

Article

Study on the Driving Mechanism of Ecohydrological Regime in the Wandering Section of the Lower Yellow River

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Abstract: Climate change and human activities exert significant impacts on runoff generation and convergence mechanisms. Understanding the evolution mechanisms and driving forces of runoff is crucial for the sustainable development of water resources. This study is based on the runoff data of the Huayuankou (HYK), Jiahetan (JHT), and Gaocun (GC) stations in the lower reaches of the Yellow River from 1951 to 2019. The objectives are to identify and quantify the hydrological pattern and its driving mechanism of the three stations by the Mann–Kendall test, cumulative deviation method, wavelet analysis, the IHA-RVA method, SCRCO method, and the Budyko method. Our study revealed that the runoff disturbance points at all three stations occurred in 1985. During the two periods before and after the disturbance, the trends and periodicities within the year exhibited high consistency, showing an overall downward trend, with runoff increasing in October and decreasing in June and the primary cycles being 5 and 7 years. All three stations experienced high-degree changes in their hydrological situations, with the high-degree change occupying the largest proportion. At the HYK, JHT, and GC stations, human activities accounted for 66.05%, 71.94%, and 74.38% of runoff changes, respectively. Furthermore, we verified the attribution conclusion of runoff at HYK using the Budyko model, confirming that human activities are the primary factor influencing runoff. Finally, we explored the interactive relationships along the spatial trajectory of runoff at the three stations, analyzed 32 hydrological indicators, and detailed the land use changes in the Yellow River Basin. Our research findings complement the understanding of hydrological change mechanisms in the lower reaches of the Yellow River Basin and provide a scientific basis for future water resource management and flood prevention measures.

Keywords: hydrological regime; runoff; human activities; climate change; lower Yellow River; trend analysis



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1. Introduction

Rivers play a pivotal role in sustaining regional economic and social development [1]. Among these, streamflow, as a critical component of the hydrological cycle and water resources system, represents a significant manifestation of surface water resources. It also serves as a fundamental basis for optimal allocation, rational utilization, and protection of water resources [2,3]. In recent decades, studies have revealed that climate change has had widespread impacts, including rising temperatures, uneven precipitation distribution, and

an increase in extreme weather events. These changes have directly affected water resources systems [4]. Additionally, large-scale human activities, such as agricultural production, the Grain for Green Program, the implementation of soil and water conservation measures, and the development and utilization of water resources, have significantly influenced the variation in surface runoff and sediment transport in rivers [5]. A scientific understanding of the hydrological conditions in river basins, along with accurate quantification and identification of influencing factors, can provide crucial support for rational planning of water resources and enhancing ecological and environmental quality [6,7].

The analysis of the impacts of climate change and human activities on streamflow, as well as the quantitative attribution of these impacts, has become a hot and challenging topic in current research [8,9]. Currently, widely applied attribution methods include hydrological modeling, multiple regression analysis, and comparison of cumulative slope change rates. For instance, Gu [10] used the double mass curve method to quantify the impacts of precipitation and human activities on the reduction of streamflow in the upper and middle reaches of the Yellow River. Li [11] employed the SWAT model to isolate the effects of climate change and human activities on streamflow in different sections of the Weihe River. Wang [12] used the VIC model to discover that the natural streamflow in the Baimasi sub-basin of the Yellow River is mainly controlled by climate change. However, Zeng [13] found through a comparison of different methods that empirical statistical methods are simple but lack physical mechanisms, while hydrological modeling is overly complex and requires a significant amount of data. In contrast, the comparison of cumulative slope change rates enjoys wider applicability due to its low data richness requirements and resilience to inter-annual fluctuations in observed data [14]. There are two ways to apply this method: either reflecting climate change solely through precipitation and deriving its contribution rate or considering both water (precipitation) and heat (evapotranspiration or temperature) impacts. The former approach only considers water impacts, ignoring heat impacts, which is neither objective nor comprehensive. The latter considers both water and heat impacts, but for most basins, long-term continuous observational data on evapotranspiration are difficult to obtain, leading to significant uncertainties in the calculated evapotranspiration data [15]. Meanwhile, the elasticity coefficient method based on Budyko's hypothesis has become an ideal method for quantitatively assessing streamflow changes due to its relatively simple and convenient calculation, easily accessible parameters, and physical basis that reflects the relationship between water and energy within a basin [16]. This method holds promising application prospects in streamflow attribution analysis [17].

The Yellow River, China's second-largest river, serves as one of the fundamental water supply sources in the northern part of the country. Its runoff is unevenly distributed spatially, primarily originating from the upstream and midstream regions [18]. Since the founding of New China, China has implemented various measures in the Yellow River basin, including soil erosion control, returning farmland to forests and grasslands, the construction of hydraulic engineering facilities, and flood disaster management, achieving remarkable results [19,20]. However, excessive human intervention and ecologically destructive development have also brought severe negative impacts, such as frequent river dry up, severe water pollution, and a decrease in the number and area of wetlands in the late 20th century. The impacts of human activities, including the construction and operation of dams, land use changes, and industrial and agricultural production on the runoff of the basin have become increasingly significant [18]. Therefore, studying the quantitative attribution analysis of inter-annual and intra-annual runoff changes and the influence mechanisms of factors affecting runoff changes is of great significance for understanding the evolution characteristics of runoff in the basin.

The objectives of this study are as follows: (1) to identify the disturbance year based on annual data from 1951 to 2019 for various sections and divide the entire period into a baseline period (1951–1985) and a measurement period (1986–2019) based on changes in runoff increments; (2) to analyze the characteristics of changes in hydrological runoff conditions before and after the disturbance; (3) to quantify the degree of change in hydrological

indicators during different periods using the IHA-RVA methodology; (4) to introduce the slope of cumulative change rate method (SCRCQ) to quantify the impacts of climate change (precipitation) and human activities on runoff variations, and to assess the contributions of precipitation and human activities to the changes in runoff increments in the lower reaches of the Yellow River; and (5) to explore the reasons for the degree of change in different hydrological indicators and the mechanisms underlying runoff variations.

