Runoff change in the Yellow River Basin of China from 1960 to 2020 and its driving factors (Postprint)

Authors: WANG Baoliang

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Abstract

Analysing runoff changes and how these are affected by climate change and human activities is deemed crucial to elucidate the ecological and hydrological response mechanisms of rivers. The Indicators of Hydrologic Alteration and the Range of Variability Approach (IHA-RVA) method, as well as the ecological indicator method, were employed to quantitatively assess the degree of hydrologic change and ecological response processes in the Yellow River Basin from 1960 to 2020. Using Budyko' s water heat coupling balance theory, the relative contributions of various driving factors (such as precipitation, potential evapotranspiration, and underlying surface) to runoff changes in the Yellow River Basin were quantitatively evaluated. The results show that the annual average runoff and precipitation in the Yellow River Basin had a downwards trend, whereas the potential evapotranspiration exhibited an upwards trend from 1960 to 2020. In approximately 1985, it was reported that the hydrological regime of the main stream underwent an abrupt change. The degree of hydrological change was observed to gradually increase from upstream to downstream, with a range of 34.00%-54.00%, all of which are moderate changes. However, significant differences have been noted among different ecological indicators, with a fluctuation index of 90.00% at the outlet of downstream hydrological stations, reaching a high level of change. After the mutation, the biodiversity index of flow in the middle and lower reaches of the Yellow River was generally lower than that in the base period. The research results also indicate that the driving factor for runoff changes in the upper reach of the Yellow River Basin is mainly precipitation, with a contribution rate of 39.31%-54.70%. Moreover, the driving factor for runoff changes in the middle and lower reaches is mainly human activities, having a contribution rate of 63.70%-84.37%. These results can serve as a basis to strengthen the protection and restoration efforts in the Yellow River Basin and further promote the rational development and use of water resources in the Yellow River.

Full Text

Preamble

Runoff Change in the Yellow River Basin of China from 1960 to 2020 and Its Driving Factors

Baoliang WANG[1], Hongxiang WANG[1], Xuyang JIAO[1], Lintong HUANG[1], Hao CHEN[1], Wenxian GUO[2]*

[1] School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China
[2] College of Water Resources, North China University of Water Resources and Electric Power, Zhengzhou 450046, China

Abstract: Analyzing runoff changes and their responses to climate change and human activities is crucial for elucidating the ecological and hydrological response mechanisms of rivers. This study employed the Indicators of Hydrologic Alteration and Range of Variability Approach (IHA-RVA) method, along with ecological indicator methods, to quantitatively assess the degree of hydrologic alteration and ecological response processes in the Yellow River Basin from 1960 to 2020. Using Budyko' s water-heat coupling balance theory, we evaluated the relative contributions of various driving factors (precipitation, potential evapotranspiration, and underlying surface) to runoff changes. The results show that while annual average runoff exhibited a decreasing trend, both precipitation and potential evapotranspiration showed increasing trends during 1960–2020. An abrupt change in the hydrological regime occurred around 1985. The degree of hydrological alteration gradually increased from upstream to downstream, ranging from 34.00% to 54.00%, indicating moderate changes overall. However, significant differences were observed among ecological indicators, with a fluctuation index reaching 90.00% at downstream hydrological stations, representing a high level of alteration. Following the regime shift, the biodiversity index of flow in the middle and lower reaches was generally lower than during the baseline period.

The results further indicate that precipitation is the primary driver of runoff changes in the upper Yellow River Basin, with a contribution rate of 39.31%–54.70%, whereas human activities dominate runoff changes in the middle and lower reaches, contributing 63.70%–84.37%. These findings provide a scientific basis for strengthening protection and restoration efforts in the Yellow River Basin and promoting rational water resource development and utilization.

Keywords: Budyko theory; hydrological regime; attribution analysis; ecological responses; Yellow River; climate change; human activity; runoff

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1 Introduction

Ecological-hydrological processes in rivers are critical for maintaining the balance and integrity of river basin ecosystems and are essential for sustainable water resource development and the survival of numerous species (Sofi et al., 2020; Gao et al., 2022). In recent years, climate change impacts such as altered precipitation patterns and potential evapotranspiration, combined with intensified human activities including reservoir construction and land use changes, have modified water circulation patterns within basins. These changes affect water resource development and use while gradually transforming the ecological environment, particularly in arid regions where impacts are more pronounced (Wang et al., 2021; Liu et al., 2022; Wang et al., 2023). Therefore, analyzing the evolution and attribution of river hydrological regimes is particularly important for evaluating river health.

Numerous researchers have conducted quantitative analyses of hydrological changes in rivers worldwide. Taye et al. (2011) employed hydrological models to evaluate climate change effects on the Nile River' s hydrological regime, predicting that long-term changes in rainfall and potential evapotranspiration would decrease future discharge. Sorribas et al. (2016) used hydrological models to assess climate change and human activity impacts on the Amazon River, projecting that rainfall changes would reduce river flow in the eastern Amazon Basin. Cheng et al. (2019) verified hydrological changes in the Yangtze River Basin resulting from climate change and human activities using various hydrological indicators, finding that precipitation variations and major reservoir construction during the 1970s caused runoff declines, with human activities accounting for 63.00%-77.00% of this phenomenon.

