

Attribution Analysis of Runoff Variation in the Datong River Basin, Qinghai-Tibet Plateau (Postprint)

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Abstract

The Datong River Basin is located at the northeastern edge of the Tibetan Plateau, featuring a sensitive and fragile ecological environment. Research on water resources evolution and attribution under changing environments is of great significance for protecting the regional water ecological environment and ensuring water ecological civilization construction. Using statistical methods such as linear trend estimation, concentration degree, concentration period, ordered cluster test, and wavelet analysis, this study analyzed the interannual variation, intra-annual distribution, periodicity, and abrupt change characteristics of basin runoff. Based on the cumulative slope change rate method and double mass curve, the impacts of climatic factors and human activities on runoff variation were quantitatively assessed. The results indicate: (1) Over the past 60 years, the Datong River Basin has experienced significant warming and wetting, with average annual temperature, precipitation, and potential evaporation increasing at rates of $0.42\text{ }^{\circ}\text{C} \cdot (10\text{a})^{-1}$, $8.9\text{ mm} \cdot (10\text{a})^{-1}$, and $5.6\text{ mm} \cdot (10\text{a})^{-1}$, respectively, while annual runoff shows a decreasing trend with a rate of $0.67 \times 10^8 \text{ m}^3 \cdot (10\text{a})^{-1}$. (2) The runoff concentration degree and non-uniformity coefficient show a weak decreasing trend, dry season runoff exhibits a significant increasing trend, annual distribution becomes more uniform, and the concentration period shows a delaying trend at a rate of $3.0\text{ d} \cdot (10\text{a})^{-1}$. (3) Annual runoff shows significant periodic oscillations at approximately 44-year scales, with an abrupt change occurring in 1990. After the mutation, runoff decreased by $3.52 \times 10^8 \text{ m}^3$, glacier distribution in the basin shows a decreasing trend, and vegetation coverage shows no significant change. (4) The contribution rates of climate and human activities to runoff reduction in the Datong River are -17.7% and 117.7%, respectively. Precipitation is the main source of water supply for the basin, and inter-basin water transfer is the primary driving factor causing runoff reduction.

Full Text

Preamble

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Attribution Analysis of Runoff Change in the Datong River Basin, Qinghai-Tibet Plateau

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Abstract: The Datong River Basin is located on the northeastern edge of the Qinghai-Tibet Plateau, characterized by a sensitive and fragile ecological environment. Research on water resource evolution and attribution under changing environments is crucial for protecting regional water ecology and ensuring water ecological civilization construction. This study employs statistical methods including linear trend estimation, concentration degree, concentration period, ordered clustering test, and wavelet analysis to examine interannual variation, seasonal distribution, periodicity, and abrupt change characteristics of basin runoff. Based on the cumulative slope change rate method and double mass curve, the impacts of climatic factors and human activities on runoff variation are quantitatively evaluated. The results indicate: (1) The climate in the Datong River Basin has shown significant warming and humidification, with average annual temperature, precipitation, and potential evapotranspiration increasing at rates of $0.42\text{ }^{\circ}\text{C} \cdot (10\text{a})^{-1}$, $8.9\text{ mm} \cdot (10\text{a})^{-1}$, and $5.6\text{ mm} \cdot (10\text{a})^{-1}$, respectively. Annual runoff exhibits a decreasing trend with a rate of $0.67 \times 10^8\text{ m}^3 \cdot (10\text{a})^{-1}$. (2) Runoff concentration degree and unevenness coefficient show a weak declining trend, while dry season runoff demonstrates a significant increasing trend, indicating more uniform seasonal distribution with a delayed concentration period at a rate of $3.0\text{ d} \cdot (10\text{a})^{-1}$. (3) Annual runoff exhibits significant oscillation at approximately 44-year scales, with an abrupt change occurring around 1990. Post-mutation runoff decreased by $3.52 \times 10^8\text{ m}^3$. Glacier distribution in the basin shows a decreasing trend, while vegetation cover remains largely unchanged. (4) Climate change and human activities contribute -17.7% and 117.7% to runoff reduction, respectively. Precipitation constitutes the primary water source, while inter-basin water transfer represents the main anthropogenic driver of runoff decline.

