# Variation Characteristics of Runoff and Precipitation in the Upper Yellow River over the Past 60 Years (Postprint)

**Authors:** Artistic Achievement

**Date:** 2022-08-08T00:00:00+00:00

## Abstract

To investigate the variation characteristics of runoff and precipitation in the upper Yellow River basin, based on nearly 60 years of precipitation and runoff data from three hydrological stations (Tangnaihai, Xiaheyan, and Toudaoguai), this study employed linear trend test, Mann-Kendall test (M-K trend test), Spearman rank correlation test, M-K change-point test, Pettitt non-parametric test, ordered cluster analysis, cumulative anomaly method, and double mass curve to conduct a comparative analysis of precipitation and runoff variation characteristics in the upper Yellow River basin and its different sub-regions, and discussed the response relationship of runoff to precipitation. The results show that: precipitation in the upper Yellow River basin exhibits an insignificant increasing trend, with an abrupt change occurring in 2003 and a change rate of 4.67% before and after the change-point; runoff shows a significant decreasing trend, with the change-point year being 1986 and a change rate of 35.34% before and after the change-point. The annual precipitation trends in the three sub-regions show significant increase, insignificant increase, and significant decrease, respectively, while runoff in all sub-regions demonstrates a decreasing trend. When Region I above Tangnaihai is taken as the reference region, the influence of precipitation factors on runoff in Region II (Tangnaihai–Xiaheyan) reaches 25.08%, with non-precipitation factors accounting for 74.92%; in Region III (Xiaheyan–Toudaoguai), the influence of precipitation on runoff is 32.14%, with non-precipitation factors accounting for 67.86%. The research findings provide a reference for integrated water resources management and scientific allocation in the Yellow River basin.

# Variation Characteristics of Runoff and Precipitation in the Upper Yellow River over the Past 60 Years

**CHENG Yi**[1,2], **WU Lanzhen**[3], **LIU Fenggui**[1], **SHEN Yanjun**[1,2]
[1]College of Geographical Science, Qinghai Normal University, Xining 810008, China
[2]Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050022, China
[3]College of Water Conservancy and Hydropower Engineering, Gansu Agricultural University, Lanzhou 730070, China

**Abstract:** To investigate the variation characteristics of runoff and precipitation in the upper Yellow River, this study analyzed precipitation and runoff data from three hydrological stations (Tangnaihai, Xiaheyan, and Toudaoguai) over the past 60 years using linear trend test, Mann-Kendall (M-K) trend test, Spearman' s rank correlation test, Pettitt' s nonparametric test, orderly clustering analysis, cumulative anomaly method, and double-mass curve. The results reveal an insignificant increasing trend in precipitation across the upper Yellow River, with an abrupt change occurring in 2003 and a change rate of 2.49% before and after the mutation. Runoff exhibits a significant decreasing trend, with an abrupt change in 1986 and a change rate of 35.34% before and after the mutation. When the region above Tangnaihai station is taken as the baseline, precipitation in the Tangnaihai-Xiaheyan and Xiaheyan-Toudaoguai subregions shows significant increase and significant decrease trends, respectively, while runoff in all subregions demonstrates decreasing trends. Precipitation factors account for 25.08% of runoff variation in the Tangnaihai-Xiaheyan subregion and 32.14% in the Xiaheyan-Toudaoguai subregion, indicating that non-precipitation factors dominate runoff changes. These findings provide scientific references for integrated water resources management and allocation in the Yellow River Basin.

**Keywords:** Upper Yellow River and its subregions; runoff; precipitation; variation characteristics; response relationship

## 1 Introduction

Precipitation and runoff are critical components of the natural water cycle that profoundly influence regional water resources. Precipitation represents the most important factor determining the spatiotemporal distribution of water resources and serves as a key indicator of regional physical geography characteristics. Runoff constitutes a major component and primary manifestation of water resources, representing a crucial link in surface water cycling and a fundamental element of water balance, as well as the primary source for socioeconomic water use. However, runoff variation is affected by precipitation changes, making it essential to study the patterns and characteristics of regional precipitation and runoff, their interrelationships, and influencing factors to understand hydrological evolution and provide references for integrated water resources management.

The Yellow River, China’ s second longest river, serves as a vital water source for northwestern and northern China, supporting 13% of the nation’ s cultivated land and 12% of its population. The basin hosts three regional urban agglomerations (Guanzhong Plain, Central Plains, and Shandong Peninsula) and four local urban agglomerations (Lanzhou-Xining, Ningxia Yellow River, Hohhot-Baotou-Ordos-Yulin, and Central Shanxi), playing a crucial role in China’ s socioeconomic development and ecological security. However, influenced by its geographical location and East Asian monsoon climate, most of the basin belongs to arid and semi-arid regions with annual precipitation between 200–600 mm and natural water endowment far from adequate. Per capita water resources are only 27% of the national average, with water shortages reaching 8.60$×10^{9}$ m$^{3}$ and a shortage rate as high as 38.6%, creating prominent supply-demand contradictions.

