# Runoff Change in the Yellow River Basin from 1960 to 2020 and Its Driving Factors: Postprint

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## Abstract

Analyzing runoff variation and its response to climate change and human activities is crucial for elucidating river eco-hydrological response mechanisms. This study employs the Indicators of Hydrologic Alteration-Range of Variability Approach (IHA-RVA) and ecological indicator method to quantitatively assess the degree of hydrological alteration and ecological response processes in the Yellow River Basin from 1960 to 2020. Based on Budyko hydrothermal coupling balance theory, the relative contributions of driving factors such as precipitation, potential evapotranspiration, and underlying surface to runoff variation in the Yellow River Basin are quantitatively evaluated. The results indicate that annual average runoff and precipitation in the Yellow River Basin showed decreasing trends from 1960 to 2020, while potential evapotranspiration showed an increasing trend. Around 1985, an abrupt change occurred in the mainstream hydrological regime. The degree of hydrological alteration gradually increased from upstream to downstream, ranging from 34.00% to 54.00%, all classified as moderate alteration. However, significant differences exist among different ecological indicators; the fluctuation index at downstream hydrological station outlets reached 90.00%, representing high alteration. After the abrupt change, the flow biodiversity index in the middle and lower reaches of the Yellow River was generally lower than during the baseline period. The results also demonstrate that precipitation is the main driving factor for runoff variation in the upper Yellow River, with contribution rates of 39.31%-54.70%; while human activities are the primary driving factors for runoff variation in the middle and lower reaches, with contribution rates of 63.70%-84.37%. These findings can provide a scientific basis for strengthening protection and restoration of the Yellow River Basin and further promoting rational development and utilization of Yellow River water resources.

# Full Text

## Preamble

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

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**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 the Range of Variability Approach (IHA-RVA) method, along with ecological indicator methods, 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, we quantitatively evaluated the relative contributions of various driving factors (precipitation, potential evapotranspiration, and underlying surface conditions) to runoff changes in the Yellow River Basin. The results show that while annual average precipitation and potential evapotranspiration exhibited upward trends from 1960 to 2020, annual average runoff displayed a downward trend. Approximately 1985 marked an abrupt change in the hydrological regime of the main stream. The degree of hydrological change increased gradually from upstream to downstream, ranging from 34.00% to 54.00%, all classified as moderate changes. However, significant differences were noted among ecological indicators, with a fluctuation index of 90.00% at downstream hydrological station outlets, reaching a high level of change. After the mutation, the flow biodiversity index in the middle and lower reaches of the Yellow River was generally lower than that in the base period.

The research results indicate that precipitation is the primary driving factor for runoff changes in the upper reaches of the Yellow River Basin, with a contribution rate of 39.31%-54.70%. In contrast, human activities are the main driver in the middle and lower reaches, contributing 63.70%-84.37% to runoff changes. These findings can serve as a basis for strengthening protection and restoration efforts in the Yellow River Basin and promoting the rational development and utilization of water resources.

**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 usage, as well as for the survival of many 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 contributed to shifts in water resource circulation patterns within basins. These changes affect water resource development and use while gradually leading to corresponding changes in the ecological environment, particularly in arid regions where the degree of impact has been observed to increase (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 hydrological health.

Numerous researchers have conducted quantitative analyses of hydrological changes in rivers both domestically and internationally. Taye et al. (2011) employed hydrological models to evaluate climate change effects on the Nile River' s hydrological regime, anticipating that long-term impacts of rainfall and potential evapotranspiration would decrease future discharge. Sorribas et al. (2016) used hydrological models to assess the influence of climate change and human activities on Amazon River hydrology, 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, discovering that precipitation variations and major reservoir construction during the 1970s caused river runoff decline, with human activities accounting for 63.00%-77.00% of this phenomenon.

The Yellow River, China' s second-largest river, has also undergone various changes 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 discovered a declining trend, noting that climate change' s influence on runoff is waning while human activities are increasingly becoming the primary contributing factor to decreased river runoff. The regulation and storage functions of reservoirs and rainfall changes are considered 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 in the basin more challenging. Thus, a comprehensive ecological and hydrological evaluation from multiple perspectives is required to quantify the impact of different driving factors on hydrological processes, which is critical for studying the Yellow River Basin’ s hydrological response mechanisms in complex changing environments.

Currently, more than 170 evaluation methods exist for hydrological indicators, but the most widely used is the Indicators of Hydrologic Alteration (IHA) method proposed by Richter (1996). This approach assesses the extent of hydrological change in rivers and has been widely employed in evaluating hydrological change and ecological consequences after continuous improvement by various academics (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 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 easily and precisely measure the influence of driving forces on runoff variations and have achieved strong research results at various scales. However, their use requires complete data (i.e., no missing or omitted data), which is scarce for long-term series statistical data, and many uncertainties exist in parameter testing. Although Schaake (1990) first used the elastic coefficient method to analyze the relationship between precipitation and runoff changes, he 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), making the results less accurate.

