the main stream of the Zuli River vary with precipitation changes. However, the impact of human activities on runoff variation far exceeds that of climate change. Specifically, human activities contribute 74.47% while climate change contributes 25.53% to runoff variation.

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