2. Methodology

2.1. Study Area and Data

The Yellow River Basin, located between $102^{\circ}47'$ to $108^{\circ}22'$ east longitude and $34^{\circ}22'$ to $48^{\circ}27'$ north latitude, which originates from Bayankala Mountain in the west, borders the Bohai in the east, reaches the Qinling Mountains in the south, and reaches Yinshan Mountain in the north. Karriqu at the north foot of Bayankala Mountain is the direct source of the Yellow River, which originates from Yaradazze Peak in the Bayankala Mountain Range, with an altitude of 4675 m. The average flow rate is 1774.5 cubic meters per second, all the way through 5464 km, and finally flows into the Bohai. The Yellow River is the fifth longest river in the world and the second-longest river in China (after the Yangtze River), with total length of about 5464 km, water level of 4480 m, and total basin area of 752,400 square kilometers. The wandering section of the lower Yellow River starts from Xiaolangdi Dam and ends at Gaocun, Dongming County, Shandong Province. There are three hydrology stations in the wandering section, which are HYK, Gaocun (GC), and Jiahetan (JHT) (Figure 1), from upstream to downstream.

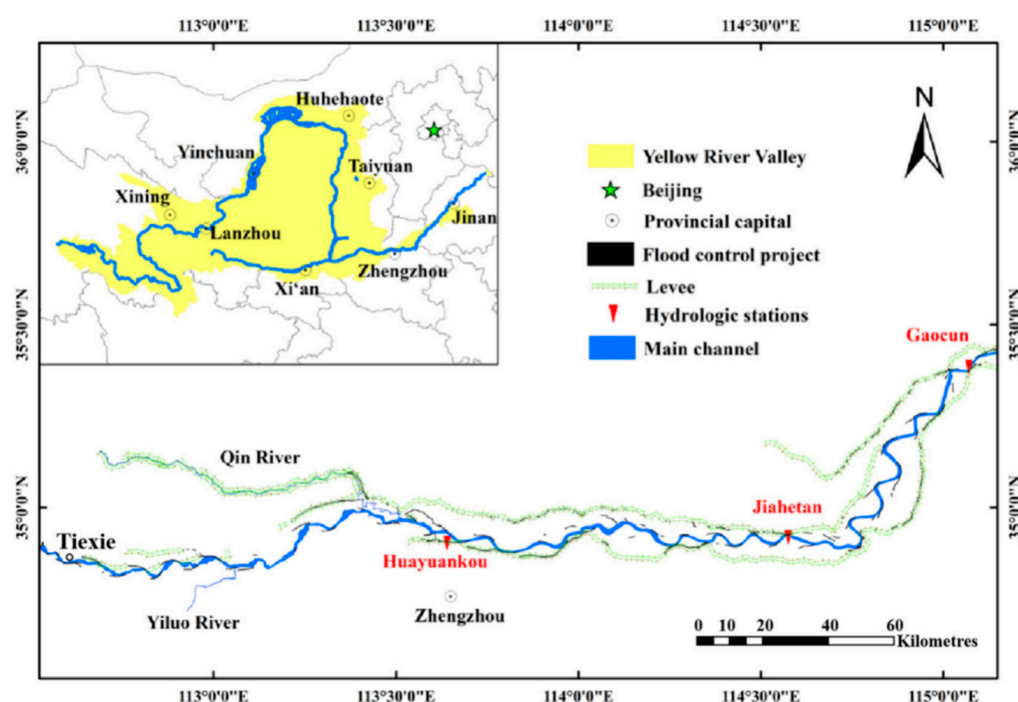


Figure 1. Overview of the wandering reach in the lower Yellow River.

In this research, the hydrological runoff data were obtained from the Yellow River Conservancy Commission (<http://www.yrcc.gov.cn/>, accessed on 12 June 2023), and the time span of data from the three hydrological stations was 1951–2019. The meteorological data are from China Meteorological Administration (<https://www.cma.gov.cn/>, accessed on 15 August 2023), and the span was consistent with the runoff data, ranging from 1951 to 2019. In this study, 53 meteorological information types (mainly rainfall and evapotranspiration, of which evapotranspiration is calculated based on the FAO Penman–Monteith) were used in the Yellow River Basin. Finally, the detailed rainfall and evapotranspiration

characteristics of the three hydrographic stations were calculated using the Tyson polygon method. The data of land use/cover was obtained from the Data Center for Resources and Environmental Sciences (<http://www.resdc.cn>, accessed on 20 August 2023), with a resolution of 90 m. Land use/cover is classified into 6 categories: cultivated land, forest land, grassland, water area, construction land, and unused land.

2.2. Trend and Mutability Characteristics Analysis

In the current research, we undertook a comprehensive analysis to explore the intricate hydrological time series characteristics of the Yellow River Basin, employing a synergistic approach that integrates the non-parametric Mann–Kendall (MK) statistical test and the cumulative deviation method. The MK test, first introduced by Mann [21] and later refined by Meyer, assesses trends in time series data by comparing the magnitudes of sequential pairs of data points. Specifically, an upward trend is signified when a data point exceeds its subsequent counterpart, whereas a decrease signals a downward trend [22]. Additionally, the MK test's proficiency in detecting abrupt changes within time series data offers a valuable resource for further analysis of hydrological patterns [23]. Complementing the MK test, the cumulative deviation method offers a straightforward yet effective means of identifying trends and abrupt changes in hydrological time series. This method involves calculating the deviation of each data point from the mean of the entire series and subsequently accumulating these deviations. By examining the trajectory of the cumulative deviation curve, researchers can deduce both the overall trend and potential abrupt changes within the time series. An upward slope in the curve indicates an increasing trend, while a downward slope signifies a decreasing trend. Moreover, the inflection points observed in the curve may serve as indicators of significant hydrological shifts or abrupt changes within the time series.

2.3. Hydrological Index Characteristics Analysis

Richter et al. [24] developed the index of hydrological alteration assessment (IHA) for hydrological change attributed to the extent of human disturbance in an ecosystem and proposed a series of change methods based on the range of variability approach (RVA). The method proposed by Richter et al. [25] has been widely used in the USA and Poland [26,27]. The RVA was chosen to investigate the degree of influence of human activities and climate change on the hydrological conditions. A total of 32 hydrological indicators of the IHA were selected and numbered 1–32 (Table 1):

$$D_t = \left| \frac{N_i - N_e}{N_e} \right|; \quad (1)$$

$$D_O = \left(\frac{1}{n} \sum_{i=1}^n D_i^2 \right)^{0.5}; \quad (2)$$

where D_i is the degree of change of a single factor; N_i is the number of years in the RVA reading range after the change of the i factor; N_e is the estimated number of years in the RVA reading range after the change; it can be assessed by $r \cdot N_T$, where r is the proportion of IHA falling within the RVA target reading value before the disturbance. The degree of hydrological change of individual indicators cannot reflect the overall degree of change, so this paper uses the overall degree of hydrological change D_O . To reflect the overall change in hydrology, $0 < (D_i)D < 33\%$ is low change, $33\% < (D_i)D < 67\%$ is moderate change, and $67\% < (D_i)D < 100\%$ is high change.