Keywords: runoff evolution; cumulative slope change rate method; climate change; human activities; Datong River Basin

1. Study Area Overview

The Datong River, the largest first-order tributary of the Huangshui River, originates from the Tuole Nanshan Mountains in Tianjun County, Qinghai Province. Geographically situated between 98°30' ~103°15' E and 36°30' ~38°25' N, the main stream spans 572 km with a drainage area of 15,126 km². The river source elevation is 4,520 m, while the estuary elevation is 1,727 m, yielding an average channel gradient of 4.19%. The river system exhibits a dendritic pattern with well-developed tributaries. The upper reach extends from the source to Gadatan (308.4 km), featuring major right-bank tributaries including Moriqu, Jiangcangqu, and Yong'an River. The middle reach from Gadatan to Liancheng (223.4 km) displays a pinnate drainage pattern with main tributaries such as Baishui River, Laohugou, and Tuolagou. The lower reach below Liancheng (40.2 km) continues this pattern.

The Datong River Basin belongs to an inland alpine climate zone characterized by long winters, short summers, extended freezing periods, cold temperatures, and abundant annual precipitation with concurrent rainfall and heat. The multi-year average temperature ranges from -0.3 to 8.0 °C, with extreme minimum and maximum temperatures of -34.1 °C and 35.8 °C, respectively. Mean annual precipitation is 500.6 mm, with precipitation and runoff distribution following similar seasonal patterns.

[Figure 1: see original paper]

2.1 Data Sources

The Xiangtang Hydrological Station at the basin outlet controls a drainage area of 15,126 km² and has conducted observations since 1945, providing complete and continuous daily runoff data compiled by the Yellow River Commission. Meteorological data including daily precipitation, temperature, relative humidity, sunshine duration, and wind speed from five stations within and around the basin from 1960 to 2020 were obtained from the China Meteorological Data Network (<http://data.cma.cn>). Areal precipitation, potential evapotranspiration, and mean temperature were calculated using the Thiessen polygon method. Considering data series length and completeness, a unified 1960-2020 series was adopted for hydro-meteorological element analysis. Glacier distribution data [9] and surface vegetation index products [10] were sourced from the National Tibetan Plateau Data Center (<http://data.tpdc.ac.cn>), based on Landsat series imagery from 1980-2015 with 30 m spatial resolution and annual temporal resolution for glacier change quantification. Vegetation index products with 30 m spatial resolution were synthesized using the maximum value composite method to calculate monthly Normalized Difference Vegetation Index (NDVI) and subsequently Fractional Vegetation Cover (FVC).

2.2.1 Potential Evapotranspiration

Potential evapotranspiration was calculated using the Penman-Monteith formula [11]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is potential evapotranspiration ($\text{mm} \cdot \text{d}^{-1}$), R_n is net radiation at the surface ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), G is soil heat flux ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), T_{mean} is mean daily temperature ($^{\circ}\text{C}$), u_2 is wind speed at 2 m height ($\text{m} \cdot \text{s}^{-1}$), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure curve ($\text{kPa} \cdot ^{\circ}\text{C}^{-1}$), and γ is the hygrometer constant ($\text{kPa} \cdot ^{\circ}\text{C}^{-1}$).

