Postprint: Study on Precipitation Variation Characteristics in the Shule River Basin

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Abstract

Based on annual and monthly precipitation data from five hydrological stations in the Shule River Basin spanning 1956–2020, this study employs methods including linear trend analysis, moving average, cumulative anomaly, Mann-Kendall mutation test, and wavelet analysis to investigate the interannual variation processes of precipitation and its changing characteristics in terms of abruptness, trend, periodicity, persistence, non-uniformity, and concentration. The results indicate that annual precipitation at each station exhibits varying degrees of increasing trend, with each station also showing distinct abrupt change characteristics. Precipitation across the entire basin over the past 60 years demonstrates relatively non-uniform distribution on the temporal scale, while exhibiting spatial characteristics of greater precipitation in the upper reaches and lesser precipitation in the lower reaches. Specifically, Changmabao Station and Dangchengwan Station show significant increasing trends in annual precipitation, whereas Panjiazhuang Station, Shuangtabao Reservoir Station, and Danghe Reservoir Station show insignificant increasing trends. Analysis indicates that precipitation in the basin will continue to exhibit an increasing trend for a period of time in the future.

Full Text

Characteristics of Precipitation Changes in the Shule River Basin

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Abstract: Based on annual and monthly precipitation data from five hydrological stations in the Shule River Basin from 1956 to 2020, this study employed linear trend analysis, moving average, cumulative anomaly, Mann-Kendall mutation test, wavelet analysis, and other methods to investigate the interannual variation processes of precipitation and its characteristics of abrupt change, trend, periodicity, persistence, heterogeneity, and concentration. The results demonstrate that annual precipitation at each station in the Shule River Basin exhibited varying degrees of increasing trends, with distinct mutation characteristics observed across stations. Over the past 60 years, precipitation distribution has been relatively uneven temporally, while spatially showing a pattern of greater precipitation in upstream areas and less in downstream regions. Specifically, Changmabao and Dangchengwan stations showed significant increasing trends in annual precipitation, whereas the increasing trends at Panjiazhuang, Shuangtabao Reservoir, and Danghe Reservoir stations were less pronounced. Analysis indicates that precipitation in the basin will continue to exhibit an increasing trend in the coming period.

Keywords: Shule River; precipitation; Mann-Kendall test; trend; periodicity; R/S analysis

1 Study Area Overview

The Shule River Basin is located at the western end of the Hexi Corridor and constitutes one of the three major inland river basins in Gansu Province. Geographically situated between 38°00 –42°48 N and 92°11 –98°30 E, the basin covers an area of 4.13×10^{4} km^2. The terrain slopes from southeast to northwest, with the main stream extending 670 km and elevations ranging from 800 to 5730 m. The basin experiences a typical continental arid to semi-arid climate, with precipitation concentrated in June–September. Annual precipitation varies from 40.2 to 57.5 mm in plain areas to 2577.4–2653.2 mm in mountainous regions, where topographic blocking and lifting of moisture result in relatively abundant precipitation. The Changmabao station is located in the upper Shule River, Panjiazhuang and Shuangtabao Reservoir stations are situated in the middle and lower reaches of the main stream, while Dangchengwan station lies in the upper Dang River tributary and Danghe Reservoir station is positioned in the middle Dang River.

2.1 Data Sources and Processing

All data were obtained from Gansu Provincial Hydrological Stations. Monthly precipitation data from five hydrological stations in the Shule River Basin (Changmabao, Panjiazhuang, Shuangtabao Reservoir, Dangchengwan, and Danghe Reservoir) from 1956 to 2020 were selected as the basis for analyzing precipitation variation characteristics in the basin.

2.2 Research Methods

This study employed linear trend fitting and moving average methods to describe precipitation variation trends and characteristics. Cumulative anomaly analysis was used to identify interannual variation patterns and determine approximate mutation times through maximum absolute values. The Mann-Kendall test, a non-parametric method, effectively analyzes abrupt changes and trends. Wavelet analysis transforms the relationship between precipitation and time into one between precipitation frequency and time, identifying periodicities by examining variations between period and frequency. Vector methods for precipitation distribution were used to derive heterogeneity and concentration indices, effectively reflecting non-uniform distribution characteristics. Rescaled range analysis (R/S) and the Hurst exponent quantitatively describe correlations in long time series data, with the exponent magnitude serving as a basis for predicting future trends.

