Postprint: Study on Runoff Variation and Its Driving Factors in the Jinghe River Basin over the Past 70 Years

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Abstract

Quantitatively evaluating watershed runoff change characteristics and conducting attribution identification research constitute the foundation for addressing climate change and achieving rational development and utilization of water resources. This study takes the Jinghe River Basin as the research area, employing methods including the M-K test, moving t-test, and wavelet analysis to analyze the change characteristics of hydro-meteorological elements in the basin over the past 70 a, and evaluates the contribution rates of climate change and human activities to runoff change based on the Budyko hypothesis. The results indicate: (1) The annual runoff depth in the Jinghe River Basin decreased at a rate of 0.41 $\mathrm{mm \cdot a^{-1}}$, with a significant abrupt reduction occurring in 1996, representing a 43.49% decrease compared to the pre-abrupt period. (2) The first, second, and third primary periods of annual runoff depth in the basin are 41 a, 58 a, and 15 a characteristic time scales, respectively. (3) Runoff change in the basin is relatively sensitive to changes in both flood season precipitation and potential evapotranspiration, with the sensitivity of runoff change to precipitation being 2.3–5.3 times that to potential evapotranspiration. (4) Human activities are the primary influencing factor of runoff change in the basin, with contribution rates to annual, flood season, and non-flood season runoff changes of 90.43%, 63.75%, and 94.08%, respectively. The research results can provide a scientific basis for integrated regional water resources management and scientific allocation, and offer certain guiding significance for soil and water loss control in the Loess Plateau.

Full Text

Runoff Change and Its Driving Factors in the Jinghe River Basin Over the Past 70 Years

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Abstract

Quantitative evaluation and attribution identification of runoff change characteristics are fundamental to achieving rational water resource development and utilization in response to climate change. This study examines the Jinghe River Basin as the research area, employing the Mann-Kendall test, sliding t-test, wavelet analysis, and other methods to analyze the hydrometeorological element variation characteristics. Based on the Budyko hypothesis, we evaluate the contributions of climate change and human activities to runoff variation. The results indicate that: (1) The annual runoff depth in the Jinghe River Basin decreased at a rate of 0.41 $\mathrm{mm \cdot a^{-1}}$, with a significant abrupt reduction occurring in 1996, representing a 43.49% decrease compared to the pre-abrupt change period. (2) The first, second, and third primary periods of annual runoff depth are 41 years, 58 years, and 15 years, respectively, representing characteristic time scales. (3) Runoff variation in the basin is relatively sensitive to changes in both precipitation and potential evapotranspiration during the flood season, with precipitation sensitivity being 2.3–5.3 times that of potential evapotranspiration. (4) Human activities are the primary influencing factor of runoff variation in the basin, contributing 90.43%, 63.75%, and 94.08% to annual, flood season, and non-flood season runoff changes, respectively. These findings provide a scientific basis for the comprehensive management and rational allocation of regional water resources and offer guidance for soil erosion control in the Loess Plateau.

Keywords: runoff changes; human activity; climate change; Budyko hypothesis; Jinghe River Basin

1. Introduction

Watershed hydrological systems are jointly influenced by climate change and human activities. On one hand, variations in climatic elements affect water supply and discharge within watersheds, directly or indirectly altering hydrological cycle processes. On the other hand, human activities influence runoff generation and concentration mechanisms by modifying underlying surface conditions and constructing water conservancy facilities, thereby changing the temporal and spatial distribution of water resources and hydrological cycle patterns. Numerous studies have demonstrated that human activities are the primary driver of runoff changes in the Yellow River Basin, with contribution rates exceeding 50% in the Kuye River, Fen River, and Beiluo River basins in the middle and upper reaches of the Yellow River in recent years. Although the contribution rates of human activities to runoff changes in the Wei River and Qingjian River basins are relatively smaller, they still exceed 40%.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that global average temperature has increased by 0.85°C over the past 130 years, with most mid-latitude regions likely to experience increased extreme precipitation in the future. In recent years, against the backdrop of rapid socioeconomic development and the comprehensive implementation of the "Grain for Green" program in China, watershed hydrological cycle processes have undergone significant changes. The current stage emphasizes water resource management based on water availability and capacity, constraining the development and utilization of water resources by human activities to suppress unreasonable water demand.