2.2.2 Trend and Abrupt Change Detection

Linear Trend Estimation: For a variable y_i with sample size n and corresponding time x_i , the linear regression equation is established as:

$$y_i = ax_i + b \quad (i = 1, 2, \dots, n)$$

where a is the regression coefficient and b is the constant, estimated via least squares. The correlation coefficient r between x_i and y_i is calculated as:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

Ordered Clustering Test: This method identifies optimal segmentation points by minimizing the sum of squared deviations before and after the potential mutation point:

$$V_\tau = \sum_{t=1}^{\tau} (x_t - \bar{x}_\tau)^2, \quad V_{n-\tau} = \sum_{t=\tau+1}^n (x_t - \bar{x}_{n-\tau})^2$$

where V_τ and $V_{n-\tau}$ represent the sum of squared deviations before and after the segmentation point τ , respectively; x_t is the sequence value; \bar{x}_τ and $\bar{x}_{n-\tau}$ are the means before and after τ . The total sum of squared deviations $S_n(\tau) = V_\tau + V_{n-\tau}$ reaches its minimum at the optimal segmentation point.

Pettitt Test: This non-parametric test effectively identifies abrupt changes in hydro-meteorological series. For a time series x of length n , a rank series is constructed:

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{otherwise} \end{cases} \quad (j = 1, 2, \dots, i)$$

The test statistic is $k_t = \max |U_{t,n}|$ where $U_{t,n} = \sum_{i=1}^t \sum_{j=i+1}^n r_i$. The corresponding time t of the maximum statistic represents the mutation point. The significance probability is $P = 2 \exp[-6k_t^2/(n^3 + n^2)]$, and when $P < 0.5$, the detected mutation point is statistically significant.

2.2.3 Wavelet Periodicity Analysis

Wavelet analysis [17], developed from Fourier transform, clearly reveals multiple variation cycles hidden in time series and is widely applied in hydro-meteorological periodicity identification. Wavelet variance identifies oscillation intensity and periodic characteristics across scales, with larger variance values indicating more pronounced cycles. For a wavelet function ψ , the continuous wavelet transform is:

$$W_f(a, b) = \frac{1}{\sqrt{|a|}} \int_R f(t) \psi\left(\frac{t-b}{a}\right) dt$$

where $W_f(a, b)$ is the wavelet coefficient, a is the scale factor, b is the translation factor, and R represents the real number domain.

2.2.4 Runoff Change Attribution Identification

Cumulative Slope Change Rate Method: This method establishes linear relationships between impact factors and years during baseline and mutation periods, calculating contribution rates through slope change rate ratios. The slope change rates of cumulative precipitation, potential evapotranspiration, and runoff are:

$$\Delta P = (P_b - P_a)/P_a, \quad \Delta ET = (ET_b - ET_a)/ET_a, \quad \Delta R = (R_b - R_a)/R_a$$

where ΔP , ΔET , and ΔR represent change rates relative to the natural period; P_a , ET_a , R_a and P_b , ET_b , R_b are pre- and post-mutation linear relationship slopes, respectively. Positive (negative) values indicate slope increase (decrease).

Typically, runoff correlates positively with precipitation and negatively with potential evapotranspiration:

$$C_P = \frac{\Delta P}{\Delta R} \times 100\%, \quad C_{ET} = -\frac{\Delta ET}{\Delta R} \times 100\%$$

where C_P and C_{ET} are precipitation and potential evapotranspiration contributions to runoff change. Human activity contribution is $C_H = 1 - C_P - C_{ET}$.

Double Mass Curve Method: This method validates attribution results. Under natural conditions, cumulative precipitation-runoff should form a straight line with fixed slope. Significant slope changes indicate increasing human impact, with the change year identified as the mutation point. Using baseline period precipitation-runoff relationships and change-period precipitation, theoretical runoff under precipitation influence alone is calculated. The difference from baseline runoff represents precipitation impact, with the residual attributed to human activities.