The Yellow River, China' s second-largest river, has also experienced varying degrees of change in recent years. Over the past decade, scholars have conducted comprehensive studies on its hydrological conditions (Cuo et al., 2013; Gao et al., 2016; Li et al., 2016; Zhang et al., 2018). Shi et al. (2017) examined long-term runoff changes and found a declining trend, with climate change impacts waning while human activities increasingly became the primary factor reducing river runoff. Reservoir regulation and storage functions, along with rainfall changes, were identified as the most important factors directly affecting Yellow River runoff. Moreover, hydrological process changes in the Yellow River Basin are not limited to a single time scale or direction but are more three-dimensional and complex, making water resource management increasingly challenging. Therefore, a comprehensive ecological and hydrological evaluation from multiple perspectives is required to quantify the impacts of different driving factors on hydrological processes, which is critical for understanding hydrological response mechanisms in complex changing environments.

Currently, over 170 evaluation methods exist for hydrological indicators, with the Indicators of Hydrologic Alteration (IHA) method proposed by Richter (1996) being the most widely used. This approach assesses the extent of hydrological change in rivers and has been extensively applied to evaluate hydrological alteration and ecological consequences following continuous improvements by various scholars (Gao et al., 2009; Kim et al., 2011; Zhou et al., 2021). Since changes in river hydrological regimes have comparable effects on ecosystems, quantitative examination of these impacts on biodiversity is essential for assessing ecosystem changes (Rolls et al., 2018; Cui et al., 2020). Pettersson (1998) found that the Shannon Index (a diversity index) is a simple and reliable tool for identifying biodiversity changes, and Yang et al. (2008) successfully applied it to river ecological evaluation.

To quantitatively study the effects of different driving forces on river runoff variations, scholars have employed various methodologies, primarily hydrological models and elastic coefficient methods. Hydrological models can precisely measure the influence of driving forces on runoff variations and have produced robust research findings at various scales. However, they require complete data (i.e., no missing data), which is scarce for long-term series, and involve considerable uncertainties in parameter calibration. Although Schaake (1990) first used the elastic coefficient method to analyze precipitation-runoff relationships, this approach failed to consider other climate change factors such as potential evapotranspiration, temperature, and wind speed (Dooge et al., 1999; Fu et al., 2007; Yang and Yang, 2011; Liu et al., 2013), reducing accuracy. To address this limitation and produce more comprehensive results, Choudhury (1999) and Yang et al. (2008) proposed a basin water-heat coupling equilibrium equation based on Budyko theory, refining the assessment of climate change impacts on precipitation and potential evapotranspiration. This enables more accurate and convenient analysis of the temporal contribution rates of different driving factors to basin runoff changes and has been widely applied. Wang et al. (2012) used Budyko theory and differential equations to investigate contribution rates of climate change and human activities to Yellow River runoff changes, attributing variations primarily to reservoir construction and land use changes, with human activities accounting for 57.29%–83.61% of the total. However, previous studies rarely considered the effects of river evapotranspiration and temperature or the response relationships between various factors, and failed to quantify ecological impacts by combining them with ecological-hydrological indicators.

Building upon this foundation, our study further refines the two major driving forces—climate change and human activities—into specific influencing components to thoroughly examine changes in the Yellow River's hydrological processes. The objectives are: (1) to examine changes in runoff, precipitation, and potential evapotranspiration in the Yellow River Basin from 1960 to 2020; (2) to calculate the degree of hydrological alteration in the upper, middle, and lower reaches, comprehensively analyze overall hydrological changes, and assess ecosystem risk; (3) to quantitatively evaluate the influence of hydrological regime changes on biodiversity; and (4) to quantitatively investigate the contribution rates of different driving forces to main stream runoff variations. This study provides a statistical examination of runoff variation impacts on the Yellow River' s hydrological processes and offers a basis for water resource management departments to develop more rational water resource utilization strategies.

2 Materials and Methods

2.1 Study Area

The Yellow River is the world' s fifth-largest river, with a total length of approximately 5464 km and a basin area of 7.95$\times10^{5}$ km^2 (32°10 -41°50 N, 95°53 -119°05 E). It flows through nine Chinese provinces before emptying into the Bohai Sea (Xu et al., 2005; Zhu et al., 2016). The main river channel can be categorized into 11 sections based on distinct geographical and hydrological characteristics (Jin et al., 2020), comprising upper, middle, and lower reaches. In recent years, the hydrological regime in different sections has undergone varying degrees of change due to combined influences of precipitation, reservoir construction, and land use changes, resulting in numerous negative impacts on the ecological environment. This study selected typical hydrological stations along the main stream—Lanzhou and Toudaoguai stations in the upper reach, Longmen and Xiaolangdi stations in the middle reach, and Huayuankou and Lijin stations in the lower reach—to measure the degree of hydrological changes and the influence of driving factors on the basin' s ecological environment (Fig. 1 [Figure 1: see original paper]).