To clarify the driving factors of watershed runoff changes, numerous scholars have applied various methods, including model simulation and empirical statistical models. Currently, SWAT and MODFLOW models are widely used in research on runoff change driving factors. For example, Wu et al. studied climate and land use changes and their impacts on runoff in the Jinghe River Basin using the SWAT model, concluding that human activities are the main factor causing runoff changes. Zhang et al. used a coupled SWAT-MODFLOW model to quantitatively analyze runoff changes in the Yan River Basin of the middle Yellow River, finding that underlying surface changes accounted for 29.03%-65.79% of total human activity impacts. Yu et al. investigated the driving factors of hydrological evolution in the Xiliao River Basin, concluding that natural factors had greater impacts on wetland changes than human activities.

Additionally, the Budyko hypothesis, which considers water and energy balance, has been widely applied in empirical statistical models. Sun et al. validated the applicability of the Budyko hypothesis in the Yellow River Basin using hydrometeorological data from 13 sub-basins. Yang et al. quantitatively analyzed the contributions of climate and underlying surface changes to runoff variation in different sub-basins of the Yellow River Basin using the Budyko hypothesis, demonstrating its broad application prospects. Zhang et al. studied runoff change attribution in 13 sub-basins of the Loess Plateau, providing plant available water coefficients for different vegetation types.

While model simulation can more accurately represent water migration and transformation processes in the atmosphere, surface, and soil, it requires high methodological applicability and data precision and involves relatively complex calculations. The Budyko hypothesis, based on relevant physical theories and assumptions to analyze watershed hydrological process mechanisms, is more straightforward and convenient than hydrological models. Therefore, this study employs the Budyko hypothesis to investigate the driving factors of runoff changes in the Jinghe River Basin.

As the largest tributary of the Wei River and a secondary tributary of the Yellow River, the Jinghe River Basin is located in the ecologically fragile Loess Plateau with severe soil erosion. Water resource shortages in the basin severely constrain regional socioeconomic development. Particularly since the 21st century, rapid population growth and increased farmland irrigation area have led to substantial runoff reduction. Strengthening the positive guiding role of human activities on hydrological changes and achieving harmonious coexistence between humans and nature urgently require research on hydrological evolution patterns and attribution in the Jinghe River Basin. This study analyzes hydrometeorological evolution patterns from multiple perspectives and quantitatively assesses the impacts of climate change and human activities on hydrological changes based on the Budyko hypothesis, aiming to provide reasonable and effective decision-making support for efficient water resource utilization and scientific allocation in the Jinghe River Basin.

1.1 Study Area Overview

The Jinghe River originates from the eastern foothills of Liupan Mountain in Jingyuan County, Ningxia Hui Autonomous Region. The basin covers an area of 45,421 km^2, accounting for 33.70% of the Wei River Basin area. The river flows through Shaanxi, Gansu, and Ningxia provinces and empties into the Wei River at Chenjiatan, Gaoling District, Xi'an City, Shaanxi Province, with a total length of 455.1 km. The basin has a temperate continental climate characterized by concurrent rainfall and heat, and distinct four seasons. The multi-year average precipitation (1956-2000) is 527.9 mm, with maximum annual precipitation of 727.1 mm and minimum of 325.6 mm. Precipitation is mainly concentrated in July-September, accounting for 56.0% of annual precipitation, while December-February precipitation accounts for only 15.2%. The basin is dominated by hills and terraces with a well-developed river system. The location, topography, and drainage system of the Jinghe River Basin are shown in [Figure 1: see original paper].

1.2 Data Sources

Daily meteorological data from 18 national meteorological stations within and around the Jinghe River Basin from 1951 to 2019 were obtained from the China Meteorological Data Network (http://data.cma.cn). Runoff data from the Zhangjiashan Hydrological Station were derived from the "Statistical Characteristics of Measured Water and Sediment at Major Hydrological Stations in the Yellow River Basin" compiled by the Yellow River Conservancy Commission of the Ministry of Water Resources. Digital Elevation Model (DEM) data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn). Multi-period land use data were sourced from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn).