3.1 Interannual Variation Trend Analysis

The Datong River Basin climate demonstrates clear warming and humidification trends (Table 1). Mean annual temperature shows a highly significant increasing trend of $0.42 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$, exceeding the global rate of $0.26 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$. Annual precipitation increases at $8.9 \text{ mm} \cdot (10\text{a})^{-1}$, while potential evapotranspiration increases at $5.6 \text{ mm} \cdot (10\text{a})^{-1}$. Annual runoff exhibits a decreasing trend of $0.67 \times 10^8 \text{ m}^3 \cdot (10\text{a})^{-1}$, with maximum and minimum values of $50.19 \times 10^8 \text{ m}^3$ (1989) and $19.95 \times 10^8 \text{ m}^3$ (2002), respectively, yielding an extreme ratio of 2.5. Annual precipitation, potential evapotranspiration, and runoff all pass significance tests at $\alpha=0.05$.

3.2 Runoff Intra-annual Variation Characteristics

Runoff concentration degree and unevenness coefficient show weak declining trends, indicating increasingly uniform seasonal distribution. Flood season (May-October) runoff proportion decreases, while dry season (November-April) runoff increases significantly, reflecting improved ecological conditions and enhanced water storage capacity. The concentration period exhibits a delayed trend at $3.0 \text{ d} \cdot (10\text{a})^{-1}$, with the 2010s average delayed by 8 days compared to the 1960s. Summer runoff (June-August) accounts for 48.1% of annual total, far exceeding other seasons, yet shows a decreasing trend.

3.3 Runoff Periodicity Analysis

Wavelet analysis reveals primary periodic oscillations at approximately 44-year scales, with the most significant peak indicating the first dominant period. Secondary periods exist at 22-year and 12-year scales. At the ~44-year scale, runoff has experienced alternating wet-dry transitions since the 1960s, with the current wet period continuing as the wavelet contour remains unclosed.

[Figure 4: see original paper]

3.4 Runoff Abrupt Change Characteristics

Preliminary diagnosis via process lines and cumulative anomalies suggests an abrupt change around 1990. The Pettitt test identifies 1990 as the maximum statistic point ($k_t = 458$, $P = 0.063 < 0.5$), while ordered clustering shows minimum sum of squared deviations in 1990, confirming a significant mutation. Comprehensive detection methods establish 1990 as the mutation year. Accelerated hydropower development since the late 1980s and the 1994 completion of the “Datong-to-Qinwangchuan” water transfer project represent primary causes of this abrupt change.

[Figure 5: see original paper]

3.5 Quantitative Assessment of Runoff Change

Cumulative curves of annual runoff depth, precipitation, and potential evapotranspiration show distinct slope changes around 1990 (Figure 6). Post-mutation precipitation and potential evapotranspiration cumulative slope change rates are positive, while runoff depth slope change rate is negative, confirming increasing precipitation/evapotranspiration but decreasing runoff. Compared to the baseline period (1960-1990), the change period (1991-2020) shows runoff reduction of $3.52 \times 10^8 \text{ m}^3$ (12.1%), precipitation increase of 14.5 mm (2.9%), and potential evapotranspiration increase of 11.1 mm (2.0%).

Using the cumulative slope change rate method, climate change contributions are: precipitation increase (-31.4%, negative contribution) and evapotranspiration increase (13.7%, positive contribution). Human activities contribute 117.7% to runoff reduction, indicating they dominate runoff change.

3.6 Double Mass Curve Validation

Double mass curve validation yields similar results: climate change increases runoff by $1.40 \times 10^8 \text{ m}^3$ (contribution rate -39.8%), while human activities decrease runoff by $4.92 \times 10^8 \text{ m}^3$ (contribution rate 139.8%). These results closely match the cumulative slope change rate method, confirming reliability.

[Figure 7: see original paper]

3.7.1 Meteorological Factors' Impact Analysis

Key meteorological factors include precipitation, temperature, and evapotranspiration. Precipitation is the dominant positive contributor, accounting for 80.4% of annual runoff during the flood season. Temperature shows negative correlation with annual runoff—while warming increases evapotranspiration (reducing runoff), it also accelerates snow/ice melt. Glacier area interpretation reveals overall reduction from 37.0 km² in 1990 to 21.3 km² in 2020, stabilizing after 2015, but this contributes insignificantly to runoff change.