2.2 Data

Daily runoff data for the Yellow River Basin from 1960 to 2020 were obtained from the *Yellow River Basin Hydrological Yearbook* (Yellow River Conservancy Commission of the Ministry of Water Resources, 1961-2021) and records from the six selected hydrological stations. Daily meteorological data were acquired from the China Meteorological Data website (http://data.cma.cn/) and records from 33 meteorological stations shown in Figure 1. Land use data at 30 m resolution were obtained from the Resource and Environmental Science and Data Center, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (http://www.resdc.cn).

2.3 Methods

2.3.1 Trend-Free Pre-Whitening-Mann-Kendall (TFPW-MK) Test

The Trend-Free Pre-Whitening (TFPW) test is commonly used to detect trends in hydrological sequences without interference from other factors (Desa and Jemain, 2013; Blain, 2015; Emamgholizadeh, 2015). For time series data X (t = 1, 2, ···, t ; t is the sequence length), the calculation steps are as follows:

$$\eta = \text{median}\left(\frac{x_b - x_a}{b - a}\right), \quad (1)$$

$$Y_t = X_t - \eta \cdot t, \quad (2)$$

$$Y_t' = Y_t - \varepsilon \cdot Y_{t-1}, \quad (3)$$

$$X_t' = Y_t' + \eta \cdot t, \quad (4)$$

where is the slope of the sequence to be detected; a and b are variables to be detected; x and x_b are the corresponding values of variables a and b in the natural sequence; Y is the residual series after subtracting the trend; Y $_1$ is the next time period of Y ; Y is the independent white noise sequence after removing the autocorrelation term; X is the sequence obtained after TFPW processing; and is the first-order autocorrelation coefficient.

The Mann-Kendall (MK) significance test is performed on the new sequences:

$$U = \frac{m - E(m)}{\sqrt{\mathrm{var}(m)}}, \quad (5)$$

where U is the statistic value of the MK test and m is the number of nodes. When m $\geq$ 10, U approximately follows a normal distribution, with mean value E(U) and variance var(U) calculated by Equation 6:

$$\mathrm{var}(U) = \frac{n(n-1)(2n+5)}{18}, \quad (6)$$

where n is the sequence length. The standardized test statistic Z_{MK} is:

$$Z_{MK} = \begin{cases} \frac{U-1}{\sqrt{\mathrm{var}(U)}}, & U > 0 \\ 0, & U = 0 \\ \frac{U+1}{\sqrt{\mathrm{var}(U)}}, & U < 0 \end{cases}, \quad (7)$$

At the α-significant level, the sequence shows an increasing trend if |Z_{MK}| > Z_(1-α/2) and a decreasing trend otherwise, where α can be 0.10, 0.05, or 0.01. The significance level α = 0.05 is generally used, giving critical values of ±Z_{MK}(1-α/2) = $±$1.96.

2.3.2 MK Mutation Test and Pettitt Mutation Test The MK test is used for detecting mutations in precipitation, potential evapotranspiration, runoff, and temperature data, offering wide applicability and simple calculation (Hamed and Rao, 1998; Hamed, 2008). The specific steps are:

(1) For time series (x_1, x_2, ···, x_j, ···, x_i, ···, x_n), where j and i are sampling times with j < i and n is the number of data points, construct sequence s_k:

$$s_k = \sum_{i=1}^{k} \sum_{j=1}^{i-1} \operatorname{sgn}(x_i - x_j), \quad k = 1, 2, ..., n, \quad (8)$$

where s_k is the sum of times that the value at time i is greater than the value at time j. The value _i is:

$$\eta_i = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \le x_j \end{cases}, \quad j = 1, 2, ..., i - 1. \quad (9)$$

(2) Assuming the time series data are random and independent, define statistic UF_k:

$$UF_k = \frac{s_k - E(s_k)}{\sqrt{\operatorname{var}(s_k)}}, \quad k = 1, 2, ..., n, \quad (10)$$

where UF_k follows a standard normal distribution with $\mathrm{UF}_1 = 0$ when k = 1; E(s_k) is the average value of s_k; and var(s_k) is the variance of s_k.

(3) Arrange the time series in reverse order and calculate another statistic UB_k using Equations 8-13:

$$UB_k = -UF_k, \quad k = n, n - 1, ..., 1. \quad (13)$$

Like UF_k, $\mathrm{UB}_1 = 0$ when k = 1. If the UB_k and UF_k curves intersect between the two critical lines, the corresponding time of intersection indicates when the mutation begins.

The Pettitt mutation test is based on the Mann-Whitney non-parametric test, which can identify abrupt change points and quantify their statistical significance (Rybski and Neumann, 2011; Conte et al., 2019). The Mann-Whitney non-parametric statistic is:

$$U_{f,N} = U_{f-1,N} + \sum_{h=1}^{N} \operatorname{sgn}(x_f - x_h), \quad f = 1, 2, ..., N, \quad (14)$$

where U_f,N is the test statistic at possible mutation point f; U_f-1,N is the test statistic at point f-1; x_f is the fth observation; x_h is the hth observation; and N is the sample size. The mutation statistic K_f,N and significance statistic P are:

$$K_{f,N} = \max_{1 \leq f \leq N} |U_{f,N}|, \quad (15)$$

$$P = 2 \cdot \exp\left(\frac{-6K_{f,N}^2}{N^3 + N^2}\right). \quad (16)$$

Generally, when P $\leq$ 0.05, the data are considered to contain mutation points.