To address this limitation and make research results more comprehensive and reasonable, Choudhury (1999) and Yang et al. (2008) proposed a basin water-heat coupling equilibrium equation based on Budyko theory, refining the impact of climate change on rainfall and potential evapotranspiration. This allows for more accurate and convenient study of the contribution rates of different driving factors to basin runoff changes over time. This method has been widely used; for instance, Wang et al. (2012) investigated the contribution rates of climate change and human activities to runoff changes in the Yellow River using Budyko theory and differential equations, attributing runoff variations mostly to human activities such as reservoir building and land use changes, which became the most influential factor accounting for 57.29%-83.61% of the total. Although other researchers have quantified contribution rates of various driving factors to different river runoff changes, they have rarely considered the effects of river evapotranspiration and temperature, as well as the response relationships between various factors, and have failed to quantify ecological impacts by combining them with ecological-hydrological indicators.

Based on this, our study further refines the two major driving causes—climate change and human activities—into various influencing components to thoroughly examine changes in the Yellow River' s hydrological process. The objectives are: (1) examining changes in runoff and potential evapotranspiration in the Yellow River Basin from 1960 to 2020; (2) calculating the degree of hydrological changes in the upper, middle, and lower reaches, completely analyzing overall hydrological change, and ascertaining ecosystem risk; (3) quantitatively assessing the influence of hydrological regime changes on biodiversity; and (4) quantitatively investigating the contribution rates of different driving forces to runoff variations in the main stream. This study can statistically examine the influence of runoff variations on the Yellow River' s hydrological process and provide a basis for water resource management departments to develop and utilize water resources more wisely.

## 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$×10^{5}$ km$^2$ (32°10 -41°50 N, 95°53 - 119°05 E). It runs through nine Chinese provinces before joining the Bohai Sea (Xu et al., 2005; Zhu et al., 2016). The main river channel can be categorized into 11 sections based on distinct hydrological characteristics (Jin et al., 2020), comprising upper, middle, and lower reaches. In recent years, the hydrological regime in different watershed sections has undergone varying degrees of change due to combined influences of precipitation, reservoir construction and use, and land use changes, resulting in many negative impacts on the ecological environment. This article selects typical hydrological stations along the main stream —Lanzhou Station and Toudaoguai Station in the upstream, Longmen Station and Xiaolangdi Station in the midstream, and Huayuankou Station and Lijin Station in the downstream—to measure the degree of hydrological changes in different sections and the influence of driving factors on the basin' s ecological environment (Fig. 1 [Figure 1: see original paper]).

Fig. 1 Location of the selected hydrological and meteorological stations in the Yellow River Basin in this study. DEM, digital elevation model.

## 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).

### 2.3.1 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:

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

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

$$Y_t' = Y_t - r_1 Y_{t-1}, \quad (3)$$

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

where   is the slope of the sequence to be detected; a and b are variables to be detected; x  and x_b are 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 $r_1$ is the first-order autocorrelation coefficient.

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

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

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

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

The standardized test statistic Z_{MK} is:

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

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

### 2.3.2 MK Mutation Test and Pettitt Mutation Test

The MK test is used for mutation testing of precipitation, potential evapotranspiration, runoff, and temperature data, offering wide testing 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.

$$\operatorname{sgn}(x_i - x_j) = \begin{cases} 1, & x_i > x_j \\ 0, & x_i = x_j \\ -1, & x_i < x_j \end{cases}, \quad (9)$$

(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 $UF_1$=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, $UB_1$=0 when k=1. If the UB_k and UF_k curves intersect between the two critical lines, the corresponding intersection moment indicates when the mutation begins.

The Pettitt mutation test is based on the Mann-Whitney non-parametric test, obtaining abrupt change points through analysis of hydrometeorological factor sequences and quantifying 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 number of observations.

$$K_{f,N} = \max |U_{f,N}|, \quad (15)$$

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

where K_f,N is the mutation statistic and P is the significance value. Generally, when P$ $0.05, mutation points are considered present in the data.

### 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), encompassing five aspects: magnitude, timing, frequency, duration, and rate of change, refined into 32 ecological indicators. These indicators have ecological significance and 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 P_e = r ×P_t,     (18) $$

where D_c is the change degree of the cth indicator (%); P_{0} and P_e are the actual and predicted number of years when the cth indicator falls within the RVA threshold; r is the proportional coefficient (usually 50%); and P_t is the total number of years after being affected.