1.3 Research Methods

This study employs the Penman-Monteith formula to calculate potential evapotranspiration in the Jinghe River Basin, linear regression to analyze runoff trends, the Mann-Kendall (M-K) test and sliding t-test to detect abrupt changes in annual runoff time series, wavelet analysis to examine runoff periodicity, and the Budyko framework to investigate runoff change driving factors.

1.3.1 Penman-Monteith Formula Based on the Food and Agriculture Organization (FAO) Penman-Monteith method, potential evapotranspiration at each station is calculated as:

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

where ET_0 is potential evapotranspiration ($\mathrm{mm \cdot d^{-1}}$), G is soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), T is mean daily temperature (°C), R_n is net radiation ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), e_s and e_a are saturation vapor pressure and actual vapor pressure (kPa), respectively, Δ is the slope of the saturation vapor pressure curve ($\mathrm{kPa \cdot {}^\circ C^{-1}}$), and γ is the psychrometric constant ($\mathrm{kPa \cdot {}^\circ C^{-1}}$).

1.3.2 Linear Regression Method Linear regression establishes a simple linear equation $y = ax + b$ to reflect linear trends and rates of change. The slope a indicates the trend direction: if $a > 0$, y increases with x; if $a < 0$, y decreases with x; if $a = 0$, the overall trend remains unchanged.

1.3.3 Mann-Kendall Test The M-K test constructs a rank sequence S_k for abrupt change detection:

$$S_k = \sum_{i=1}^{k}\sum_{j=i+1}^{n}\alpha_{ij} \quad (k = 2, 3, \cdots, n)$$

where α_{ij} is a statistical quantity calculated as:

$$\alpha_{ij} = \begin{cases} 1 & \text{if } x_i > x_j \\ 0 & \text{otherwise} \end{cases}$$

From S_k, we calculate UF_k:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{V(S_k)}} \quad (k = 1, 2, \cdots, n)$$

where $UF_1 = 0$, and $E(S_k)$ and $V(S_k)$ are the mean and variance of S_k, respectively. When $UF_k > 0$, the sequence shows an upward trend; when $UF_k < 0$, it shows a downward trend. If UF_k exceeds the critical value, the trend is significant. By reversing the time series and repeating the calculation, we obtain UB_k. If UF_k and UB_k intersect within the confidence interval, an abrupt change occurs at that point.

1.3.4 Sliding t-Test The sliding t-test analyzes abrupt changes in hydrological time series:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

where $\bar{x}_1$ and $\bar{x}_2$ are sample means, n_1 and n_2 are sample sizes, and s is the statistical quantity calculated as:

$$s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

where s_1^2 and s_2^2 are sample variances.

1.3.5 Wavelet Analysis Wavelet functions are oscillatory functions that rapidly decay to zero, satisfying $\int_{-\infty}^{+\infty} \psi(t)dt = 0$. Given the characteristics of hydrological time series, the Morlet wavelet function is selected:

$$\psi(t) = e^{i\omega_0 t} e^{-t^2/2}$$

where ω_0 is a constant and t is time.

1.3.6 Budyko Hypothesis for Quantitative Attribution of Runoff Changes Based on the Budyko hypothesis, Milly proposed a formula for calculating runoff changes caused by climate variation:

$$\Delta R_c = \alpha \Delta P + \beta \Delta ET_0$$

where ΔP is precipitation change (mm), ΔET_0 is potential evapotranspiration change (mm), ΔR_c is runoff change caused by climate variation (mm), and α and β are runoff change per unit change in precipitation and potential evapotranspiration, respectively. ϕ is the ratio of potential evapotranspiration to precipitation.