3.1 Annual Precipitation Variation Characteristics

The five hydrological stations in the Shule River Basin all showed increasing precipitation trends, with characteristic values presented in Table 1. The Changmabao station exhibited a linear tendency rate of 0.505 $mm \cdot a^{-1}$, equivalent to an average annual increase of 5.05 mm per decade, with mean annual precipitation of 152.03 mm. The Panjiazhuang station showed a linear tendency rate of 0.069 $mm \cdot a^{-1}$ (0.69 mm per decade) with mean annual precipitation of 32.83 mm. The Shuangtabao Reservoir station had a linear tendency rate of 0.111 $mm \cdot a^{-1}$ (1.11 mm per decade) and mean annual precipitation of 44.28 mm. The Dangchengwan station demonstrated a linear tendency rate of 0.923 $mm \cdot a^{-1}$ (9.23 mm per decade) with mean annual precipitation of 156.78 mm. The Danghe Reservoir station showed a linear tendency rate of 0.056 $mm \cdot a^{-1}$ (0.56 mm per decade) and mean annual precipitation of 53.42 mm.

Overall, precipitation at all stations increased to varying degrees, with the ranking of decadal tendency rates as: Dangchengwan (9.23 $mm \cdot (10a)^{-1}$) > Changmabao (5.05 $mm \cdot (10a)^{-1}$) > Shuangtabao Reservoir (1.11 $mm \cdot (10a)^{-1}$) > Panjiazhuang (0.69 $mm \cdot (10a)^{-1}$) > Danghe Reservoir (0.56 $mm \cdot (10a)^{-1}$). The cumulative anomaly curves revealed that the periods 1960–1975 (Panjiazhuang), 1960–1970 (Shuangtabao Reservoir), 1960–1970 (Dangchengwan), and 1960–1975 (Danghe Reservoir) showed downward trends, indicating relatively dry periods. Conversely, the periods 1975–2020 (Panjiazhuang), 1970–2020 (Shuangtabao Reservoir), 1970–2020 (Dangchengwan), and 1975–2020 (Danghe Reservoir) exhibited upward trends, indicating relatively wet periods. The moving average curves showed that, except for Dangchengwan station which remained relatively stable before 1970 then increased rapidly, all other stations displayed slowly increasing fluctuating trends.

3.2 Abrupt Change Characteristics of Precipitation

Mann-Kendall test results indicate that UFk and UBk curves intersected primarily around 1975 at Changmabao station, with the intersection point within the critical lines ($±1.96), suggestinganabruptchangeoccurredaround1975.Sincethe1970s, UFkvalueshavebeenpo = 1.96). At Panjiazhuang station, UFk and UBk intersected around 1970 within the critical lines, indicating an abrupt change around 1970. Since the mid-1970s, UFk > 0, showing an increasing trend that became particularly significant in the early period when passing the 0.05 significance level.

At Shuangtabao Reservoir station, UFk and UBk intersected around 1970 within the critical lines, indicating an abrupt change around 1970. Since the 1970s, UFk > 0, showing an increasing trend, especially significant in the late 1970s to mid-1980s when passing the 0.05 significance level. At Dangchengwan station, UFk and UBk intersected around 1970 within the critical lines, indicating an abrupt change around 1970. Since the 1970s, UFk > 0, showing an increasing trend, particularly significant in the early period when passing the 0.05 significance level. At Danghe Reservoir station, UFk and UBk showed no obvious intersection, indicating no abrupt change phenomenon. However, since the 1970s, UFk > 0, showing an increasing trend, particularly significant in the early period when passing the 0.05 significance level.