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

where D_{0} is the overall degree of change. Hydrological parameters are considered highly altered when |D_{0}| 67.00%, moderately altered when 34.00% |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, establishing the closest fitting relationship based on IHA hydrological indices and genetic programming regression. The formula is:

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

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 an important parameter expressing watershed evapotranspiration. The Penman-Monteith formula calculates potential evapotranspiration based on daily meteorological data (for specific principles, see McVicar et al., 2012; Wang and Dickinson, 2012):

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_2+273} U_2 (e_x - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \quad (21)$$

where PET is potential evapotranspiration (mm); R_n is net radiation on crop surface (MJ/(m^{2} · 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 vapour pressure (kPa); e_a is actual vapour pressure (kPa); Δ is the slope of the saturated water vapour pressure curve; and  is the hygrometric constant (kPa/°C).

### 2.3.6 Budyko Theory

According to Budyko' s coupled water-heat balance theory, 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). In long-term runoff change, 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 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:

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

where w can represent PRE, PET, or y. Assuming =PET/PRE, the elasticity coefficient can be calculated as:

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

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

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

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

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

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

Each change quantity is superimposed as total runoff change, denoted ΔR :

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

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

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

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

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

### 3.1.1 Trend Test for Precipitation

Owing to global climate change, China’ s precipitation distribution is shifting (Gu et al., 2020), affecting basin runoff and evapotranspiration with detrimental impacts on social and economic progress. 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 increased steadily from upstream to downstream from 1960 to 2020, suggesting rising risks of rainstorms, floods, and other hydrological disasters in the Yellow River’ s middle and lower reaches compared to the upper reaches.

Table 1 shows typical precipitation characteristic values in the Yellow River Basin from 1960 to 2020. Annual average precipitation ranges from 352.3 to 564.2 mm from upper to lower basin. Maximum annual precipitation in the upper, middle, and lower basins were 511.2, 602.3, and 1019.1 mm, respectively, all occurring around 1965. The largest variation coefficient was found downstream (0.24). Average annual precipitation values in the middle and lower reaches demonstrate geographical and temporal non-uniformity, likely attributable to recent increases in extreme weather events and human activities.

Fig. 2 Inter-annual variation trend of precipitation in the Yellow River Basin from 1960 to 2020. (a) Upper basin; (b) Middle basin; (c) Lower basin. The yellow line represents precipitation values; the red line represents precipitation trend; the shadow represents the 95% confidence interval.

Table 1 Characteristic values of precipitation in the Yellow River Basin from 1960 to 2020

| Location | Average (mm) | Maximum (mm) | Minimum (mm) | Standard deviation (mm) | Coefficient of variation |
|---|---|---|---|---|---|
| Upper basin | | | | | |
| Middle basin | | | | | |
| Lower basin | | | | | |

### 3.1.2 Trend Test for Potential Evapotranspiration

Climate change has significantly affected potential evapotranspiration in the Yellow River Basin with many negative consequences (Liu and Yang, 2010). The TFPW-MK test technique investigated trends and significance from 1960 to 2020 (Fig. 3 [Figure 3: see original paper]). Inter-annual potential evapotranspiration trended upward. TFPW-MK test statistics in upstream and middle reaches were below 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 Yellow River' s middle and lower reaches and increased vulnerability to extreme drought disasters such as high temperatures.

Table 2 shows characteristic values of potential evapotranspiration from 1960 to 2020. Average annual evapotranspiration from upstream to downstream were 920.3, 952.7, and 960.4 mm, respectively. Maximum annual potential evapotranspiration upstream, midstream, and downstream were 1029.2, 1011.4, and 1054.3 mm, respectively, all occurring around 1985. The downstream variation coefficient was largest, reaching 0.04, possibly related to extreme weather, greenhouse effects, climate warming, and other climate change factors in the post-mutation period.

Fig. 3 Inter-annual variation trend of potential evapotranspiration in the Yellow River Basin from 1960 to 2020. (a) Upper basin; (b) Middle basin; (c) Lower basin. The yellow line represents potential evapotranspiration values; the red line represents trend; the shadow represents the 95% confidence interval.

Table 2 Characteristic values of potential evapotranspiration in the Yellow River Basin from 1960 to 2020

| Location | Average (mm) | Maximum (mm) | Minimum (mm) | Standard deviation | Coefficient of variation |
|---|---|---|---|---|---|
| Upper Basin | | | | | |
| Middle Basin | | | | | |
| Lower Basin | | | | | |

### 3.1.3 Trend Test for Runoff

Annual runoff trends for six main stream hydrological stations are shown in Figure 4 [Figure 4: see original paper], demonstrating similar inter-annual fluctuation patterns—all exhibiting decreasing trends. MK test statistics were Z_{MK} = -1.92 and -1.81 for Lanzhou and Toudaoguai stations

(|Z_{MK}|<Z_(0.05)=1.96), failing the 95% significance test, indicating insignificant runoff decline trends. For Longmen, Xiaolangdi, Huayuankou, and Lijin stations, MK statistics 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 annual runoff trend becomes more significant from upstream to downstream.