Consequently, numerous scholars have conducted extensive research on key hydrological elements (runoff and precipitation) and their influencing factors in the Yellow River Basin. For instance, Bao et al. analyzed the effects of different precipitation magnitudes on runoff changes in the Yellow River source region using daily precipitation and runoff data. Wei et al. investigated spatial distribution characteristics of runoff abundance and deficiency and their influencing factors in the region above Lanzhou. Ning et al. examined runoff variation trends in typical watersheds of the middle Yellow River and explained the roles of climate change and human activities. Pan et al. explored variation characteristics and patterns of runoff and precipitation in the lower Yellow River over 50 years. Wang et al. analyzed overall variation characteristics of runoff processes across the Yellow River Basin using multi-dimensional runoff regime indicators. Although scholars have investigated precipitation and runoff variation patterns using different methods, station data, and time series, research findings show certain discrepancies, and most studies on upper Yellow River precipitation and runoff have concentrated on the source region above Tangnaihai station. Research covering the entire upper region (source to Toudaoguai) remains limited, with most focusing on pre- and post-mutation changes and influencing factors rather than sub-regional precipitation-runoff responses, which remain largely unexplored.

Therefore, based on the upper Yellow River’ s geographical characteristics and using typical hydrological stations as boundaries, this study divides the upper Yellow River into three subregions to investigate precipitation and runoff variation trends and their responses, providing scientific support for ecological protection and high-quality development in the Yellow River Basin.

## 2.1 Data Sources

This study uses annual measured runoff data from three hydrological stations in the upper Yellow River (Tangnaihai, Xiaheyan, and Toudaoguai) from

1960-2019, obtained from the National Earth System Science Data Center (http://www.geodata.cn). Precipitation data for the same period were validated against observations from 45 independent meteorological stations. For subregional analysis, runoff data for the region above Tangnaihai uses measured data from Tangnaihai station; runoff variation for Tangnaihai-Xiaheyan and Xiaheyan-Toudaoguai subregions uses the difference between corresponding hydrological stations.

## 2.2 Research Methods

**Trend Tests:** Linear trend estimation is the most direct and effective method for trend analysis, establishing a linear function between element x  and time sequence i to test trend significance. Moving average is a fundamental trend-fitting technique that reduces data freedom while enhancing sequence correlation, using smoothed values to display trends. The Mann-Kendall (M-K) trend test is a nonparametric method requiring no specific distribution and resistant to outliers, using statistic Z to determine trend direction and significance ($|Z| > Z_{\alpha/2}$ at $\alpha = 0.05$ indicates significance). Spearman’ s rank correlation test is another nonparametric method using rank correlation coefficient (r ) to identify trends, with t-test verifying significance.

**Mutation Tests:** The M-K test identifies mutation points through intersection of forward and backward statistics U within confidence intervals. Pettitt’s test is a nonparametric method robust to outliers, detecting mutations by maximizing statistic U , . Significance is tested using statistic $P = 2\exp[-6U\,,^{2}/(N^{3}+N^{2})]$, with $P < \alpha$ indicating significant mutation. Orderly clustering analysis calculates optimal segmentation points minimizing within-class variance while maximizing between-class variance. The cumulative anomaly method reflects trends through cumulative departure curves, with turning points indicating mutations.

**Double-Mass Curve Method:** This commonly used method analyzes consistency and trends in hydro-meteorological elements. Under natural conditions, cumulative runoff depth (R) relates to cumulative precipitation (P) as $R = kP + b$. When disturbed, the relationship changes, allowing quantification of non-precipitation impacts through differences between simulated and measured runoff.

## 3.1.1 Variation Trends of Precipitation and Runoff in the Upper Yellow River

Analysis of annual precipitation data and measured runoff at Toudaoguai station shows average precipitation of 419.9 mm, with maximum in 1967 (559.3 mm) and minimum in 2002 (241.0 mm). The linear trend indicates an insignificant increase of 1.80 $\mathrm{mm}\cdot(10\mathrm{a})^{-1}$. Runoff shows a significant decreasing trend of $1.94\times10^{8}$ $\mathrm{m}^{3}\cdot(10\mathrm{a})^{-1}$, with maximum in 1964 ($4.38\times10^{8}$ $\mathrm{m}^{3}$) and minimum in 2002 ($1.12\times10^{8}$ $\mathrm{m}^{3}$). M-K and Spearman tests confirm precipitation’ s insignificant increase ($Z = 0.78$, $|Z| < Z_{\alpha/2} = 1.96$; $r = 0.09$

$> 0$) and runoff' s significant decrease ($Z = -3.82$, $|Z| > Z_{\alpha/2} = 1.96$; $r = -0.51 < 0$, $|T| = 3.82 > T_{\alpha/2} = 2.01$).