Considering vegetation effects on the Loess Plateau, Zhang et al. proposed a Budyko analytical expression:

$$\frac{E}{P} = 1 + \frac{ET_0}{P} - \left[1 + \left(\frac{ET_0}{P}\right)^{\omega}\right]^{1/\omega}$$

where ω is the vegetation water use coefficient (ranging from 0.1 to 2.0), reflecting different vegetation types' water absorption from soil. Zhang et al. recommended $\omega = 0.5$ for grasses (including soil evaporation) and $\omega = 2.0$ for forests. Using this expression, α and β can be simplified as:

$$\alpha = \frac{1 + 2\phi}{(1 + \phi^{\omega})^{1/\omega}} - 1$$

$$\beta = 1 - \frac{1 + 2\phi}{(1 + \phi^{\omega})^{1/\omega}}$$

2. Results

2.1 Climate Change Characteristics

Based on meteorological data from 1951-2019 in the Jinghe River Basin, linear regression analysis reveals increasing trends in precipitation, potential evapotranspiration, maximum temperature, minimum temperature, and mean temperature, with rates of 0.20 $\mathrm{mm} \cdot \mathrm{a}^{-1}$, 0.032°C $\cdot\, \mathrm{a}^{-1}$, 0.027°C $\cdot\, \mathrm{a}^{-1}$, and 0.028°C $\cdot\, \mathrm{a}^{-1}$, respectively. Conversely, sunshine duration, relative humidity, and wind speed show decreasing trends at rates of 0.002 $\mathrm{h} \cdot \mathrm{a}^{-1}$, 0.054% $\cdot\, \mathrm{a}^{-1}$, and 0.028°C $\cdot\, \mathrm{a}^{-1}$, respectively [Figure 2: see original paper].

2.2 Runoff Change Characteristics

The interannual variation characteristics of runoff depth in different periods from 1951-2018 are shown in [Figure 3: see original paper]. The annual runoff depth decreased at a rate of 0.41 $\mathrm{mm} \cdot \mathrm{a}^{-1}$, with flood season runoff depth decreasing at

0.27 mm $\cdot$ a^{-1}, approximately 1.5 times that of the non-flood season. Maximum annual, flood season, and non-flood season runoff depths occurred in 1964 (90.44 mm, 62.23 mm, and 29.38 mm, respectively), while minimum values occurred in 2001 (5.44 mm, 5.83 mm, and 1.71 mm, respectively), indicating greater interannual variability in flood season runoff depth.

Abrupt change analysis of runoff time series at Zhangjiashan Hydrological Station using the M-K test and sliding t-test is shown in [Figure 4: see original paper]. The M-K test indicates an abrupt change in 1996. The sliding t-test with a 10-year step size shows that the intersection point falls within the 95% confidence interval, confirming 1996 as the year of abrupt runoff change. Considering both methods, 1996 is identified as the year of significant runoff reduction.

Wavelet coefficient real parts and variance diagrams reflect periodic characteristics of hydrological elements [Figure 5: see original paper]. Annual runoff exhibits three primary periods: short cycles of 10–20 years and long cycles of 30–60 years, with the first, second, and third primary periods being 41 years, 58 years, and 15 years, respectively.

Statistical characteristics of hydrometeorological elements before and after the abrupt change show that post-abrupt change runoff depth decreased by 43.49% compared to pre-abrupt change . Among meteorological elements, only relative humidity and wind speed decreased post-abrupt change (by 3.59% and 6.96%, respectively), while precipitation, potential evapotranspiration, sunshine duration, and temperatures increased. Coefficients of variation for all elements decreased post-abrupt change, indicating reduced variability.

2.3 Driving Factors of Runoff Change

Land cover areas in different periods are shown in [Figure 6: see original paper]. During the baseline period (1960–1995), average farmland, grassland, forestland, desert, and water areas were 19,848 km^2, 18,948 km^2, 4,277 km^2, 743 km^2, and 206 km^2, respectively. During the change period (1996–2019), farmland decreased by 244 km^2, while forestland and grassland increased by 126 km^2 and 244 km^2, respectively.

Using recommended vegetation water use coefficients from Zhang et al. and land use areas, the basin’ s vegetation water use coefficients were calculated as 0.72, 0.78, and 0.74 for the baseline, change, and entire periods, respectively. The increase is primarily due to conversion from grasses to forest vegetation, with forest area increasing by 244 km^2.