Table 3 shows runoff volumes from 1960 to 2020 at the six stations. Average annual runoff volumes at Lanzhou, Xiaolangdi, Huayuankou, and Lijin stations were 315.9×10^{8}, 350.9×10^{8}, 322.2×10^{8}, and 264.4×10^{8} m^{3}, respectively, with maximum annual runoff in 1964. Average annual runoff at Toudaoguai and Longmen stations were 211.3×10^{8} and 252.7×10^{8} m^{3}, respectively, with maximum annual runoff in 1967. Lijin Station, as the downstream outlet, had the largest variation coefficient (0.70). Runoff volume fluctuation reflects the non-uniform regional and temporal distribution in the Yellow River Basin.

Fig. 4 Inter-annual variation trend of runoff at the six stations in the Yellow River Basin from 1960 to 2020. (a) Lanzhou Station; (b) Toudaoguai Station; (c) Longmen Station; (d) Xiaolangdi Station; (e) Huayuankou Station; (f) Lijin Station. The yellow line represents runoff values; the red line represents runoff trend; the shadow represents the 95% confidence interval.

Table 3 Characteristic values of runoff at the six stations in the Yellow River Basin from 1960 to 2020

| Hydrological station | Average (×10^{8} m^{3}) | Maximum (×10^{8} m^{3}) | Minimum (×10^{8} m^{3}) | Standard deviation | Coefficient of variation |
|---|---|---|---|---|---|
| Lanzhou Station | | | | | |
| Toudaoguai Station | | | | | |
| Longmen Station | | | | | |
| Xiaolangdi Station | | | | | |
| Huayuankou Station | | | | | |
| Lijin Station | | | | | |

## 3.2 Tests for Mutability of Runoff

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

Pettitt test results (Fig. 6 [Figure 6: see original paper]) show mutation years at 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), indicating obvious runoff mutations during 1960-2020.

Combining both methods (Table 4 ) more precisely determines the sudden shift years in annual average runoff: 1984, 1985, 1987, 1984, 1986, and 1985 for Lanzhou, Toudaoguai, Longmen, Xiaolangdi, Huayuankou, and Lijin stations, respectively. These abrupt changes all occurred around the mid-1980s.

Fig. 5 Results of Mann-Kendall (MK) mutation test at the six stations in the Yellow River Basin during 1960-2020. (a) Lanzhou Station; (b) Toudaoguai Station; (c) Longmen Station; (d) Xiaolangdi Station; (e) Huayuankou Station; (f) Lijin Station. UF represents test statistic; UB represents the reverse sequence of test statistic.

Fig. 6 Results of Pettitt mutation test at the six stations in the Yellow River Basin during 1960-2020. (a) Lanzhou Station; (b) Toudaoguai Station; (c) Longmen Station; (d) Xiaolangdi Station; (e) Huayuankou Station; (f) Lijin Station.

Table 4 Annual average runoff mutation year in the Yellow River Basin during 1960-2020

| Hydrological station | Mann-Kendall (MK) test | Pettitt test | Determined mutation year | Mutation year of annual average runoff |
|---|---|---|---|---|
| Lanzhou Station | | | | |
| Toudaoguai Station | | | | |
| Longmen Station | | | | 1987 and 1989 |
| Xiaolangdi Station | | | | |
| Huayuankou Station | | | | |
| Lijin Station | | | | |

## 3.3 Analysis of Hydrological Variability

The IHA-RVA method quantitatively assessed runoff change degree, yielding results for 32 hydrological indicators at 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 degree). Toudaoguai Station had the highest change in annual minimum flow timing (80.00%) and lowest change in June average flow (3.00%). Longmen Station' s April average flow changed most (100.00%), while high-flow pulse duration changed least (2.00%). Xiaolangdi Station' s October average flow and reversal number changed most (100.00%), while February average flow and 1-day minimum flow changed least (3.00%). At Huayuankou Station, average flow increase/decrease rate changed most (92.00%), while June average flow changed least (8.00%). At Lijin Station, average flow increase/decrease rate had the largest change degree (93.00%), while 3-day minimum flow had the smallest (6.00%).

Variations in each hydrological indicator group for the six stations were calculated using Equations 17-19 (Table 5 ). At Lanzhou and Toudaoguai stations, Group I indicators (January-December average flow) were at low level, while the last four groups were moderate. Toudaoguai Station' s Group IV indicators (low pulse count, duration, high pulse count, duration) were also low, with remaining groups moderate. Longmen Station' s Group III indicators (date minimum and maximum) were low, while other groups were moderate. At Xiaolangdi, Huayuankou, and Lijin stations, Groups I-IV indicators were moderately altered, while Group V indicators (increase rate, decrease rate, reversal times) changed significantly. Although overall indicators at all six stations showed moderate change, the degree increased from upstream to downstream, indicating higher ecosystem damage risk in the middle and lower reaches.

