

Variation Characteristics of Floods in the Upper Mountainous Region of the Shule River, 1956-2021 (Postprint)

Authors: Wang Xueliang

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Abstract

Based on measured flood data from the Changmabao hydrological station at the outlet of the Changma River in the upper Shule River basin from 1956-2021, together with temperature and precipitation data from the Yuerhong rainfall station and TuoLe meteorological station within or adjacent to the basin, we employed Sen' s slope estimator and the Mann-Kendall test to conduct sampling analyses of the change characteristics of annual maximum peak discharge (AMPD) series, peaks-over-threshold (POT3M) series, and different magnitude flood series based on the Generalized Extreme Value (GEV) distribution. The results indicate: (1) From 1956-2021, both flood magnitude and frequency at the Changmabao hydrological station on the Changma River in the upper Shule River basin exhibited significant increasing trends, wherein the magnitude change trends for the AMPD and POT3M series passed significance tests at the 0.01 level, the frequency change trend for the POT3M series passed the significance test at the 0.05 level, and floods of different magnitudes based on the GEV distribution were dominated by small floods, with the total flood frequency passing the significance test at the 0.01 level. (2) After 1987, temperature and precipitation displayed fluctuating increasing trends, and the primary causes for the significant increases in magnitude and frequency across the three sampled flood series were increased meltwater from glaciers, alpine snowpack, and permafrost induced by heavy rainfall and warming.

Full Text

Abstract

Based on measured flood data from 1956 to 2021 at the Changmabao hydrological station located at the outlet of the Changma River in the upper Shule River basin, together with temperature and precipitation data from the Yu'

erhong rainfall station within the basin and the Tuole meteorological station in the surrounding area, this study analyzes variation characteristics of flood series using Sen's slope estimator and the Mann-Kendall test. Three types of flood series were examined: annual maximum peak discharge (AMPD), peaks over threshold (POT3M), and floods at different levels based on the generalized extreme value (GEV) distribution. The results demonstrate that both the magnitude and frequency of floods at Changmabao station increased significantly during the study period. The AMPD and POT3M magnitude series passed significance tests at the 0.01 level, while the POT3M frequency series passed at the 0.05 level. Floods based on the GEV distribution were predominantly small floods, with total flood frequency showing a highly significant increasing trend ($P < 0.01$). After 1987, temperature and precipitation exhibited fluctuating but significant increases, with heavy rainfall and enhanced meltwater from glaciers, alpine snow, and permafrost driven by warming identified as the primary causes of the observed increases in flood magnitude and frequency across all three sampling methods.

Keywords: Shule River; Changmabao hydrological station; flood; variation characteristics

1. Introduction

River flooding represents one of the most concerning natural disaster issues worldwide. According to United Nations statistics, floods constitute the most frequently recorded natural disaster globally, accounting for 43% of all disasters with average annual losses estimated at \$104 billion. The impacts of flooding and variation characteristics across different regions have attracted widespread attention, becoming a focal point in hydrological research worldwide. Studies have examined relationships between flood magnitude/frequency and regional temperature increases, heavy precipitation, and accelerated hydrological cycles. Recent research indicates that climate change in Europe has altered not only flood timing but also increased autumn and winter precipitation, leading to more floods in northwestern Europe while decreasing them in the southeast due to reduced precipitation, higher temperatures, and increased evaporation.

In China, scholars have conducted research on floods in arid and semi-arid regions of northwest China. Zhang et al. found that flood magnitude in the Tarim River basin has increased since the 1980s, particularly in high-latitude rivers. Jiang et al. and Mao et al. documented increasing flood trends in typical alpine basins of the Tianshan Mountains, including the Aksu, Toxkan, Kumalak, Manas, and Ürümqi rivers. Wang et al. reported that floods in the Shiyang River, originating in the Qilian Mountains, are dominated by small summer floods with increasing frequency, showing regional differences between decreasing trends in the east and increasing trends in the west. The Shule River lies in the western part of the Qilian Mountains and Hexi Corridor, with previous research indicating that the Changmabao station has a multi-year average runoff of $10.3 \times 10^8 \text{ m}^3$, making its water resources critically important for the

extremely water-scarce middle and lower reaches.