3.7.2 Vegetation Change Impact Analysis

The sparsely populated basin has low development intensity, with forests and grasslands covering most area. Short-term underlying surface conditions remain relatively stable, so changes primarily reflect vegetation functional variation. While some studies suggest increased Fractional Vegetation Cover (FVC) reduces runoff, others indicate enhanced water yield capacity. In the Datong River Basin, FVC trends are insignificant and weakly correlated with runoff, indicating minimal impact.

3.7.3 Water Conservancy Projects Impact Analysis

Water Storage Projects: The basin hosts 18 hydropower stations (including 2 reservoirs) with total installed capacity of 566.97 MW, primarily in the middle-lower reaches. Except for the Kunnazixia and Shitouxia reservoirs (which regulate runoff and floods), most run-of-river stations have minimal storage impact. Reservoir operation redistributes natural inflow, reducing flood season concentration and increasing dry season flow (Figure 8).

Water Diversion Projects: Under the basin water allocation plan, designed inter-basin transfer totals 1.443×10^9 m³, including: Datong-to-Xining (0.750×10^9 m³), Datong-to-Qinwangchuan (0.250×10^9 m³), and Datong-to-Huangshui (0.443×10^9 m³). The Datong-to-Qinwangchuan project (completed 1994) diverts water from downstream of Tiantang Station to Qinwangchuan, with maximum annual diversion of 0.191×10^9 m³ (2015). The Datong-to-Xining project (under construction) transferred 0.117×10^9 m³ annually to Baoku River (2015–2020). Since 1994, annual diverted water exceeds 30% of Xiangtang Station's natural runoff, making inter-basin transfer the key factor driving runoff reduction.

[Figure 8: see original paper]

[Figure 9: see original paper]

4 Conclusions

Based on hydro-meteorological data from the Datong River Basin, this study analyzed runoff evolution characteristics and quantitatively assessed climate change and human activity impacts using the cumulative slope change rate method and double mass curve validation. The main conclusions are:

1. The Datong River Basin climate has warmed and humidified significantly, with temperature, precipitation, and potential evapotranspiration increasing at $0.42 \text{ }^\circ\text{C} \cdot (10\text{a})^{-1}$, $8.9 \text{ mm} \cdot (10\text{a})^{-1}$, and $5.6 \text{ mm} \cdot (10\text{a})^{-1}$, respectively. Annual runoff shows a decreasing trend of $0.67 \times 10^8 \text{ m}^3 \cdot (10\text{a})^{-1}$, with an abrupt change in 1990 reducing runoff by $3.52 \times 10^8 \text{ m}^3$ (12.1%).
2. Runoff concentration degree and unevenness coefficient exhibit weak de-

clining trends, with dry season runoff increasing significantly. Seasonal distribution has become more uniform, and the concentration period has delayed at $3.0 \text{ d} \cdot (10\text{a})^{-1}$.

3. Annual runoff displays significant periodic oscillations at ~ 44 -year scales, representing the first dominant period. The current wet period's wavelet contour remains unclosed, suggesting continued above-normal runoff in the near future.
4. Climate change and human activities contribute -17.7% and 117.7% to runoff reduction, respectively. Precipitation is the primary water source, while inter-basin water transfer constitutes the main anthropogenic driver of runoff decline.