Table 1. Indexes of IHA.

IHA Parameter	Parametric Indicators	Number
Group 1: Magnitude of monthly water conditions	Monthly average flows	January to December corresponding to numbers 1–12, respectively
Group 2: Magnitude and duration of annual extreme water conditions	1, 3, 7, 30, 90 d minimum and maximum flows, baseflow index	Corresponding to numbers 13–23, respectively
Group 3: Timing of annual extreme water conditions	Time of occurrence of annual maximum and minimum 1-day mean flows (Roman days)	Corresponding to numbers 24–25, respectively
Group 4: Frequency and duration of high and low pulses	Number of high and low pulse flow occurrences and average duration	Corresponding to numbers 26–29, respectively
Group 5: Rate and frequency of water condition changes	Average rate of water rise, average rate of water fall and number of reversals	Corresponding to numbers 30–32, respectively

2.4. Periodic Characteristic Analysis

In 1974, engineer Morlet introduced the concept of wavelet transform and after more than a decade of theoretical refinement, wavelet analysis has been widely used for the periodic analysis of long series [28]. The time–frequency multi-resolution function of wavelet analysis has good applicability in the study of non-stationary time series problems. The Morlet wavelet function is expressed as follows [29]:

$$\varphi(t) = e^{ict} e^{-t^2/2}; \quad (3)$$

where $\varphi(t)$ is the wavelet function, c is the wavelet center frequency, and t is time.

$$\text{Var}(a) = \int_{-\infty}^{+\infty} |W_f(a, b)|^2; \quad (4)$$

where $W_f(a, b)$ is the wavelet transform function, a is the scale factor, and b is the time factor. $\text{Var}(a)$ is the wavelet variance, which reflects the distribution of the energy of the signal fluctuations with scale a . Therefore, the relative strength of the main period and different scale perturbations present in a time series can be determined.

In this study, cross-wavelet transform (XWT) analysis and wavelet coherence (WTC) analysis were combined to quantify the resonant periodicity and correlation between two time series across multiple seasonal scales [30]. The XWT analysis reveals the shared fluctuation patterns in the time–frequency space of two time series. It identifies regions in the time–frequency space where the two series exhibit consistent periodic strengths, indicating common fluctuations between the two series at the same temporal scale and during the same time interval. The WTC analysis, on the other hand, evaluates the correlation between the two time series in the time–frequency space. It calculates the similarity of the fluctuation patterns between the two series and maps out the distribution of these similarities in the time–frequency space. A higher WTC value suggests a stronger correlation between the two time series within that specific time and frequency range. For detailed computational procedures, readers may refer to Vazifekkhah and Kahya [31] and Chang [32].

2.5. Driving Mechanism Analysis

The slope changing ratio of cumulative quantity method (SCRCQ) is a widely used method in studying river runoff, which was proposed by Wang Random et al., in 2012 [33]. It employs the year as the independent variable and cumulative precipitation or cumulative runoff depth as the dependent variable. Since the year is an objective existence, measuring cumulative quantities can eliminate errors caused by inter-annual variations, making the comparison results more accurate and valid. Therefore, the year and cumulative quantities

have a high correlation, allowing for the quantification of precipitation changes and, to a certain extent, facilitating the measurement of the rate of change in runoff depth [34]. In this study, based on the disturbance year, we designate the pre-disturbance period as period A and the post-disturbance period as period B. The slope of the relationship between cumulative runoff, cumulative precipitation, and the year in period A are denoted as S_{Ra} and S_{Pa} , respectively, while in period B, they are denoted as S_{Rb} and S_{Pb} . The slope change rate of cumulative runoff and cumulative precipitation is defined as follows:

$$\begin{cases} R_{SR} = [(S_{Rb} - S_{Ra}) / S_{Ra}] \times 100\%; \\ R_{SP} = [(S_{Pb} - S_{Pa}) / S_{Pa}] \times 100\%; \end{cases} \quad (5)$$

$$\begin{cases} C_p = (R_{SP} / R_{SR}) \times 100\%; \\ C_H = 1 - C_p \end{cases} \quad (6)$$

where R_{SR} and R_{SP} , respectively, represent the rate of change in the influence period relative to the base period. C_p represents the contribution rate of annual precipitation to annual runoff change; C_H is the contribution rate of human activities to annual runoff change, and the units are %.

3. Results

3.1. Trend and Disturbance Characteristics

The Mann–Kendall trend test was employed to quantitatively assess the long-term flow variation patterns in the wandering reach of the lower Yellow River. The analysis results are presented in Figure 2. The analysis reveals that the flow variation patterns at the three hydrological stations of HYK, JHT, and GC are largely consistent. The intersection points of the UF and UB curves for these stations within the confidence interval are all around 1985, indicating that the disturbance year for flow occurred around 1985. After 1985, the flow has been consistently declining, with Mann–Kendall statistics of -5.32 , -5.41 , and -5.53 , all exceeding the critical value of 2.58 at a significance level of $\alpha = 0.01$, indicating a significant decrease in flow. Additionally, the cumulative deviation method was used to scientifically validate the Mann–Kendall test results. As shown in Figure 2, the overall flow in the lower Yellow River Basin showed an upward trend from 1951 to 1985, and a significant downward trend after 1985, further confirming that the disturbance year for flow variation in the lower Yellow River Basin is 1985.