Based on these coefficients, hydrometeorological parameter characteristics were calculated . From baseline to change period, precipitation increased while runoff decreased in all periods. Potential evapotranspiration increased except during the flood season. Runoff changes are sensitive to both precipitation and potential evapotranspiration, with highest sensitivity during the change period. Precipitation sensitivity is 2.3–5.3 times that of potential evapotranspiration.

Precipitation contributes -7.72%, -16.76%, and -12.78% to annual, flood season, and non-flood season runoff changes, respectively, while potential evapotranspiration contributes 17.29%, 53.01%, and 18.70%.

Attribution analysis using the Zhang-Milly formula shows that human activities and climate change caused reductions of 16.13 mm and 1.71 mm in annual runoff depth post-abrupt change, respectively . Flood season reductions were 7.65 mm and 5.64 mm, while non-flood season reductions were 0.36 mm and 5.64 mm. Human activity contribution rates were 90.43%, 63.75%, and 94.08% for annual, flood season, and non-flood season runoff changes, respectively.

3. Discussion

Numerous studies on runoff change driving factors in the Yellow River Basin indicate that human activities are the primary influencing factor, affecting the water cycle process by altering underlying surface conditions. Various factors including land use change, water resource development, and water conservancy projects significantly impact runoff. Due to limited basic data, this study categorized precipitation and evapotranspiration as climatic factors and all other factors as human activities, which may introduce some deviation from actual results. Future research should further investigate the impacts of different driving factors on runoff changes in the Jinghe River Basin.

Located in the ecologically fragile Loess Plateau with severe soil erosion, the Jinghe River Basin’ s runoff is more susceptible to human activities than other Yellow River sub-basins. This study demonstrates that human activities have a far greater impact on runoff changes than climate change, with contribution rates of 63.75%, 90.43%, and 94.08% for annual, flood season, and non-flood season runoff, respectively. These results are consistent with Wu et al.’ s SWAT model findings for this basin, though the longer time series in this study yields slightly higher human activity contribution rates. The greater impact on non-flood season versus flood season runoff aligns with Budyko hypothesis-based studies showing human activities primarily affect average flows in non-flood seasons, followed by annual maximum flows.

The differential contributions across seasons are mainly related to irrigation district development and water conservancy facilities. The basin contains numerous irrigation districts, with 31.37% of multi-year average runoff used for agricultural irrigation. Most large reservoirs operate as annual regulation reservoirs with “peak shaving and dry season compensation”functions, making human activities more influential during non-flood seasons. The 2.3–5.3 times higher sensitivity to precipitation than potential evapotranspiration indicates runoff is highly responsive to precipitation changes, consistent with most studies. However, the small precipitation change magnitude (e.g., 0.84 mm in flood season, only one-tenth of potential evapotranspiration change) results in relatively small precipitation contribution rates.

4. Conclusions

This study analyzes hydrometeorological evolution patterns and quantitatively assesses climate change and human activity contributions to runoff variation in the Jinghe River Basin. The main conclusions are:

1. Annual runoff depth decreased at 0.41 $\mathrm{mm} \cdot \mathrm{a}^{-1}$ from 1951-2018, with flood season reduction rate approximately 1.5 times that of the non-flood season. Precipitation, potential evapotranspiration, and temperature showed increasing trends, while sunshine duration, relative humidity, and wind speed decreased.

2. Annual runoff depth experienced a significant abrupt reduction in 1996, decreasing by 43.49% post-abrupt change, with flood season reduction accounting for 63.66% of the total. Annual runoff exhibits short cycles of 10–20 years and long cycles of 30–60 years, with primary periods of 41 years, 58 years, and 15 years.

3. Human activities are the dominant factor affecting runoff changes, contributing 90.43%, 63.75%, and 94.08% to annual, flood season, and non-flood season runoff changes, respectively. Climate change impacts are primarily dominated by potential evapotranspiration changes, contributing 17.29%, 53.01%, and 18.70% to respective periods.

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