2.3.3 Indicators of Hydrologic Alteration-Range of Variability Approach (IHA-RVA) Method Richter et al. (1996) proposed the Range of Variability Approach (RVA), which includes five aspects: flow magnitude, timing, frequency, duration, and rate of change, refined into 32 ecological indicators. Each indicator has ecological significance and can effectively reflect changes in river hydrological conditions. The degree of change (DC) of a single hydrological indicator is calculated as:

$$D_c = \frac{|P_0 - P_e|}{P_e} \times 100\%, \quad (17)$$

where D_c is the change degree of the cth indicator (%); P_0 is the actual number of years when the cth indicator falls within the RVA threshold; P_e is the predicted number of years (usually 50% of the total); and P_t is the total number of years after being affected.

The overall degree of change D_0 is:

$$D_0 = \frac{1}{n} \sum_{c=1}^{n} D_c, \quad (19)$$

where n is the number of indicators. Hydrological parameters are considered highly altered when $|D_0| \geq 67.00\%$, moderately altered when $34.00\% \leq |D_0| < 67.00\%$, and lowly altered when $|D_0| < 34.00\%$.

2.3.4 Ecological Response Analysis Yang et al. (2008) applied the Shannon Index to establish relationships between IHA hydrological indices and biodiversity. The formula is:

$$SI = D_{\min} + Q_3 + Q_5 + \text{Min}_3 + \text{Min}_7 + \text{Max}_3 + R_{\text{rate}}, \quad (20)$$

where SI is the Shannon Index reflecting species diversity; D_{min} is the Julian day with minimum water level; Q_3 and Q_5 are average flows in March and May; Min_3 and Min_7 are 3- and 7-day minimum flows; Max_3 is 3-day maximum flow; and R_{rate} is the rate of water rise.

2.3.5 Penman-Monteith Formula Potential evapotranspiration is a key parameter for watershed evapotranspiration. The Penman-Monteith formula calculates potential evapotranspiration using daily meteorological data (McVicar et al., 2012; Wang and Dickinson, 2012):

$$PET = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{\mathrm{T}_2+273}U_2(e_x - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \quad (21)$$

where PET is potential evapotranspiration (mm); R_n is net radiation on the crop surface ($\mathrm{MJ/(m^2 \cdot d)}$); T_2 is mean daily air temperature at 2 m height (°C); U_2 is wind speed at 2 m height (m/s); e_x is saturated water vapor pressure (kPa); e_a is actual vapor pressure (kPa); Δ is the slope of the saturated water vapor pressure curve; and λ is the hygrometric constant (kPa/°C).

2.3.6 Budyko Theory According to Budyko' s coupled water-heat balance theory, the basin water balance can be expressed as:

$$R = PRE - E - \Delta S, \quad (22)$$

where R is average runoff depth (mm); PRE is average precipitation (mm); E is average actual evaporation (mm); and ΔS is change in water storage (mm). For long-term runoff changes, ΔS 0.

The water balance equation on an average annual scale is:

$$\frac{E}{PRE} = F\left(\frac{PET}{PRE}, y\right), \quad (23)$$

where y is the characteristic parameter of the watershed underlying surface, which can be derived given R, PRE, and PET. Since PRE, PET, and y are independent variables, the total differential form of annual runoff is:

$$dR = \frac{\partial R}{\partial PRE}dPRE + \frac{\partial R}{\partial PET}dPET + \frac{\partial R}{\partial y}dy. \quad (24)$$

Assuming γ = PET/PRE, the elasticity coefficient can be calculated as:

$$\varepsilon_w = \frac{\partial R/R}{\partial w/w}, \quad (25)$$

where w can be PRE, PET, or y. The elasticity coefficients are:

$$\varepsilon_{PRE} = \frac{1 + \gamma y}{(1 + \gamma y)^2 - y}, \quad (26)$$

where _{PRE} is the precipitation elasticity coefficient; _{PET} is the potential evapotranspiration elasticity coefficient; and _y is the underlying surface elasticity coefficient.

The variation in runoff depth induced by each influencing factor can be determined using the elasticity coefficient:

$$\Delta R_w = \varepsilon_w \cdot \frac{\Delta w}{w} \cdot R, \quad (27)$$

where ΔR_w is the change in runoff by each parameter; w represents PRE, PET, or y; _w is runoff sensitivity to parameter w; and Δw is the change in each parameter.

The total change in runoff ΔR is the superposition of individual changes:

$$\Delta R' = \Delta R_{PRE} + \Delta R_{PET} + \Delta R_{HA}, \quad (28)$$

where ΔR_{PRE} is runoff depth change due to precipitation; ΔR_{PET} is change due to potential evapotranspiration; and ΔR_{HA} is change due to human activities. In this study, underlying surface changes represent human activity influence, so ΔR_{HA} = ΔR_y.