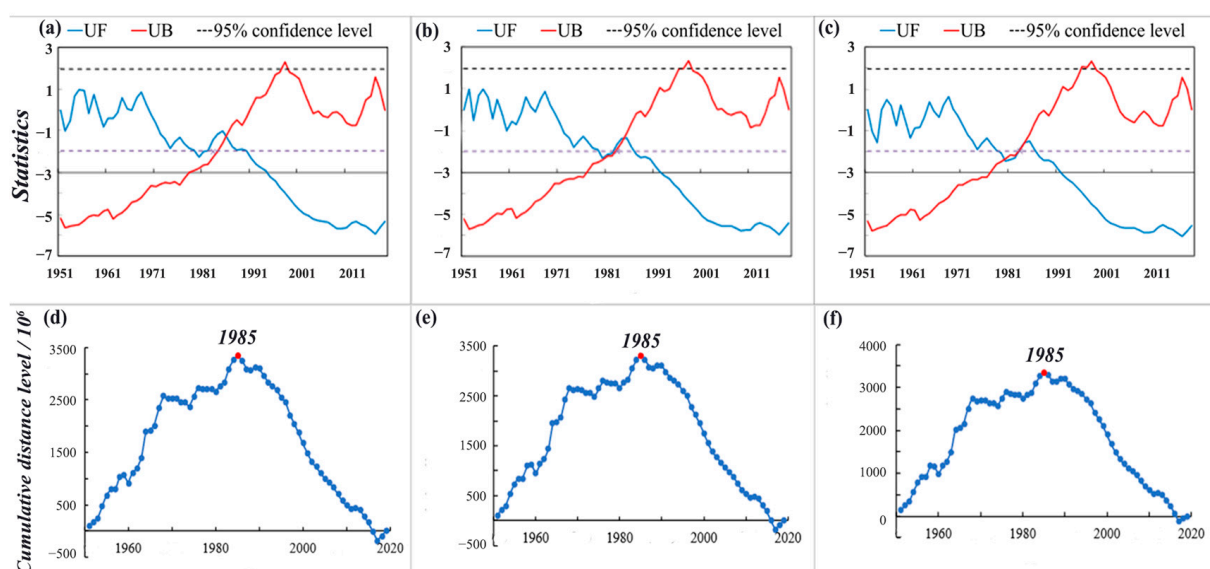


Figure 2. MK test curves from 1951 to 2019. Cumulative anomaly curves from 1951 to 2019. (a) HYK; (b) JHT; (c) GC.

3.2. Characteristics of the Hydrological Regime

Based on the characteristics of abrupt change years, we divided the pre-abrupt change period (1951–1985) and post-abrupt change period (1986–2019) to further analyze the hydrological regime characteristics of different periods (Figure 3). On an annual scale, the runoff at HYK shows a significant downward trend, with an average annual flow of 1158.83 m³/s. Before the disturbance year, it declined at a rate of 5.47 m³/s per year and then started to increase slowly at a rate of 1.48 m³/s after the disturbance year. The average runoff decreased from 1449.732 m³/s before the disturbance to 859.3703 m³/s after the disturbance. Similarly, the runoff at JHT and GC also exhibited significant downward trends, with average annual flows of 1119.251 m³/s and 1087.245 m³/s, respectively. Before the disturbance, they declined at rates of 7.8 m³/s and 9.09 m³/s per year and then began to increase slowly at rates of 2.74 m³/s and 2.93 m³/s, respectively. The average runoff values decreased from 1418.894 m³/s and 1399.232 m³/s before the disturbance to 810.7956 m³/s and 766.0829 m³/s after the disturbance, respectively. The rates of runoff change along the river increased successively.

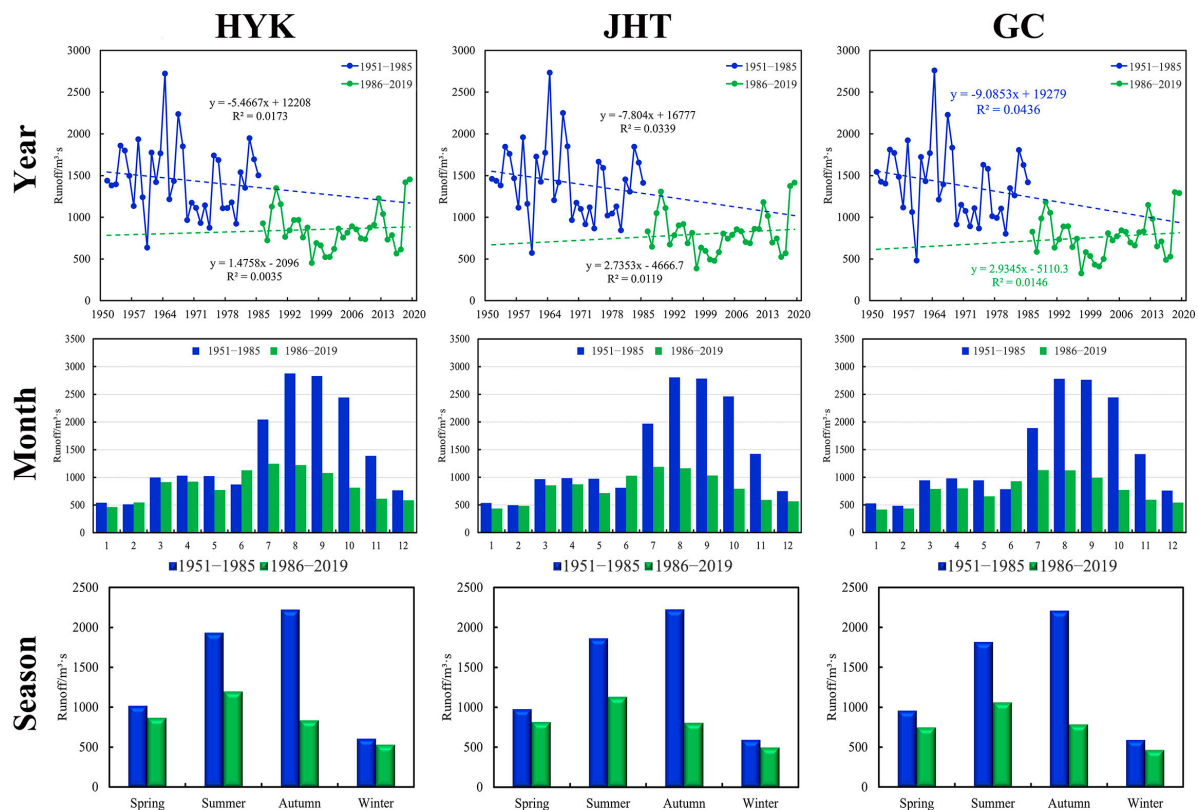


Figure 3. Hydrological regime of the wandering section of the Yellow River Basin before and after abrupt change.