3.3 Precipitation Trend Characteristics

The precipitation trend coefficients for each station are shown in Table 2. All five stations showed positive values, indicating increasing trends. The Z-values from Mann-Kendall trend tests were: Changmabao (2.47) and Dangchengwan (2.31), both exceeding the 1.96 threshold at the 95% confidence level, indicating significant increasing trends. In contrast, Panjiazhuang (0.69), Shuangtabao Reservoir (0.89), and Danghe Reservoir (0.57) had Z-values below 1.96, indicating non-significant increasing trends.

3.4 Precipitation Periodicity Characteristics

Wavelet analysis of precipitation in the Shule River Basin over the past 60 years revealed multiple characteristic timescales. At Changmabao station, the wavelet real-part diagram showed three main timescales: 55–60 years, 5–10 years, and 2–5 years. The wavelet variance diagram displayed three distinct peaks, indicating first, second, and third main periods of 55–60 years, 5–10 years, and 2–5 years, respectively. At Panjiazhuang station, three characteristic timescales were identified: 28–34 years, 8–12 years, and 2–5 years, with three distinct peaks corresponding to first, second, and third main periods of 28–34 years, 8–12 years, and 2–5 years.

At Shuangtabao Reservoir station, three characteristic timescales were observed: 53–58 years, 10–15 years, and 2–5 years, with three distinct peaks indicating first, second, and third main periods of 53–58 years, 10–15 years, and 2–5 years.

At Dangchengwan station, three characteristic timescales were identified: 30–35 years, 8–12 years, and 2–5 years, with three distinct peaks corresponding to first, second, and third main periods of 30–35 years, 8–12 years, and 2–5 years. At Danghe Reservoir station, three characteristic timescales were found: 33 years, 8–12 years, and 2–5 years, with three distinct peaks indicating first, second, and third main periods of 33 years, 8–12 years, and 2–5 years.

3.5 Precipitation Persistence Analysis

Hurst exponent values for each station were: Changmabao (0.72), Panjiazhuang (0.68), Shuangtabao Reservoir (0.71), Dangchengwan (0.69), and Danghe Reservoir (0.70), all exceeding 0.5. This indicates that future precipitation will maintain the same trend as the past, exhibiting positive persistence characteristics. Therefore, precipitation at these stations is predicted to show increasing trends in the coming period. The Hurst exponent was highest at Changmabao station (0.72), indicating the strongest positive persistence.

3.6 Precipitation Concentration and Heterogeneity

The precipitation concentration degree (PCD) across the Shule River Basin fluctuated between 0.19 and 0.89, with a multi-year average of 0.34–0.70. The PCD showed weak decreasing trends at all stations, with tendency rates of -0.017 $\cdot$ $(10a)^{-1}$ at Panjiazhuang, -0.015 $\cdot$ $(10a)^{-1}$ at Shuangtabao Reservoir, -0.003 $\cdot$ $(10a)^{-1}$ at Dangchengwan, and -0.01 $\cdot$ $(10a)^{-1}$ at Danghe Reservoir, indicating a tendency toward more uniform distribution. All stations had PCD values above the multi-year average, indicating relatively concentrated precipitation distribution, with Changmabao showing the highest concentration.

The intra-annual distribution heterogeneity coefficient (C) ranged between 0.19 and 0.87 across the basin, with multi-year averages of 0.32–0.72, indicating relatively uneven annual precipitation distribution. The heterogeneity coefficient showed decreasing trends over the past 60 years, with tendency rates of -0.002 $\cdot$ $(10a)^{-1}$ at Changmabao, -0.002 $\cdot$ $(10a)^{-1}$ at Panjiazhuang, -0.008 $\cdot$ $(10a)^{-1}$ at Shuangtabao Reservoir, -0.012 $\cdot$ $(10a)^{-1}$ at Dangchengwan, and -0.007 $\cdot$ $(10a)^{-1}$ at Danghe Reservoir, suggesting a gradual trend toward more uniform distribution.

4 Analysis of Spatial Differences in Precipitation Change Trends

This comprehensive analysis of annual precipitation variation characteristics, trends, periodicity, persistence, heterogeneity, and concentration in the Shule River Basin differs from previous studies that relied solely on conventional linear analysis or focused on individual sites, which had limitations for understanding the entire basin. Trend analysis and testing demonstrate that precipitation in this region has shown an increasing trend over the past several decades, consistent with findings from Sun et al. and Liu. Analysis of the five hydrological stations reveals that annual precipitation decreases from east to west and from south to north, consistent with Zhang et al. and Zheng et al., who found attenuation from upstream to downstream and increasing trends across the basin.