The contribution rates of precipitation, potential evapotranspiration, and underlying surface changes are:

$$\eta_{PRE} = \frac{\Delta R_{PRE}}{\Delta R'} \times 100\%, \quad \eta_{PET} = \frac{\Delta R_{PET}}{\Delta R'} \times 100\%, \quad \eta_{HA} = \frac{\Delta R_{HA}}{\Delta R'} \times 100\%, \quad (29)$$

where _{PRE} is precipitation contribution (%); _{PET} is potential evapotranspiration contribution (%); and _{HA} is human activity contribution (%).

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3 Results

3.1 Trend Tests for Hydrometeorological Variables

3.1.1 Trend Test for Precipitation Due to global climate change, precipitation distribution patterns in China are shifting (Gu et al., 2020), affecting basin runoff and evapotranspiration with detrimental impacts on socioeconomic development. Extreme climatic and hydrological phenomena such as severe rain and flooding result in temporal and spatial precipitation shifts. The inter-annual precipitation pattern in the Yellow River Basin from 1960 to 2020 is depicted in Figure 2 [Figure 2: see original paper], showing a negative trend. The TFPW-MK test statistics were all less than critical values at the 0.05 significance level

(|Z_{MK}| < 1.96), indicating non-significant trends. Precipitation gradually increased from upstream to downstream during 1960–2020, suggesting rising risks of rainstorms, floods, and other hydrological disasters in the middle and lower reaches compared to the upper reach.

Table 1 shows characteristic precipitation values. Annual average precipitation ranges from 352.3 mm in the upper basin to 564.2 mm in the lower basin. Maximum annual precipitation in the upper, middle, and lower basins was 511.2 mm, 602.3 mm, and 1019.1 mm, respectively, all occurring around 1965. The largest variation coefficient (0.24) occurred downstream. The average annual precipitation in the middle and lower reaches demonstrates geographical and temporal non-uniformity, likely attributable to increased extreme weather events and human activities.

3.1.2 Trend Test for Potential Evapotranspiration Climate change has significantly affected potential evapotranspiration in the Yellow River Basin with numerous negative consequences (Liu and Yang, 2010). The TFPW-MK test technique was used to investigate trends and significance during 1960–2020 (Fig. 3 [Figure 3: see original paper]). Inter-annual potential evapotranspiration showed an upward trend. TFPW-MK test statistics in the upstream and middle reaches were less than the 95% significance level (|Z_{MK}| < 1.96), indicating non-significant trends. Downstream TFPW-MK test statistics exceeded the 95% significance level (|Z_{MK}| ≥ 1.96), passing the 0.05 significance test. Potential evapotranspiration increased gradually from upstream to downstream, resulting in frequent hydrological and meteorological droughts in the middle and lower reaches and increased vulnerability to extreme drought disasters.

Table 2 shows characteristic potential evapotranspiration values. Average annual evapotranspiration from upstream to downstream was 920.3 mm, 952.7 mm, and 960.4 mm. Maximum annual potential evapotranspiration in the upper, middle, and lower reaches was 1029.2 mm, 1011.4 mm, and 1054.3 mm, respectively, all occurring around 1985. The downstream variation coefficient was largest (0.04), possibly related to extreme weather, greenhouse effects, and climate warming in the post-mutation period.

3.1.3 Trend Test for Runoff Annual runoff trends for the six main stream hydrological stations are shown in Figure 4 [Figure 4: see original paper], demonstrating similar inter-annual fluctuations with decreasing trends at all stations. MK test statistics for Lanzhou and Toudaoguai stations were Z_{MK} = –1.92 and –1.81 (|Z_{MK}| < Z_(0.05) = 1.96), failing the 95% significance test, indicating non-significant declining trends. MK test statistics for Longmen, Xiaolangdi, Huayuankou, and Lijin stations were Z_{MK} = –2.12, –3.22, –4.43, and –5.51 (|Z_{MK}| > Z_(0.05/2) = 1.96), all passing the 95% significance test, indicating significant downward trends. The decreasing trend became more pronounced from upstream to downstream.

Table 3 shows runoff volumes at the six stations during 1960–2020. Average annual runoff at Lanzhou, Xiaolangdi, Huayuankou, and Lijin stations was 315.9\$×10$^{\{8\},350.9\times10}$\{8\}, 322.2×10$^{\{8\},and264.4\times10}$\{8\}\$ m^3, respectively, with maximum annual runoff in 1964. Average annual runoff at Toudaoguai and Longmen stations was 211.3\$×10^\{8\}\$ and 252.7\$×10^\{8\}\$ m^3, respectively, with maximum runoff in 1967. Lijin Station, as the downstream outlet, had the largest variation coefficient (0.70), reflecting the non-uniform regional and temporal distribution of runoff in the Yellow River Basin.