Examining the monthly runoff series before and after the disturbance year, the three hydrological stations of HYK, JHT, and GC in the Yellow River Basin exhibited similar trends and patterns. Comparing the two phases before and after the disturbance, it was found that in February, only HYK showed an upward trend, while JHT and GC showed downward trends. This could be attributed to specific meteorological conditions or upstream inflow influencing the HYK station, leading to increased runoff. In June, all three stations exhibited an upward trend in runoff, with HYK having the highest increase rate of 29.5%. This could be related to the rainy season in June in the Yellow River Basin, leading to increased precipitation. Except for June, all three stations showed a downward trend in runoff. October was the month with the most significant decline in runoff at all three stations, reaching 66.69% (HYK), 67.83% (JHT), and 68.4% (GC), with average decreases

of 1627.66 m³/s, 1752.58 m³/s, and 1670.32 m³/s, respectively. This could be related to climatic characteristics, increased agricultural water demand, and upstream reservoir operations in October.

From the perspective of seasonal runoff series before and after the disturbance year, the runoff changes at the three stations showed a high degree of consistency on a seasonal scale, with all seasons experiencing a downward trend. Among them, autumn showed the most significant decline, with reductions of 62.37%, 63.81%, and 64.44% at HYK, JHT, and GC, respectively. This could be attributed to various factors such as climatic characteristics in autumn, increased agricultural irrigation water demand, and upstream reservoir storage operations. Summer, although a season with more precipitation, still showed a downward trend in runoff at all three stations. This could be related to high evaporation rates and high water demand in summer. The decline in spring and winter was similar and relatively gradual, which could be attributed to climatic characteristics, precipitation, and water demand in these two seasons.

3.3. Periodic Characteristics of the Hydrological Regime

The runoff series at the three stations (HYK, JHT, and GC) exhibit similar periodic fluctuations, with primary cycles of 5 and 7 years (Figure 4). This indicates that every 5 or 7 years, the runoff at these three stations undergoes a relatively significant change. Such periodic variations can be attributed to climatic factors (such as seasonal variations in precipitation), geographical conditions (such as river orientation and topography), and human activities (such as reservoir operations and agricultural irrigation). Specifically, on a 5-year scale, HYK experienced 13 alternating cycles of “wet–dry”, while on a 7-year scale, it underwent 11 alternating cycles of “dry–wet”. JHT had slightly fewer “wet–dry” alternating cycles than HYK on a 5-year scale, with 10 occurrences. However, on a 7-year scale, JHT had more “dry–wet” alternating cycles than HYK, reaching 13 occurrences. GC falls into an intermediate state of runoff variation, with the number of “wet–dry” and “dry–wet” alternating cycles on both 5-year and 7-year scales being between HYK and JHT. Analyzing the wavelet variance coefficient results for different stages, the runoff at these three stations exhibited a primary 5-year cycle during the pre-disturbance period (1951–1985), but this periodic pattern became less distinct in the post-disturbance period (1986–2019). This change may be associated with alterations in precipitation patterns, changes in human activity patterns, and modifications to the river system itself.

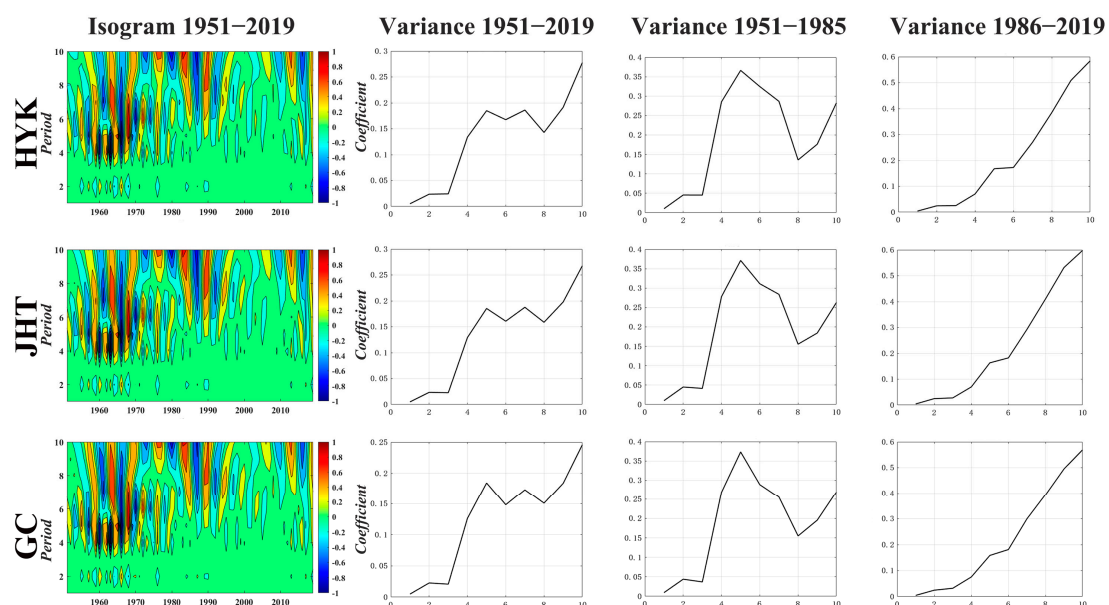


Figure 4. Periodic change characteristic diagram.

3.4. Hydrological Change Degree Characteristics

Building on the previous analysis, an evaluation of the hydrological alterations in the lower Yellow River Basin was conducted using the IHA-RVA method. Based on these alteration degree findings, we calculated the proportions of flow variation degrees across different categories and stations, resulting in Figures 5 and 6. Notably, high alteration degrees occupy the largest share in the overall statistics of flow variation degrees, ranging from 39% to 46% at each station. Moderate and low alteration degrees follow, accounting for 27% to 33% and 24% to 33% at various stations, respectively. The combined proportion of high and moderate alteration degrees exhibits a decreasing trend as one moves downstream, ranging from 75% at HYK to 73% and 66% further downstream. As depicted in Figure 5, the proportion of high-flow alteration degrees is highest in Group 5 (78%), followed by Group 2 (61%), and lowest in Group 3 (0%). This finding indicates that high alteration degrees are the dominant pattern in flow variations in the lower Yellow River, primarily driven by climate change and human activities. These factors have significant impacts on the magnitude and frequency of flow variations, as well as on the annual extreme flow values.