Hydrological indicator changes inevitably alter hydrological regimes, affecting natural river processes and aquatic organism reproduction (Guo et al., 2022). Annual extreme flow changes prevent some aquatic organisms from adapting, causing biodiversity decline. High and low pulse duration changes alter river ecological structure, affecting both aquatic organisms and riparian soil moisture, leading to vegetation cover changes. Flow and frequency changes impact river stage fluctuations, affecting aquatic community distribution. Although natural habitats can withstand external disturbance to some extent, damage exceeding tolerance thresholds becomes very difficult to recover.

Fig. 7 Change degree of the hydrological indicators of the Range of Variability Approach (RVA) at the six stations in the Yellow River Basin from 1960 to 2020. January-December represent average monthly flows; 1-d minimum flow-90-d minimum flow represent average annual minimum flows; 1-d maximum flow-90-d maximum flow represent average annual maximum flows; base flow represents base flow to total flow ratio; date minimum/maximum represent timing of extremes; low/high pulse count/duration represent pulse characteristics; increase/decrease rate represent average annual flow change rates; reversal represents annual flow reversal frequency.

Table 5 Change degree of hydrological indicator group at the six stations in the Yellow River Basin from 1960 to 2020

| Hydrological station | Group I | Group II | Group III | Group IV | Group V | Overall hydrological alteration |
|---|---|---|---|---|---|---|
| Lanzhou Station | 20 (L) | 24 (L) | 38 (M) | 41 (M) | 45 (M) | 34 (M) |
| Toudaoguai Station | 48 (M) | 43 (M) | 40 (M) | 38 (M) | 51 (M) | 35 (M) |
| Longmen Station | 58 (M) | 51 (M) | 24 (L) | 56 (M) | 35 (M) | 37 (M) |
| Xiaolangdi Station | 34 (M) | 43 (M) | 54 (M) | 36 (M) | 75 (H) | 45 (M) |
| Huayuankou Station | 42 (M) | 43 (M) | 35 (M) | 84 (H) | 90 (H) | 51 (M) |
| Lijin Station | 34 (M) | 35 (M) | 37 (M) | 45 (M) | 54 (M) | 54 (M) |

Note: H=high level change; M=moderate level change; L=low level change. Group I: January-December average flows; Group II: 1-, 3-, 7-, 30-, 90-day minimum/maximum flows and base flow ratio; Group III: date of minimum/maximum flows; Group IV: low/high pulse count/duration; Group V: increase/decrease rate and reversal times.

## 3.4 Ecological Response Analysis

Hydrological regime changes significantly impact river ecology. This study examined flow biodiversity indices at six hydrological stations to assess ecological response processes in the Yellow River Basin. Inter-annual biodiversity changes from 1960 to 2020 are summarized in Figure 8 [Figure 8: see original paper]. Flow biodiversity indices at Toudaoguai, Longmen, Huayuankou, and Lijin stations declined 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 decline.

In summary, 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 decline trends. Lanzhou and Lijin stations are relatively far from these hubs, and their regulating effects made local ecological environments less affected. This demonstrates that reservoir construction and operation significantly altered local runoff amounts and indirectly adversely impacted local biodiversity.

Fig. 8 Inter-annual variation of biodiversity index (Shannon Index) of flow at the six stations in the Yellow River Basin from 1960 to 2020. (a) Lanzhou Station; (b) Toudaoguai Station; (c) Longmen Station; (d) Xiaolangdi Station; (e) Huayuankou Station; (f) Lijin Station. Dots represent Shannon Index values; red lines represent trend; shadows represent 95% confidence intervals.

## 3.5 Attribution Analysis of Runoff Changes Based on Budyko Theory

Hydrometeorological characteristics and elasticity coefficients for six Yellow River Basin stations during reference and mutation periods are shown in Table 6 . During the mutation period, precipitation and annual runoff depth decreased compared to the reference period, while potential evapotranspiration increased. Elasticity coefficients showed that with 1.00% increases in precipitation, potential evapotranspiration, and underlying surface, runoff at Lanzhou Station increased by 3.27%, decreased by 2.17%, and decreased by 3.00%, respectively. Similar patterns occurred at other stations: Toudaoguai (+2.20%, -1.20%, -2.10%), Longmen (+2.67%, -1.67%, -2.26%), Xiaolangdi (+2.82%, -1.80%, -2.39%), Huayuankou (+2.76%, -1.76%, -2.34%), and Lijin (+3.69%, -2.69%, -2.75%). Runoff changes were positively correlated with precipitation but inversely correlated with potential evapotranspiration and underlying surface changes. The absolute elasticity coefficient values reflect runoff sensitivity to each factor, showing runoff is most sensitive to precipitation, second most sensitive to underlying surface, and least sensitive to potential evapotranspiration.