3.2 Tests for Mutability of Runoff

According to MK test results (Fig. 5 [Figure 5: see original paper]), UF (test statistic) and UB (reverse sequence) intersection points for Lanzhou, Toudaoguai, Longmen, Xiaolangdi, Huayuankou, and Lijin stations occurred in 1984, 1985, 1987/1989, 1984, 1986, and 1985, respectively. At the 0.05 significance level, the statistics |Z_{MK}| were 3.29, 3.93, 4.93, 5.34, 5.41, and 6.07 (|Z_{MK}| > 1.96), respectively, all passing the 95% significance test.

Pettitt test results (Fig. 6 [Figure 6: see original paper]) identified mutation years for the six stations as 1984, 1985, 1987, 1984, 1986, and 1985, with significance levels of 0.03, 0.04, 0.02, 0.03, 0.03, and 0.02 (all < 0.05), confirming obvious runoff mutations during 1960–2020.

Combining both methods (Table 4), the final determined mutation years for Lanzhou, Toudaoguai, Longmen, Xiaolangdi, Huayuankou, and Lijin stations were 1984, 1985, 1987, 1984, 1986, and 1985, respectively, all concentrated around the mid-1980s.

3.3 Analysis of Hydrological Variability

The IHA-RVA method was used to quantitatively assess runoff alteration, yielding changes in 32 hydrological indicators at the six stations (Fig. 7 [Figure 7: see original paper]). At Lanzhou Station, the 90-day minimum flow showed the highest change degree (83.00%), while average monthly flow changes were generally small (low alteration). Toudaoguai Station exhibited maximum change in annual minimum flow timing (80.00%) and minimum change in June average flow (3.00%). Longmen Station showed maximum change in April average flow (100.00%) and minimum change in high-flow pulse duration (2.00%). Xiaolangdi Station had maximum change in October average flow and reversal times (100.00%) and minimum change in February average flow and 1-day minimum flow (3.00%). Huayuankou Station showed maximum change in flow increase/decrease rate (92.00%) and minimum change in June average flow (8.00%). Lijin Station exhibited maximum change in flow increase/decrease rate (93.00%) and minimum change in 3-day minimum flow (6.00%).

Using Equations 17–19, variations in each indicator group were calculated (Table 5). At Lanzhou and Toudaoguai stations, Group I indicators (January–December average flow) showed low alteration, while the remaining four groups showed moderate alteration. At Toudaoguai Station, Group IV indicators (low/high pulse count and duration) were low, while other groups were moderate. At Longmen Station, Group III indicators (minimum/maximum flow dates) were low, while other groups were moderate. At Xiaolangdi, Huayuankou, and Lijin stations, Groups I–IV showed moderate alteration, while Group V (increase rate, decrease rate, reversal times) showed high alteration. Although overall hydrological indicators at all six stations were moderately altered, the degree of change increased from upstream to downstream, indicating higher ecosystem risk in the middle and lower reaches.

Hydrological indicator changes inevitably alter the hydrological regime, affecting natural river processes and aquatic organism reproduction (Guo et al., 2022). Changes in annual extreme flow rates prevent some aquatic organisms from adapting, reducing biodiversity. Alterations in high- and low-pulse durations affect river ecological structure, impacting not only aquatic organisms but also riparian soil moisture and vegetation cover. Flow magnitude and frequency changes affect river stage fluctuations, influencing aquatic community distribution. While natural habitats can withstand some disturbance, recovery becomes difficult when disturbance exceeds tolerance thresholds.

3.4 Ecological Response Analysis

Hydrological regime changes significantly impact river ecology. This study examined the flow biodiversity index at the six stations using inter-annual changes from 1960 to 2020 (Fig. 8 [Figure 8: see original paper]). The biodiversity index declined at Toudaoguai, Longmen, Huayuankou, and Lijin stations with varying degrees. Standardized test statistics (Z_{MK}) for Lanzhou, Xiaolangdi, Huayuankou, and Lijin stations were 0.09, -1.16, -1.26, and -1.41 (|Z_{MK}| < 1.96), indicating non-significant increasing trends. Statistics for Toudaoguai and Longmen stations were -3.62 and -4.75 (|Z_{MK}| > 1.96), indicating significant biodiversity declines.

Overall, the biodiversity index in the middle and lower reaches was generally low in the post-mutation period. Toudaoguai, Longmen, and Xiaolangdi stations are near Qingtongxia Hydropower Station, Tianqiao Reservoir, and Sanmenxia Hydropower Station, where human activities significantly impacted the biodiversity index, causing more pronounced declines. Lanzhou and Lijin stations are relatively distant from these projects and less affected due to their regulating effects. Reservoir construction and operation significantly altered local runoff and indirectly harmed biodiversity.