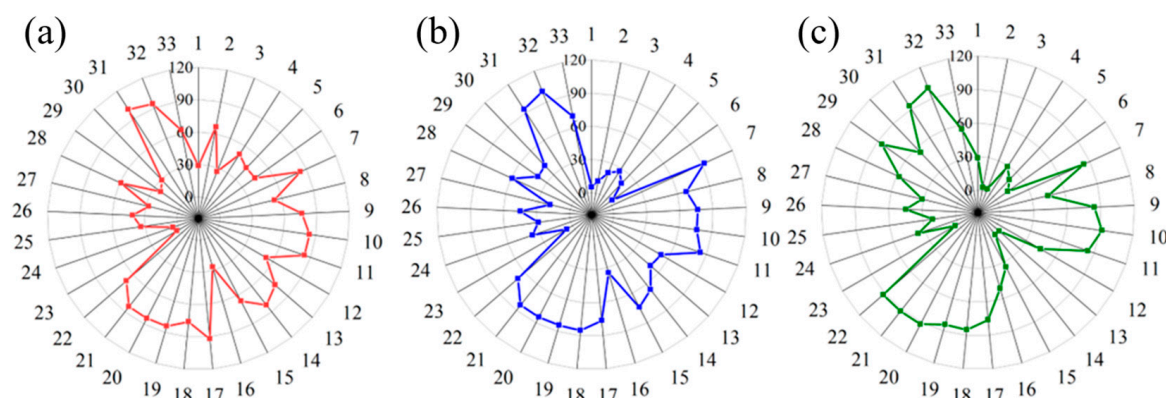


Figure 5. Hydrological change degrees. (a) HYK; (b) JHT; (c) GC.

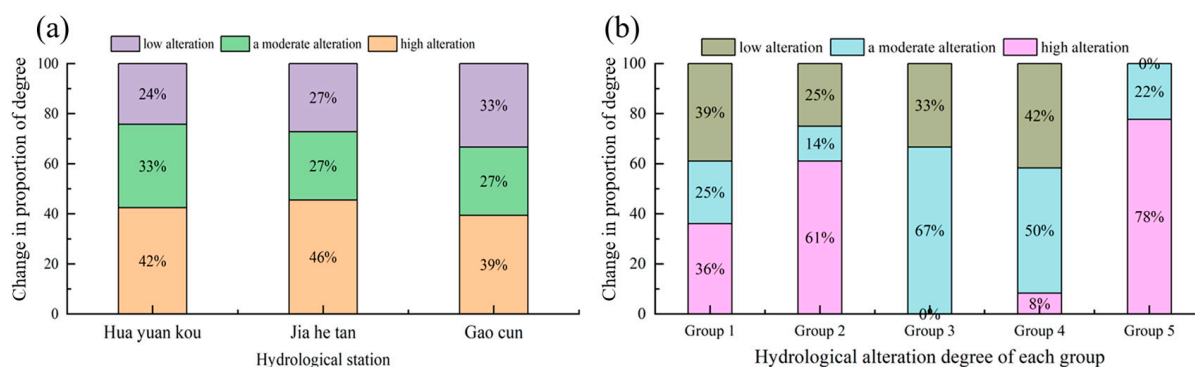


Figure 6. The proportions of different grade variation degrees of flow in (a) each hydrological station, and (b) each IHA parameter group.

3.5. Attribution Analysis Based on SCRCQ

The process of runoff yield variation was divided into two distinct periods, 1951–1985 (period A) and 1986–2019 (period B), using 1985 as the breakpoint. Linear regression analysis was performed on the annual and cumulative runoff yield data for each period, resulting in two distinct correlation equations for each station (Figure 7). Notably, the correlation coefficients (R) exceeded 0.99, and the p -values for confidence were less than 0.0001, indicating a strong linear relationship between runoff yield variation and climatic factors. It can be inferred that in period A, the runoff yield variation at each station was primarily driven by climatic factors such as rainfall and temperature, as human activities

in this region were relatively minor. However, after entering period B, a significant change occurred. The reduction rates of runoff yield at HYK, JHT, and GC were 43.87%, 45.93%, and 47.96%, respectively, while the reduction rates of rainfall were 14.89%, 12.89%, and 12.29%, respectively. Although climatic factors like rainfall still impacted runoff yield (evident from the rainfall reduction rates), the influence of human activities became more pronounced. This is evident not only in the significantly higher runoff yield reduction rates compared to rainfall reduction rates, but also in the contribution rates of human activities to runoff changes calculated using the cumulative volume slope formula. At HYK, JHT, and GC, human activities accounted for 66.05%, 71.94%, and 74.38% of the runoff changes, respectively, indicating a significant impact and an increasing trend along the river basin.