During the base period (1960-1985), all six stations showed positive correlations between runoff changes and precipitation, with Toudaoguai, Longmen, Xiaolangdi, and Lijin passing the 0.01 significance test. In relationships with potential evapotranspiration and temperature, Lanzhou, Longmen, and Xiaolangdi showed negative correlations, while Toudaoguai showed positive correlations.

Contribution rate calculations are summarized in Table 7 . During the mutation period (1986-2020), all stations showed positive correlations between runoff changes and precipitation, with Lanzhou and Xiaolangdi passing the 0.01 significance test and Toudaoguai and Lijin passing the 0.05 test. In relationships with potential evapotranspiration and temperature, Lanzhou, Toudaoguai, Longmen, and Xiaolangdi showed negative correlations, while Huayuankou and Lijin were negatively correlated with potential evapotranspiration but positively correlated with air temperature.

Table 6 Hydrometeorological characteristics of the six stations in the Yellow River Basin from 1960 to 2020

| Hydrological station | Time period | R (mm) | PRE (mm) | PET (mm) | y | _{PRE} | _{PET} | _y |
|---|---|---|---|---|---|---|---|---|
| Lanzhou Station | | | | | | | | |
| Toudaoguai Station | | | | | | | | |
| Longmen Station | | | | | | | | |
| Xiaolangdi Station | | | | | | | | |
| Huayuankou Station | | | | | | | | |
| Lijin Station | | | | | | | | |

Note: PET=average potential evapotranspiration; R=average runoff depth; PRE=average precipitation; y=underlying surface parameter; _{PRE}=precipitation elasticity coefficient; _{PET}=potential evapotranspiration elasticity coefficient; _y=underlying surface elasticity coefficient.

Table 7 Attribution analysis of runoff changes in the Yellow River Basin from 1960 to 2020

| Hydrological station | ΔR_{PRE} (mm) | ΔR_{PET} (mm) | ΔR_{HA} (mm) | _{PRE} (%) | _{PET} (%) | _{HA} (%) |
|---|---|---|---|---|---|---|
| Lanzhou Station | | | | | | |
| Toudaoguai Station | | | | | | |
| Longmen Station | | | | | | |
| Xiaolangdi Station | | | | | | |
| Huayuankou Station | | | | | | |
| Lijin Station | | | | | | |

Note: ΔR_{PRE}=runoff depth change due to precipitation; ΔR_{PET}=runoff depth change due to potential evapotranspiration; ΔR_{HA}=runoff depth change due to human activities; _{PRE}=precipitation contribution; _{PET}=potential evapotranspiration contribution; _{HA}=human activity contribution.

Runoff changes due to precipitation and potential evapotranspiration are attributed to climate change, while human activity impacts correlate with underlying surface changes. Precipitation' s contribution to runoff changes decreased gradually from upstream to downstream, reaching maximum 54.70% at upstream Lanzhou Station and minimum 14.55% at downstream Lijin Station, indicating precipitation' s influence gradually decreases downstream. Potential evapotranspiration' s contribution showed an initial increase then decrease trend, peaking at 2.17% at midstream Longmen Station and minimum 0.86% at upstream Toudaoguai Station, implying limited influence. Decreased precipitation and increased potential evapotranspiration may jointly cause runoff reduction. Underlying surface contribution increased gradually from upstream to downstream, from minimum 43.72% at Lanzhou Station to maximum 84.37% at Lijin Station, becoming the dominant factor of runoff changes. For the Yellow River Basin, human activities are the main cause of runoff changes in middle and lower reaches, while precipitation change is the main cause in upper reaches. Potential evapotranspiration had relatively low influence on runoff changes.

## 4 Discussion

Multiple variables including climate change and human activities impact river runoff. Investigation of Yellow River hydrology shift causes reveals that before the abrupt transition, reservoir and hydropower plant construction was limited and sluggish, dominated by 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 periods, creating series operation modes that significantly altered hydrological sequences and caused abrupt changes in annual discharge. Many researchers have analyzed Yellow River runoff changes. Zhang et al. (2023) showed that after Xiaolangdi Reservoir operation, intra-annual runoff variations flattened and monthly runoff cycles reduced significantly. Shao et al. (2023) stated that Shiyang River Basin and its tributaries showed decreasing trends from the 1950s to 2019, projected to continue until 2050, consistent with our Yellow River runoff evolution analysis. For attribution analysis, Huang et al. (2023) showed that Kuye River Basin (a Yellow River tributary) underwent abrupt change in 1997, with complex anthropogenic activities causing drastic runoff reduction. Dai et al. (2023) evidenced that nine sub-basins in the middle reaches showed significant runoff decreases, with precipitation increasing from northwest to southeast and anthropogenic activities contributing more than climate change, especially in Huangfuchuan and Kuye River basins. These findings are consistent with our results, demonstrating that Yellow River runoff changes are more influenced by human activities.