### 3.1.2 Abrupt Change Analysis of Precipitation and Runoff

M-K test curves suggest potential mutation years around 2003 for precipitation and 1986 for runoff. Pettitt' s test confirms precipitation mutation in 2003 (U , = 182, P = 0.88 > 0.05, insignificant) and runoff mutation in 1986 (U , = 7090, P = 0, significant). Orderly clustering analysis identifies 2003 and 1986 as optimal segmentation points with minimum variance. Cumulative anomaly curves further verify these mutations. Comprehensive analysis determines precipitation mutation in 2003 (average 415.7 mm before, 435.1 mm after, 2.49% change rate) and runoff mutation in 1986 (average 3.50$\times10^{8}$ m$^3$ before, 2.26$\times10^{8}$ m$^3$ after, 35.34% change rate).

### 3.2.1 Subregional Variation Trends of Precipitation and Runoff

Subregional analysis reveals decreasing precipitation from west to east: Zone I (source-Tangnaihai) at 537.9 mm, Zone II (Tangnaihai-Xiaheyan) at 449.3 mm, and Zone III (Xiaheyan-Toudaoguai) at 271.7 mm. Runoff variation decreases similarly, with Zone III showing negative values indicating complete consumption. Linear trends show Zone I precipitation decreasing at 2.8 mm · (10a)$^{-1}$, Zone II increasing at 9.1 mm · (10a)$^{-1}$, and Zone III decreasing at 11.5 mm · (10a)$^{-1}$. All zones show runoff decrease: Zone I at 3.5$\times10^{8}$ m$^3$ · (10a)$^{-1}$, Zone II at 11.5$\times10^{8}$ m$^3$ · (10a)$^{-1}$, and Zone III at 1.5$\times10^{8}$ m$^3$ · (10a)$^{-1}$. M-K and Spearman tests confirm Zone I precipitation insignificantly decreasing, Zone II significantly increasing, and Zone III significantly decreasing, while all zones show runoff decrease.

### 3.2.2 Response Analysis of Runoff to Precipitation Changes

Correlation analysis using Spearman, Kendall, and Pearson methods shows precipitation-runoff correlations varying by zone: Zone I ($r = 0.67$), Zone II ($r = 0.45$), and Zone III ($r = 0.53$). Using Zone I as the baseline (least human disturbance), double-mass curve analysis quantifies precipitation' s impact on runoff. Results show precipitation factors account for 25.08% of runoff variation in Zone II (non-precipitation factors 74.92%) and 32.14% in Zone III (non-precipitation factors 67.86%). This indicates human activities (e.g., reservoirs, irrigation) dominate runoff changes in Zones II and III.

## 5 Conclusions

1) Previous research on upper Yellow River runoff and precipitation has primarily focused on the source region above Tangnaihai (Zone I), with limited studies covering the entire upper region. This study uses data from

Toudaoguai control station, but the large control area spanning three plateau regions means conclusions may not represent the entire upper Yellow River. Additionally, intra-annual precipitation intensity effects warrant further investigation.

2) Over the past 60 years, precipitation in the upper Yellow River shows an insignificant increasing trend (1.80 mm · $(10\mathrm{a})^{-1}$), while runoff shows a significant decreasing trend (1.94\$×10^{8}\$ m$^{3}$ · $(10\mathrm{a})^{-1}$). Precipitation mutated in 2003 (2.49% change rate), while runoff mutated in 1986 (35.34% change rate), indicating inconsistent changes.

3) Subregional analysis reveals precipitation trends of significant increase, insignificant increase, and significant decrease for Zones I, II, and III respectively, while all zones show decreasing runoff trends. Correlation analysis shows precipitation’ s greatest impact on runoff in Zone I (source region), followed by Zone III, with Zone II showing the weakest relationship.

4) Using minimally disturbed Zone I as baseline, double-mass curve analysis indicates precipitation accounts for 25.08% of runoff variation in Zone II and 32.14% in Zone III, with non-precipitation factors (especially large reservoirs and irrigation) dominating. The substantial non-precipitation impact in Zone III aligns with its status as a major irrigation area. However, even Zone I experiences some human activities (e.g., Bando Reservoir, 2010) and climate change impacts (e.g., permafrost degradation), requiring further quantification of these non-precipitation effects.

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