The Shule River basin is influenced by the convergence of plateau monsoon and westerly circulation systems, with numerous high mountain systems, developed glaciers and snow cover, and runoff primarily formed by precipitation and meltwater in the upper reaches. Therefore, analyzing historical flood variation patterns in the Shule River under climate change is essential for protecting lives and property and supporting socioeconomic development in the middle and lower reaches. This study utilizes long-term measured flood data from the Changmabao station over the past 66 years, applying AMPD, POT3M, and GEV distribution sampling methods to analyze trends in flood magnitude and frequency, and to explore attribution relationships with climate change, providing a decision-making basis for flood control, water conservancy project construction, scheduling management, and water resources management.

2. Study Area and Data

2.1 Study Area Overview

The Shule River originates from the Ganggerxiouli Ridge in the Qilian Mountains at an elevation of 4737 m. The main stream flows from southeast to northwest between the Tuolai Nanshan and Shule Nanshan mountains, whose watershed divides generally exceed 4000 m, with the highest peak (Zawujile) reaching 5808 m. The upper reaches from the river source to the Changmaxia outlet (Changmabao station) are called the Changma River, with a length of 347 km and a catchment area of approximately $1.10 \times 10^3 \text{ km}^2$, located between $96^\circ 42' - 99^\circ 00' \text{ E}$ and $38^\circ 18' - 39^\circ 54' \text{ N}$. The entire Shule River basin covers $4.13 \times 10^3 \text{ km}^2$ between $92^\circ 54' - 99^\circ 14' \text{ E}$ and $38^\circ 36' - 41^\circ 34' \text{ N}$.

The upper Shule River, with elevations ranging from 2080 to 5808 m (average 3944 m), consists of the Daxue Mountains, Shule Nanshan, Tuolai Nanshan, and the Shule River valley. The mountainous areas feature high, steep terrain while the valley is relatively flat. Due to high altitude and cold climate, the region hosts modern alpine glaciers and permafrost. Glaciers are distributed primarily above 4248 m on both sides of the valley, covering 469.5 km^2 (approximately 14–18% of the basin area). The region exhibits a plateau mountain climate characterized by cold, dry conditions with intense solar radiation and large temperature variations.

[Figure 1: see original paper]

2.2 Data Sources

The Changmabao hydrological station at the Changma River outlet served as the flood observation site, with Yu' erhong rainfall station within the basin and Tuole meteorological station in the vicinity providing meteorological data. Yu' erhong station has continuous precipitation observations, while Tuole station data were used for comparative analysis of flood responses to precipitation and

temperature changes. Flood data from 1956–2021 at Changmabao station were obtained from the *Hydrological Yearbook of the People's Republic of China*, and meteorological data from Tuole station were sourced from the China Meteorological Administration Data Center (<http://data.cma.cn>). Basic information for the observation stations is provided in Table 1.

2.3 Methods

2.3.1 Sen's Slope Estimator Sen's slope estimator was used to analyze trends in flood magnitude and frequency for the AMPD, POT3M, and GEV-based flood series at Changmabao station, as well as temperature and precipitation trends at Yu'erhong and Tuole stations. This non-parametric method calculates the median slope between all possible pairs of time series data points, providing robust trend estimation resistant to outliers. The slope is calculated as:

$$\beta = \text{median} \left(\frac{x_j - x_k}{j - k} \right) \quad \text{for } j > k$$

where β indicates upward (positive) or downward (negative) trends, and its magnitude represents the steepness of the trend; x_j and x_k represent data values at times j and k , respectively.

2.3.2 Mann-Kendall Test The Mann-Kendall test, a widely used non-parametric method for trend analysis in hydrological and meteorological time series, was applied to assess the significance of trends. This test requires no assumption of normal distribution and is insensitive to outliers. Detailed formulations can be found in the literature.