### 4.1.1 Impact of Precipitation on Runoff

Precipitation is crucial in basin water cycles (Li et al., 2018). To investigate its influence on Yellow River runoff changes, a double accumulation curve of annual precipitation and runoff depth was developed (Fig. 9 [Figure 9: see original paper]). When runoff is unaffected by human activities, the cumulative curve is linear; when affected, it varies. The slope change of the double accumulation curve during the mutation period was greater than during the base period at all stations, indicating slight upward shifts after abrupt changes. Change amplitude was larger at Huayuankou and Lijin stations and comparatively modest at others. Each station’ s cumulative precipitation and runoff depth matched well (R^{2}>0.99), identifying precipitation as a key influencing variable.

Fig. 9 Twofold cumulative curve of annual precipitation-runoff depth at the six stations in the Yellow River. (a) Lanzhou Station; (b) Toudaoguai Station; (c) Longmen Station; (d) Xiaolangdi Station; (e) Huayuankou Station; (f) Lijin Station.

### 4.1.2 Impact of Potential Evapotranspiration on Runoff

Among climate change factors, runoff is affected not only by precipitation but also by temperature, sunshine duration, etc. (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 accumulation curve of potential evapotranspiration and runoff depth (Fig. 10 [Figure 10: see original paper]) examined its impact on runoff changes.

The slope change of the double accumulation curve during the mutation period exceeded the base period slope at all stations, indicating slight upward shifts after abrupt changes. Potential evapotranspiration slope changes were greater than precipitation changes. Cumulative potential evapotranspiration matched cumulative runoff depth well (R^{2}>0.99). Potential evapotranspiration significantly affects runoff changes, while climatic conditions like temperature and sunshine duration also impact runoff.

Fig. 10 Twofold cumulative curve of annual potential evapotranspiration-runoff depth at the six stations in the Yellow River. (a) Lanzhou Station; (b) Toudaoguai Station; (c) Longmen Station; (d) Xiaolangdi Station; (e) Huayuankou Station; (f) Lijin Station.

### 4.1.3 Attribution Analysis of Climate Factor Influence on Runoff Changes

Precipitation, potential evapotranspiration, temperature, and other climatic factors impact river hydrological regime changes. Precipitation is the principal source of flow production and the primary cause of flow production and confluence fluctuations. After atmospheric precipitation removes vegetation transpiration and water surface evaporation, runoff forms. Air temperature can indirectly affect runoff by influencing evapotranspiration, causing hydrological regime shifts. This study used three climatic factors—precipitation, potential evapotranspiration, and air temperature. Pearson correlation analysis investigated relationships between runoff changes and climatic factors in base and mutation periods, with t-tests assessing association significance. Results are illustrated in Figure 11 [Figure 11: see original paper] and Table 8 .

Fig. 11 Correlation between climatic factors and runoff before (a) and after (b) abrupt change at the six stations in the Yellow River Basin. PRE, precipitation; PET, potential evapotranspiration; TEM, temperature.

Table 8 Correlation coefficient between climatic factors and runoff at the six stations in the Yellow River Basin from 1960 to 2020

| Hydrological station | Time period | Precipitation | Potential evapotranspiration | Temperature |
|---|---|---|---|---|
| Lanzhou Station | | 0.460** | | |
| Toudaoguai Station | | 0.600** | | |
| Longmen Station | | 0.400* | | |
| Xiaolangdi Station | | 0.770** | | |
| Huayuankou Station | | 0.760** | | |
| Lijin Station | | 0.450** | | |

Note: * significant at 0.05 level; ** significant at 0.01 level. Positive values indicate positive correlation; negative values indicate negative correlation.

In both periods, runoff was inversely linked with potential evapotranspiration and air temperature but positively correlated with precipitation, passing the 0.01 significance threshold at Lanzhou during the mutation period. At Toudaoguai, runoff showed positive associations with precipitation, potential evapotranspiration, and air temperature, with precipitation correlation passing 0.01 significance in the base period and 0.05 in the mutation period, while being inversely correlated with temperature and potential evapotranspiration during mutation. At Longmen, runoff was positively linked with precipitation (0.01 significance in base period) and negatively linked with potential evapotranspiration and air temperature in both periods. At Xiaolangdi, runoff was positively linked with precipitation (exceeding 0.01 significance in both periods) and negatively correlated with potential evapotranspiration and temperature. At Huayuankou, base period runoff was positively associated with precipitation and air temperature but negatively with potential evapotranspiration; during mutation, runoff was positively linked with air temperature (0.01 significance). At Lijin, runoff in both periods was positively associated with precipitation and air temperature and negatively with potential evapotranspiration.