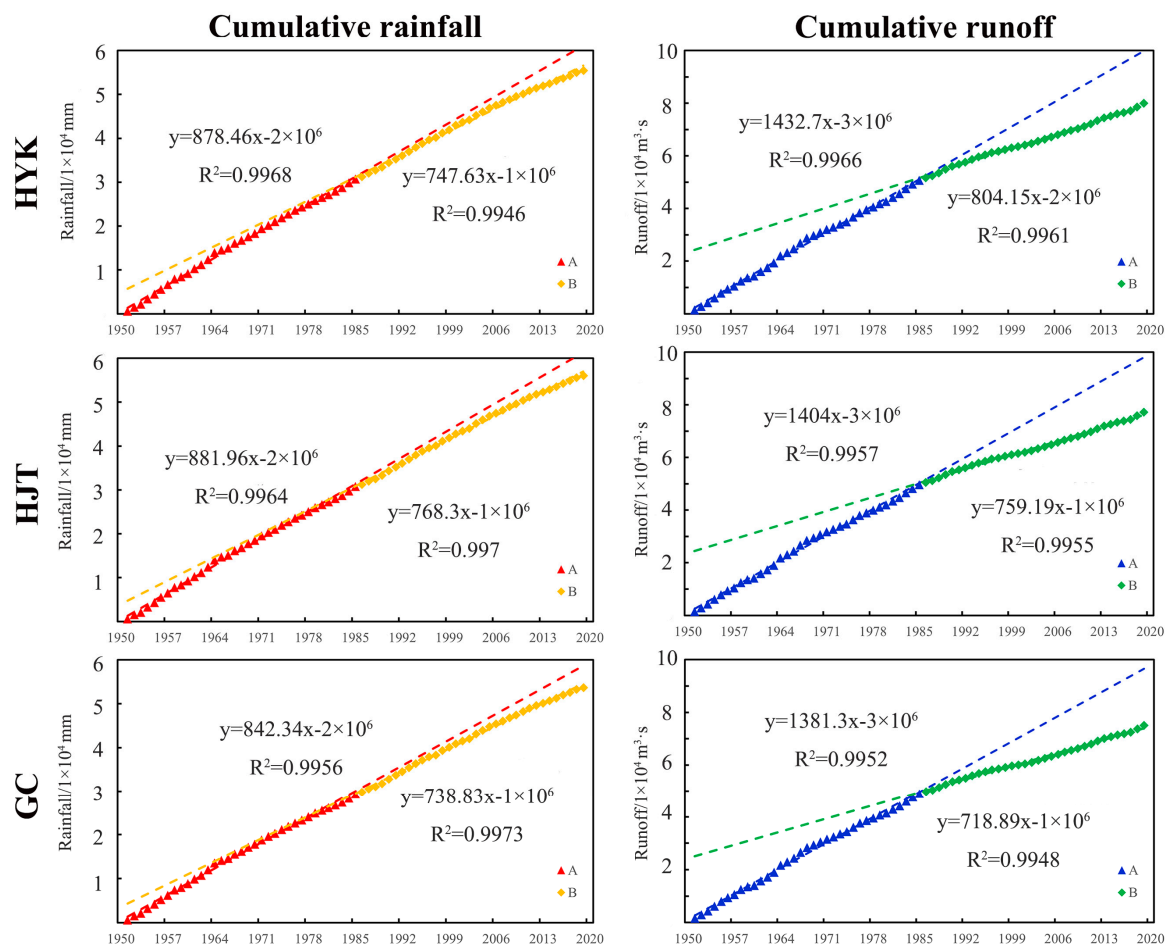


Figure 7. Diagram of evolution characteristics of SCRCQ method.

3.6. Change Degree Analysis of Hydrological Index in Yellow River Basin

3.6.1. Variation Characteristics of Monthly and Annual Maximum Flow

Figure 8 compares the median monthly river flows before and after the hydrological changes in the lower Yellow River. As evident from the comparative chart, the intra-annual flow variations at the three hydrological stations exhibit similar patterns after the abrupt change. Post-disturbance, the intra-annual flows in the lower Yellow River decreased to varying degrees, with the most significant decline occurring during the flood season from July to November, reaching a maximum reduction of 1687 m³/s. In contrast, the flow decline during the non-flood season is not as significant. The substantial difference in flow variations between the flood and non-flood seasons after the disturbance is closely related to human activities, particularly the role of reservoir dams in regulating the flood season flows in the lower Yellow River.

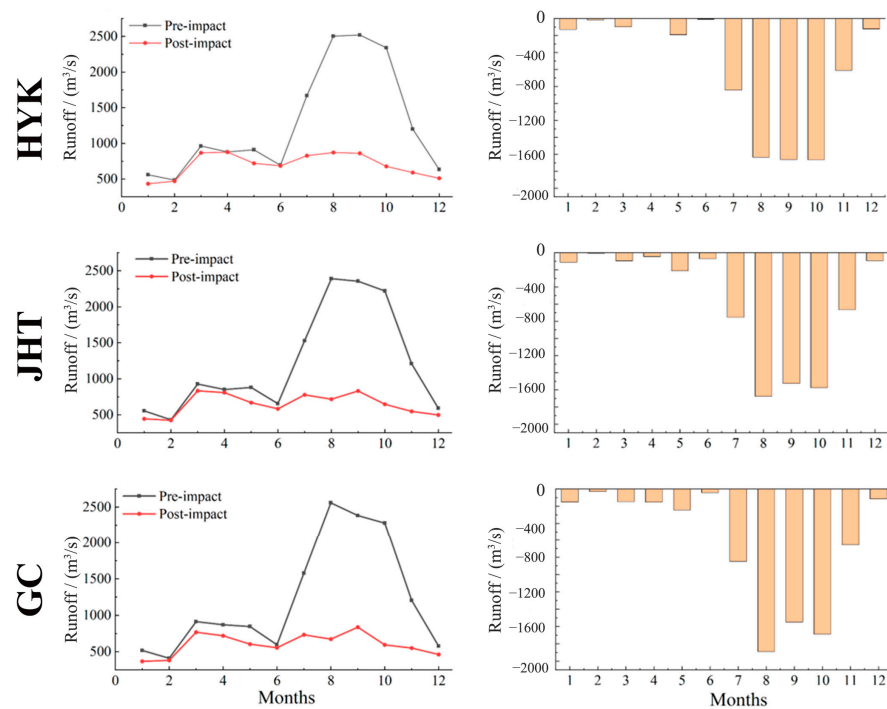


Figure 8. Monthly flow variations at each hydrological station before and after the sudden change and monthly flow difference before and after the change.

Moreover, the annual extreme flow patterns at the three hydrological stations exhibit similar trends (Figure 9). The annual minimum flows for 1, 3, and 7 days increased to varying degrees, with more significant increases observed at the JHT and GC stations. In contrast, the annual minimum flows for 30 and 90 days decreased to varying degrees, with the 90-day minimum flow exhibiting the most significant decline, ranging from 76% to 84%, representing a high degree of change. After the disturbance, the annual maximum flows at all three stations are lower than those before the disturbance, which is consistent with the trend test results indicating a downward trend in flows in the lower Yellow River after the disturbance.