2.3.3 POT3M Flood Series Sampling For peaks-over-threshold series, no universally accepted objective method exists for threshold selection. Some scholars determine thresholds corresponding to 2.4–3.0 floods per year through trial calculations. This study ultimately selected a threshold yielding approximately three floods annually (POT3M). To ensure independence of sampled flood peaks, the method proposed by Lang et al. was adopted, considering both flood duration and minimum inter-event flow, which has proven applicable in arid and semi-arid northwest China. All sampled flood peaks in this study satisfied independence criteria based on duration (D) and minimum intermediate discharge (Q_{\min}):

$$D > 5 + \log_{10}(A) \quad \text{and} \quad Q_{\min} < \frac{Q_{\text{peak1}} + Q_{\text{peak2}}}{3}$$

where D is the duration between consecutive flood peaks, A is the catchment area, and Q_{\min} is the minimum flow between two peaks.

2.3.4 GEV Distribution-Based Flood Level Sampling The GEV distribution was fitted to flood frequency curves at Changmabao station. The Kolmogorov-Smirnov test was used for goodness-of-fit evaluation. After passing the test, theoretical return periods and corresponding discharge thresholds were calculated to classify floods into small (<20-year return period), medium (20-50-year), and large (>50-year) categories. For the arid Shule River with few annual floods, classification followed the *Hydrological Information and Forecasting Standard* (GB/T 22482-2008). The GEV distribution function is:

$$F(x) = \exp \left\{ - \left[1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right]^{-1/\xi} \right\}$$

where x is flood sequence data, ξ is the shape parameter, σ is the scale parameter, and μ is the location parameter. When $\xi < 0$, it follows a Weibull distribution; when $\xi = 0$, a Gumbel distribution; and when $\xi > 0$, a Fréchet distribution. Maximum likelihood estimation was used for parameter estimation.

3. Results and Analysis

3.1 AMPD Flood Series Characteristics

The AMPD series at Changmabao station from 1956-2021 showed substantial interannual variability (Figure 2). The maximum peak discharge was 718 m³/s (1998), the minimum was 89.2 m³/s (1962), with an extreme ratio of 8.1. The linear trend indicated an increasing pattern with a rate of 15.3 m³/s per decade. From the smoothed curve, three periods were evident: 1956-1970 (slight decrease), 1971-2000 (stable with small fluctuations, mostly below the mean), and 2001-2021 (increasing trend, mostly above the mean). The Mann-Kendall test confirmed a highly significant increasing trend ($P < 0.01$).

[Figure 2: see original paper]

3.2 POT3M Flood Series

3.2.1 Magnitude Variation POT3M flood magnitude showed an increasing trend (Figure 3). Similar to the AMPD series, three periods were identified: 1956-1970 (stable), 1971-2000 (fluctuating increase, mostly negative anomalies except 1998), and 2001-2021 (fluctuating increase). The trend passed the significance test at the 0.01 level, indicating a highly significant increase.

[Figure 3: see original paper]

3.2.2 Frequency Variation POT3M flood frequency exhibited a significant increasing trend (Figure 4). The smoothed curve revealed: 1956-1970 (slight fluctuations, relatively stable), 1971-2000 (stable period), and 2001-2021 (fluctuating increase). Unlike magnitude, the frequency trend passed the significance test at the 0.05 level.

[Figure 4: see original paper]

3.3 GEV Distribution-Based Flood Levels

3.3.1 Return Period Threshold Calculation GEV distribution fitting parameters for the AMPD series are shown in Table 3. The shape parameter (ξ) was positive (0.124), indicating a Fréchet distribution with good fit quality (K-S test $p > 0.05$). Return period thresholds calculated using MATLAB are presented in Table 4, providing reliable classification standards for small, medium, and large floods.

3.3.2 Flood Frequency Variation by Level Frequency trends for different flood levels were analyzed (Figure 5). Small floods (<20-year return period) dominated, showing a highly significant increasing trend ($P < 0.01$) with Sen's slope of 0.35 floods per decade. Medium floods (20-50-year) and large floods (>50-year) showed no significant trends. Total flood frequency was also highly significant ($P < 0.01$).