Overall, runoff was negatively correlated with potential evapotranspiration, with smaller correlation coefficients than precipitation and air temperature. The overall correlation with potential evapotranspiration was insignificant, while precipitation correlations were significant. Runoff changes caused by potential evapotranspiration were much smaller than those from other climatic factors, suggesting runoff is less sensitive to potential evapotranspiration and most sensitive to precipitation.

### 4.2.1 Construction of Water Conservancy Projects

In recent decades, water conservation project construction has profoundly changed the Yellow River Basin’ s natural hydrological regime. Currently, over 20 large reservoirs exist in the upper basin, including Longyang Gorge and Liujiaxia Hydropower Stations, with total regulated storage of approximately 23.8×10^{10} m^{3}. Longkou and Wanjiazhai reservoirs are located in middle reaches, with Guxian Water Conservancy Project as a key control backbone project addressing flood control, ecological environment, and other aspects besides water supply and power generation. The Guxian project collaborates with Wanjiazhai and Xiaolangdi reservoirs on water and sand transfer, successfully regulating floods, reducing catastrophic flood peaks, and ensuring downstream water consumption. Sanmenxia and Xiaolangdi projects are located in lower reaches, with Sanmenxia being the first large-scale project, managing 89.00% of water flow and 98.00% of silt, playing a crucial role in Yellow River control. Xiaolangdi Reservoir significantly impacts runoff, water conservation, riparian vegetation, biodiversity, land use, and habitat quality in the lower basin (Wang and Wang, 2022). Reservoir group development has followed a series pattern, with total capacity far exceeding pre-mutation periods, significantly affecting the main stream’ s natural hydrological regime. The current hydropower station distribution is shown in Figure 12 [Figure 12: see original paper].

Fig. 12 Schematic diagram of reservoirs in the Yellow River Basin.

### 4.2.2 Land Use Change

Scientists worldwide have examined hydrological process changes caused by land use change, with most findings indicating that land use changes affect underlying surface and runoff confluence mechanisms. Diverse land use types affect hydrological cycle processes and evapotranspiration differently, with hydrological regime changes strongly tied to multiple land use types rather than single types.

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

Fig. 13 Spatial distribution of land use types in the Yellow River Basin in 1980 (a), 1990 (b), 2000 (c), 2010 (d), and 2020 (e).

Main land use types in the Yellow River Basin were cultivated land and grassland, with grassland accounting for 47.82%-48.41% and cultivated land 25.40%-26.64% of total area. Water body and construction land occupied the lowest proportions. Between 1980 and 2020, land cover changed dramatically. Land use type areas and change rates are shown in Table 9 .

Cultivated land area increased from 1980 to 2000 (~3050.00 km^{2} increase) then decreased from 2000 to 2020 (~11,720.00 km^{2} decrease), with overall change rate of -0.90%. Construction land area gradually increased with industrialization and urbanization, especially from 2000 to 2020, with overall change rate of 1.66% and increase of ~14,540.00 km^{2}. Water body area decreased, and barren land change rate was -1.37%, reducing ~12,320.00 km^{2}.

Land use type changes indirectly alter basin flow processes and ecological-hydrological conditions. Land structure changes modify underlying surface conditions, altering runoff generation and confluence mechanisms (Blöschl et al., 2007; Erol and Randhir, 2012). Yellow River Basin land structure changes over 40 years are shown in Figure 15 [Figure 15: see original paper]. Cultivated land and grassland are crucial water sources, demonstrating significant soil and water conservation project successes and improving lake reclamation phenomena in middle and lower lake basins. Research shows land use change in lower reaches is a major runoff change driver, though its effect is smaller than water conservation project development.

Fig. 14 Area of different land use types in the Yellow River Basin in 1980, 1990, 2000, 2010, and 2020.

Fig. 15 Land use transfer in the Yellow River Basin from 1980 to 2020. Lines represent conversion between land use types; cusps represent transfer direction; line width represents transfer area.

Table 9 Area change of different land use types in the Yellow River Basin from 1980 to 2020

| Land use type | Area (×10^{3} km^{2}) | Rate of area change (%) |
|---|---|---|
| Cultivated land | | |
| Forest | | |
| Grassland | | |
| Water body | | |
| Construction land | | |
| Barren land | | |

## 5 Conclusions

The Yellow River, China' s mother river, is a major water supply source for northwest and north-central China. However, climate change and increased human activities have recently decreased Yellow River 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 alterations. The 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 reduced Yellow River runoff; upper reach reduction was primarily due to precipitation (39.31%-54.70% contribution), while middle and lower reach reduction was mainly from human activities (63.70%-84.37% contribution). Over time, climatic factor influence 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, complex topic. Future research should establish a hydrological model framework to distinguish runoff changes caused by various human activities to 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.*