References

- [1] Zhang Jianyun, Wang Guoqing. Quantitative identification of river runoff change and attribution[M]. Beijing: Science Press, 2014.
- [2] Du Jiani, Cai Yiqing, Liu Xisheng, et al. Attribution analysis of runoff in the Huangshui River based on the Budyko hypothesis[J]. China Rural Water and Hydropower, 2022(7): 116-121.
- [3] Wu Hengqing, Liu Saiyan, Huang Qiang, et al. SWAT model based runoff simulation of Datong River Basin[J]. Journal of Northwest A & F University (Natural Science Edition), 2015, 43(9): 210-216.
- [4] Bai Yanling, Wang Fang, Liu Yang. Quantitative analysis of runoff evolution and driving factors in the upper reaches of Datong River[J]. South North Water Transfers and Water Science & Technology, 2021, 19(1): 103-110, 167.
- [5] Wang Dachao. Runoff variation characteristics for Datong River and its influencing factors[D]. Lanzhou: Lanzhou University, 2019.
- [6] Zhang Chengfeng, Liu Cuishan, Wang Guoqing, et al. Attribution of runoff variation for the Yellow River source region based on the Budyko hypothesis[J]. China Rural Water and Hydropower, 2020(9): 90-94.
- [7] Wang Suiji, Yan Yunxia, Yan Ming, et al. Contributions of precipitation and human activities to the runoff change of the Huangfuchuan Drainage Basin: Application of comparative method of the slope changing ratio of cumulative quantity[J]. Acta Geographica Sinica, 2012, 67(3): 388-397.
- [8] Guo Aijun, Chang Jianxia, Huang Qiang, et al. Quantitative analysis of the impacts of climate change and human activities on runoff change in Weihe Basin[J]. Journal of Northwest A & F University (Natural Science Edition), 2014, 42(8): 212-220.
- [9] Li Jia, Wang Yingzheng, Li Jianjiang. Glacier outlines over the Qilian Mountain area (1980–2015)[DB]. National Tibetan Plateau/Third Pole Environment Data Center, <https://doi.org/10.11888/Geogra.tpdc.270234>.

- [10] Zhong Bo, Wu Junjun. Landsat based continuous monthly 30 m \times 30 m land surface NDVI dataset in Qilian Mountain area (1986–2017)[DB]. National Tibetan Plateau/Third Pole Environment Data Center, <https://doi.org/10.11888/Geogra.tpd.270136>.
- [11] GB/T20481-2017. National Standard of the People' s Republic of China: Grades of meteorological drought[S]. Beijing: Standard Press of China, 2017.
- [12] Wei Fengying. Modern technology of statistics, diagnosis and forecast for climate[M]. Beijing: China Meteorological Press, 2007.
- [13] Mu Xingming, Zhang Xiuqing, Gao Peng, et al. Theory of double mass curves and its applications in hydrology and meteorology[J]. Chinese Journal of Hydrology, 2010, 30(4): 47-51.
- [14] Huang Qiang, Huang Shengzhi, Pan Jingjing. Theory and methods of hydrological sequence variation diagnosis[M]. Beijing: Science Press, 2020.
- [15] Guan Yinghui, Wang Shuzhi, Wen Deping. Variations and cause analysis of runoff and sediment load in the source regions of Yangtze River[J]. Journal of Sediment Research, 2021, 46(3): 43-49, 56.
- [16] Cheng Yi, Wu Lanzhen, Liu Fenggui, et al. Changes of runoff and precipitation in the upstream of Yellow River during the past 60 years[J]. Arid Land Geography, 2022, 45(4): 1022-1031.
- [17] Yang Dawen, Zhang Shulei, Xu Xiangyu. Attribution analysis for runoff decline in Yellow River Basin during past fifty years based on Budyko hypothesis[J]. Scientia Sinica Technologica, 2015, 45(10): 1024-1034.
- [18] Cai Yiqing, Li Wenhui, Yu Zexing, et al. Temporal and spatial evolution of precipitation in the headwaters of the Yangtze River[J]. Journal of Yangtze River Scientific Research Institute, 2022, 39(5): 28-35.
- [19] Liu Yu, Guan Zilong, Tian Jiyang, et al. Runoff change and its driving factors in Jinghe River Basin in recent 70 years[J]. Arid Land Geography, 2022, 45(1): 17-26.
- [20] Alexander L V, Allen S K, Bindoff N L, et al. Summary for policymakers[M]//IPCC. Climate Change 2013: The Physical Science Basis. Cambridge: Cambridge University Press, 2013.

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