3.5 Attribution Analysis of Runoff Changes Based on Budyko Theory

Hydrometeorological characteristics and elasticity coefficients for the six stations during reference and mutation periods are shown in Table 6 . During the mutation period (1986–2020), precipitation and runoff depth decreased while potential evapotranspiration increased compared to the reference period (1960–1985). Elasticity coefficients showed that a 1.00% increase in precipitation, potential evapotranspiration, and underlying surface would change runoff at Lanzhou Station by +3.27%, -2.17%, and -3.00%; at Toudaoguai Station by +2.20%, -1.20%, and -2.10%; at Longmen Station by +2.67%, -1.67%, and -2.26%; at Xiaolangdi Station by +2.82%, -1.80%, and -2.39%; at Huayuankou Station by +2.76%, -1.76%, and -2.34%; and at Lijin Station by +3.69%, -2.69%, and -2.75%, respectively. Runoff changes were positively correlated with precipitation and negatively correlated with potential evapotranspiration and underlying surface changes. The absolute elasticity coefficient values indicate runoff is most sensitive to precipitation, followed by underlying surface, and least sensitive to potential evapotranspiration.

During the base period, all six stations showed positive correlations between runoff and precipitation, with Toudaoguai, Longmen, Xiaolangdi, and Lijin passing the 0.01 significance test. Relationships with potential evapotranspiration and temperature were mixed. During the mutation period, precipitation showed positive correlations at all stations, with Lanzhou and Xiaolangdi passing the 0.01 test and Toudaoguai and Lijin passing the 0.05 test. Most stations showed negative correlations with potential evapotranspiration and temperature.

Contribution rates of each factor to runoff changes are summarized in Table 7 . Precipitation contribution decreased gradually from upstream to downstream, reaching 54.70% at upstream Lanzhou Station and 14.55% at downstream Lijin Station. Potential evapotranspiration contribution showed an initial increase then decrease, peaking at 2.17% at midstream Longmen Station and minimum at 0.86% at upstream Toudaoguai Station, indicating limited influence. Underlying surface contribution increased gradually from upstream to downstream, from 43.72% at Lanzhou Station to 84.37% at Lijin Station, becoming the dominant factor. For the Yellow River Basin, human activities are the main cause of runoff changes in the middle and lower reaches, while precipitation dominates in the upper reaches. Potential evapotranspiration has relatively low influence.

4 Discussion

Multiple variables, including climate change and human activities, impact river runoff. Investigation of Yellow River hydrology shifts reveals that pre-mutation reservoir and hydropower plant construction was limited and slow, mostly involving small- and medium-sized reservoirs. Since 1980, many water conservation projects have been implemented, including Bapanxia, Liujiaxia, Xiaolangdi, Wanjiazhai, and Sanmenxia projects. Consequently, average storage capacity far exceeded previous totals, creating a series operation mode that significantly altered hydrological sequences and caused abrupt changes in annual discharge. Zhang et al. (2023) showed that Xiaolangdi Reservoir operation flattened intra-annual runoff variations and reduced monthly runoff cycles. Shao et al. (2023) found decreasing trends in the Shiyang River Basin from the 1950s to 2019, projected to continue until 2050, consistent with our Yellow River analysis. Huang et al. (2023) attributed abrupt Kuye River Basin runoff changes in 1997 mainly to complex anthropogenic activities. Dai et al. (2023) evidenced significant runoff decreases in nine middle-reach sub-basins, with precipitation increasing from northwest to southeast and anthropogenic contributions exceeding climate change impacts, particularly in the Huangfuchuan and Kuye River basins. These findings align with our results, demonstrating that human activities increasingly influence Yellow River runoff changes.

4.1 Climate Factor Impacts on Runoff

4.1.1 Impact of Precipitation on Runoff Precipitation is crucial in the basin water cycle (Li et al., 2018). To investigate its influence, a double-mass curve of annual precipitation and runoff depth was developed (Fig. 9 [Figure 9: see original paper]). Without human activity impacts, the cumulative curve would be linear; with human impacts, it varies. The change slope during the mutation period exceeded the base period slope at all stations, indicating a slight upward shift after the abrupt change. The slope change was larger at Huayuankou and Lijin stations and modest at others. Cumulative precipitation and runoff depth matched well ($R^2 > 0.99$), confirming precipitation as a key influencing variable.

4.1.2 Impact of Potential Evapotranspiration on Runoff Among climate factors, runoff is affected not only by precipitation but also by temperature and sunshine duration (Liu et al., 2022). This study used temperature, wind speed, and sunshine duration data to calculate potential evapotranspiration via the Penman-Monteith formula. A double-mass curve of potential evapotranspiration and runoff depth (Fig. 10 [Figure 10: see original paper]) was created to examine its impact. The change slope during the mutation period exceeded the base period slope at all stations, with a slight upward shift after the abrupt change. The potential evapotranspiration slope change was greater than that of precipitation. Cumulative potential evapotranspiration matched runoff depth well ($R^2 > 0.99$), confirming it as a significant factor affecting runoff changes.

4.1.3 Attribution Analysis of Climate Factor Influence Precipitation, potential evapotranspiration, and temperature all impact hydrological regime changes. Precipitation is the primary source of flow generation and the main cause of flow production and confluence fluctuations. After accounting for vegetation transpiration and natural evaporation, precipitation forms runoff. Air temperature indirectly affects runoff by influencing evapotranspiration, potentially altering the hydrological regime. This study examined three climate factors—precipitation, potential evapotranspiration, and air temperature—using Pearson correlation analysis to investigate relationships with runoff changes during base and mutation periods, with t-tests assessing significance (Fig. 11 [Figure 11: see original paper]; Table 8).