[Figure 5: see original paper]

3.3.3 Interdecadal Flood Frequency Variation Interdecadal analysis revealed an overall increasing trend (Figure 6). The 1950s-1960s had relatively few floods, the 1970s-2000s showed gradual increase, and the 2010s reached the maximum frequency. The evolution demonstrates a clear transition from low to high flood frequency.

[Figure 6: see original paper]

3.4 Precipitation and Temperature Variation

Annual precipitation at Yu'erhong and Tuole stations, and temperature at Tuole station, showed significant increasing trends (Figures 7-8). Yu'erhong precipitation had a multi-year average of 302.4 mm with a trend of 15.3 mm per decade ($P < 0.01$). Tuole precipitation averaged 140.3 mm with a trend of 6.9 mm per decade ($P < 0.01$). Tuole temperature averaged -2.4°C with a highly significant warming trend of 0.35°C per decade ($P < 0.01$).

Analysis of precipitation elements at Tuole station (Figure 9) showed increasing trends in both the number of days with single-event precipitation > 10 mm and annual average precipitation intensity. Precipitation and temperature were above normal after 1987, showing sustained increases.

[Figure 7: see original paper]

[Figure 8: see original paper]

[Figure 9: see original paper]

4. Discussion

The upper Shule River region consists primarily of high-altitude mountainous areas with elevation differences of 3700 m from source to Changmabao station. The basin exhibits varying topography, slopes, and underlying surfaces. Influenced by the convergence of plateau monsoon and westerly circulation, the region belongs to the westerly climate zone. Analysis of precipitation changes at Yu' erhong and Tuole stations (Figure 7) reveals that Shule River basin precipitation has increased continuously over recent decades, particularly summer precipitation accounting for an increasing proportion of annual totals. Previous studies confirm these trends: Shi et al. found that northwest China's climate shifted from warm-dry to warm-wet around the early 21st century, characterized by rising temperatures, increasing precipitation, and enhanced glacier melt and runoff. Lan et al. and Xu et al. also documented increasing precipitation trends in the upper Shule River.

Temperature trends at Tuole station (Figure 8) show significant warming. Research indicates that the upper Shule River source area has warmed significantly at 0.40°C per decade, with cold extremes in northwest China's arid region showing increasing trends. Under this warming background, cryosphere changes in glaciers, snow, and permafrost have significantly impacted runoff generation mechanisms in western cold-region basins. Glacier inventory data (first and second Chinese glacier inventories) show the Shule River has 509.87 km² of glacier cover with ice storage of approximately 28.5 km³. Since the 1960s, glacier meltwater has increased under continuous warming, contributing 42.2% of river runoff during 1960–2010. Comparative analysis shows positive correlations between precipitation/temperature at Yu' erhong/Tuole stations and flood magnitude/frequency at Changmabao station, with consistent trend patterns.

However, flood variation characteristics in the upper Shule River mountains are complex, influenced by climate change, cryosphere dynamics, and underlying surface conditions. This study employed only statistical trend analysis; further research is needed on flood simulation mechanisms and impact processes.

5. Conclusions

Based on measured flood data from Changmabao station (1956–2021) and meteorological data, this study analyzed trends in AMPD, POT3M, and GEV-based flood series. Main conclusions are:

- 1) Both magnitude and frequency of floods at Changmabao station increased significantly. AMPD and POT3M magnitudes showed highly significant increases ($P < 0.01$), while POT3M frequency increased significantly ($P < 0.05$). GEV-based floods were dominated by small floods, with total flood frequency showing highly significant increases ($P < 0.01$).
- 2) Precipitation and temperature data from Yu' erhong and Tuole stations revealed significant fluctuating increases after 1987. Heavy precipitation

and increased meltwater from glaciers, alpine snow, and permafrost due to warming were the primary drivers of significant increases in flood magnitude and frequency across all three sampling series.

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