Due to global warming and its unique geographic location, the Shule River Basin is influenced by both westerly circulation and airflow disturbances. Precipitation and snow-ice meltwater constitute the basin's primary water resources, with precipitation in the southwestern mountainous areas increasing with elevation. The basin's topography, higher in the south and lower in the north, blocks warm-moist airflow in summer, while prevailing northwest winds in winter result in minimal precipitation. This creates distinct seasonal variations in southern mountainous areas, while the northern plains cannot retain warm-moist air masses, making precipitation formation difficult and resulting in an arid climate. Unlike the Heihe and Shiyang rivers in the Hexi Corridor, which are influenced by monsoon circulation, the Shule River's mountainous climate differs significantly, causing substantially greater precipitation in southern mountains than in plain areas, decreasing from southeast to northwest. Comprehensive analysis of precipitation formation and variation characteristics is essential for rational water resource utilization and must consider multiple factors.

Although this study analyzed precipitation using long-term multi-element data, each element employed only one analytical method, which has limitations. Given the special conditions of arid inland areas, future research should combine optimal precipitation interpolation methods and consider multiple natural factors including temperature and airflow movement to analyze precipitation characteristics. While numerous studies have examined precipitation trends in this region, more in-depth understanding of future precipitation characteristics is needed, requiring multiple analytical methods to reduce errors and explore spatiotemporal variations.

5 Conclusions

Based on monthly precipitation data from five hydrological stations in the Shule River Basin, this study analyzed annual precipitation evolution characteristics and variation features, yielding the following main conclusions:

1) Multi-year average precipitation at Changmabao (1956–2020), Panjiazhuang (1960–2020), Shuangtabao Reservoir (1960–2020), Dangchengwan (1960–2020), and Danghe Reservoir (1960–2020) were 152.03 mm, 32.83 mm, 44.28 mm, 156.78 mm, and 53.42 mm, respectively. Annual precipitation increased at rates of 5.05 mm $\cdot$ $(10a)^{-1}$, 0.69 mm $\cdot$ $(10a)^{-1}$, 1.11 mm $\cdot$ $(10a)^{-1}$, 9.23 mm $\cdot$ $(10a)^{-1}$, and 0.56 mm $\cdot$ $(10a)^{-1}$, confirming that both precipitation increase rates and multi-year averages decrease from south to north across the basin.
2) Z-values from Mann-Kendall trend tests were 2.47 at Changmabao and 2.31 at Dangchengwan, exceeding the 1.96 significance threshold and indi-

cating significant increasing trends. In contrast, Z-values at Shuangtabao Reservoir (0.89), Panjiazhuang (0.69), and Danghe Reservoir (0.57) were below 1.96, indicating non-significant trends. Due to differing linear tendency rates and cumulative anomaly curve fluctuations, annual precipitation showed varying degrees of increase across stations.

3) Abrupt changes occurred around 1975 at Changmabao, 1970 at Panjiazhuang, 1970 at Shuangtabao Reservoir, and 1970 at Dangchengwan, with no significant abrupt change at Danghe Reservoir. After these mutations, precipitation showed fluctuating increases at all stations except Danghe Reservoir, which showed fluctuating decreases. All mutation characteristic curves remained within confidence level lines, consistent with trend analysis results.

4) The first main period for all stations except Dangchengwan was approximately 55–60 years, while Dangchengwan showed 30–35 years. At this primary timescale, "wet-dry" alternations occurred, with 3–8 oscillations. Dangchengwan showed particularly stable periodic changes after 1980, demonstrating global characteristics.

5) The precipitation concentration degree (0.19–0.89) and heterogeneity coefficient (0.32–0.72) showed weak decreasing trends, indicating a tendency toward more uniform distribution. All stations had positive Hurst exponents (0.68–0.72), indicating positive persistence and predicting continued precipitation increases in the future.

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