During both periods, runoff was positively correlated with precipitation and negatively correlated with potential evapotranspiration and temperature at most stations, though patterns varied. The overall correlation with precipitation was significant, while correlation with potential evapotranspiration was generally insignificant. Runoff changes caused by potential evapotranspiration were much smaller than those caused by other climate factors, indicating lower sensitivity to potential evapotranspiration and highest sensitivity to precipitation.

4.2 Human Activity Impacts on Runoff

4.2.1 Water Conservancy Project Construction Recent decades have seen profound changes to the natural hydrological regime from water conservation projects. Over 20 large reservoirs exist in the upper basin, including Longyang Gorge and Liujiaxia Hydropower Station, with total regulated storage of approximately 23.8$×10^{10}$ m^3. The middle reaches contain Longkou and Wanjiazhai reservoirs, with the Guxian Water Conservancy Project serving as a key control structure for flood control, water supply, power generation, and ecological protection. The Guxian project coordinates water and sediment transfer with Wanjiazhai and Xiaolangdi reservoirs, effectively regulating floods and ensuring downstream water consumption. Sanmenxia and Xiaolangdi projects in the lower reaches include Sanmenxia Reservoir, the first large-scale project along the Yellow River, managing 89.00% of flow and 98.00% of sediment for flood control. Xiaolangdi Reservoir significantly impacts runoff, water conservation, riparian vegetation, biodiversity, land use, and habitat quality (Wang and Wang, 2022). The reservoir group development has created a series operation pattern with total capacity far exceeding pre-mutation levels, substantially altering the natural hydrological regime. Figure 12 [Figure 12: see original paper] shows the current hydropower station distribution.

4.2.2 Land Use Change Land use change affects basin hydrological processes by altering the underlying surface and runoff confluence mechanisms. Different land use types affect the hydrological cycle and evapotranspiration differently, with regime changes strongly linked to multiple land use types rather than single types.

Chen et al. (2022) examined land use change impacts on runoff in the Yangtze River' s Zhanghe Reservoir, finding that increasing forest area slightly increased runoff while expanding construction land increased extreme hydrology frequency. Liu et al. (2013) used the Variable Infiltration Capacity model to analyze land use and climate change impacts on the Qingyi River Basin, showing that land use change increased both surface runoff and baseflow. Significant population and economic growth in the Yellow River Basin have altered vegetation cover (Fig. 13 [Figure 13: see original paper]), making it critical to address ecohydrological condition changes from land use change.

The main land use types in the Yellow River Basin are cultivated land and grassland, with grassland comprising 47.82%-48.41% of total area and cultivated land 25.40%-26.64% (Fig. 14 [Figure 14: see original paper]). Water bodies and construction land occupy the smallest proportions. Land cover changed dramatically between 1980 and 2020 (Table 9). Cultivated land area increased by approximately 3050 km^2 from 1980-2000, then decreased by 11,720 km^2 from 2000-2020, with an overall change rate of -0.90%. Construction land area gradually increased, particularly from 2000-2020, with an overall change rate of 1.66% and an increase of approximately 14,540 km^2. Water body area decreased, and barren land decreased by approximately 12,320 km^2 (overall rate -1.37%).

Land use type changes indirectly alter basin flow processes and ecological-hydrological conditions (Blöschl et al., 2007; Erol and Randhir, 2012). Figure 15 [Figure 15: see original paper] illustrates land structure changes over 40 years. Cultivated land and grassland are crucial water sources, reflecting soil and water conservation project successes and improving lake reclamation phenomena. Research indicates that while land use change in the lower reaches is a major runoff change driver, its effect is smaller than water conservation project development.

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5 Conclusions

The Yellow River, China' s mother river, is a vital water source for northwest and north-central China. However, recent climate change and intensified human activities have reduced runoff, negatively impacting ecology. This study systematically analyzed hydrological regime changes and driving factors over the past 60 years, finding that runoff abrupt changes concentrated in the mid-1980s. Hydrological alteration degrees at Lanzhou, Toudaoguai, Longmen, Xiaolangdi, Huayuankou, and Lijin stations were 34.00%, 35.00%, 37.00%, 45.00%, 51.00%, and 54.00%, respectively—all moderate alteration. The alteration degree increased from upstream to downstream, indicating serious challenges for downstream ecological protection and river health. Hydrological regime changes also caused decreasing biodiversity trends. Climate change and human activities both contributed to runoff reduction: precipitation dominated in the upper reach (39.31%-54.70% contribution), while human activities dominated in the middle and lower reaches (63.70%-84.37% contribution). Over time, climatic factor influences gradually decreased while human activity effects became larger and more dominant.

The relationship among human activities, climate change, and river biological responses is a long-term and complex topic. Future research should establish a hydrological model framework to distinguish runoff changes caused by various human activities, comprehensively analyze river hydrological system evolution, and better address adverse ecosystem effects from hydrological regime changes.

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