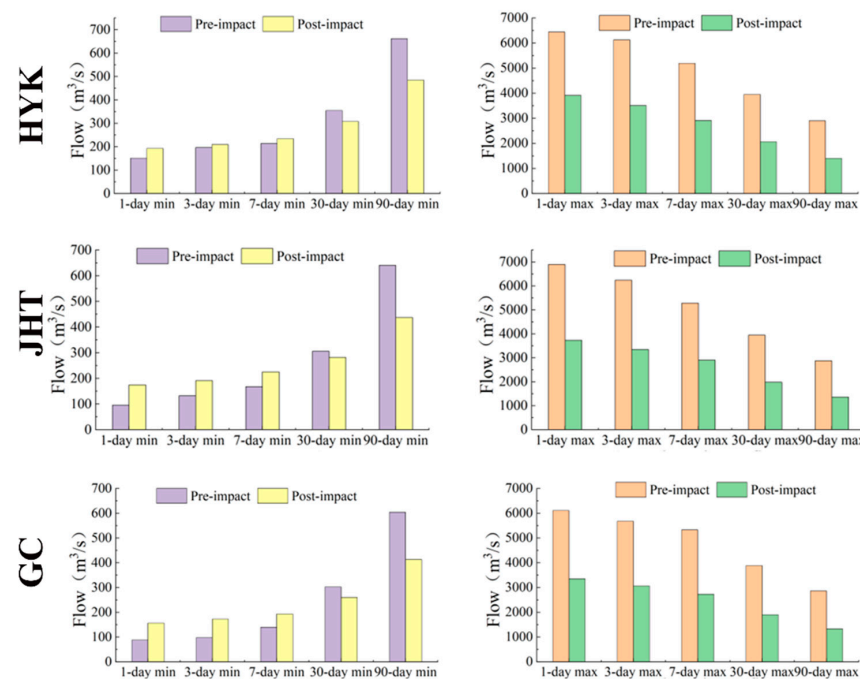


Figure 9. Annual extreme flow changes.

3.6.2. Characteristics of the Evolution of Other Hydrological Indicators

In terms of the occurrence timing of extreme flows, the timing of annual minimum flows has generally been delayed, with the longest delay observed at GC, reaching 26.5 days. This suggests that the water retention time within the basin increased before reaching the minimum flow, potentially due to factors such as climate change, water resource management, or land use changes. Conversely, the timing of annual maximum flows generally advanced, with the most significant advancement at JHT, by 43 days. This indicates that high-flow events within the basin may be becoming more frequent and sudden, necessitating enhanced flood warning and prevention measures. The degree of change in the occurrence timing of extreme flows is relatively low, indicating a limited impact of the disturbance on the timing of annual extreme flows, yet its potential implications still merit attention.

Regarding the high/low-flow pulse indicators, the frequency of high-flow pulses has generally decreased, with the most significant reduction observed at GC, reaching a change rate of 85%. This may be attributed to factors such as water resource management, soil and water conservation measures, or climate change within the basin. The duration of high-flow pulses has increased, albeit with a moderate degree of change. This implies that while the duration of high-flow events has somewhat extended, the overall variation is not drastic. In contrast, the variation in the frequency of low-flow pulses is relatively low, but the pulse duration has shortened significantly, averaging a reduction of approximately 3 days. This likely reflects an increase in the fluctuation and instability of water resource distribution within the basin, which may adversely impact the ecological environment and agricultural production.

In terms of flow variation rate and frequency indicators, all three hydrological stations exhibit high degrees of change in both flow variation rate and frequency. Specifically, the flow increase rate at HYK decreased from $7 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{d}^{-1}$ to $4 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{d}^{-1}$, while the flow decrease rates at JHT and GC are also significant, reaching a change rate of 100%. This indicates that flow variations within the basin have become more intense and unstable, potentially increasing the risks of flooding and water resource shortages.

4. Discussion

4.1. Analysis of HYK Driving Mechanism Based on Sensitivity Analysis

Due to challenges in data collection, we opted to employ the Budyko hydrothermal coupling model to quantify the driving mechanisms in the HYK watershed. This model, based on the coupled relationship between hydrological cycles and energy balances on Earth, posits a balance between long-term average evapotranspiration and precipitation, as well as underlying surface parameters, within a given watershed or region. The Budyko curve, a prevalent representation of this relationship, sheds light on the crucial mechanisms underlying hydrological cycles within watersheds. Drawing inspiration from the research conducted by He et al. [35] and Zhou et al. [36], we applied this model to explore evapotranspiration estimation methods in the HYK watershed and assess the contributions of climate and underlying surface conditions to streamflow. Through model analysis, we can quantify the impacts of various factors on streamflow, furthering our understanding of the response mechanisms of watershed hydrological cycles. Additionally, we will utilize the Budyko model to validate previous calculations based on the cumulative volume slope method (or other approaches), aiming to assess the consistency and accuracy of both methods, thereby providing scientific justification for water resource management and decision making.

A sensitivity analysis was conducted to attribute the causes of the reduction in annual runoff depth at HYK. Compared to the natural period, the annual runoff depth decreased by 27.53 mm during the period of change. The contribution rates of precipitation, potential evapotranspiration, and underlying surface changes to runoff were 28.63%, -5.1% , and -8.76% , respectively. The primary factor contributing to the reduction in annual runoff depth at HYK is human activities, accounting for 66.27% of the total. Among these, changes in the underlying surface hurt the reduction in annual runoff depth, contributing 8.76%.

Climate change contributes 33.73% to the reduction in annual runoff depth, with a positive overall effect. Specifically, precipitation contributes 28.63% to the reduction, while potential evapotranspiration has a negative effect, contributing 5.1%. The attribution analysis of annual runoff depth using the sensitivity analysis method aligns with the results obtained from the cumulative volume slope method, confirming that human activities are the primary driver of the reduction in annual runoff depth at HYK. Both human activities and climate change contribute positively to the overall reduction in annual runoff depth. This conclusion is consistent with [17,37,38].

4.2. Periodic Resonance Law along the Way

Utilizing cross wavelet and coherence wavelet analysis, we explored the relationship of response characteristics among HYK, JHT, and GC (Figure 10). Our findings reveal that from 1951 to 1970, there exist significant resonant periodic variations between HYK and JHT at scales of 2–5 years and approximately 8 years around 1980. This indicates a similar periodic pattern in runoff variations for these two regions at these timescales. Concurrently, notable resonant periodic variations at a 2–5-year scale were also observed between JHT and GC. Specifically, the runoff variation in HYK lags behind JHT by approximately 1.5 cycles, while the runoff variation in JHT lags GC by approximately 1.5 cycles. This signifies a temporal transmission or lag effect in runoff variations along upstream and downstream river segments.

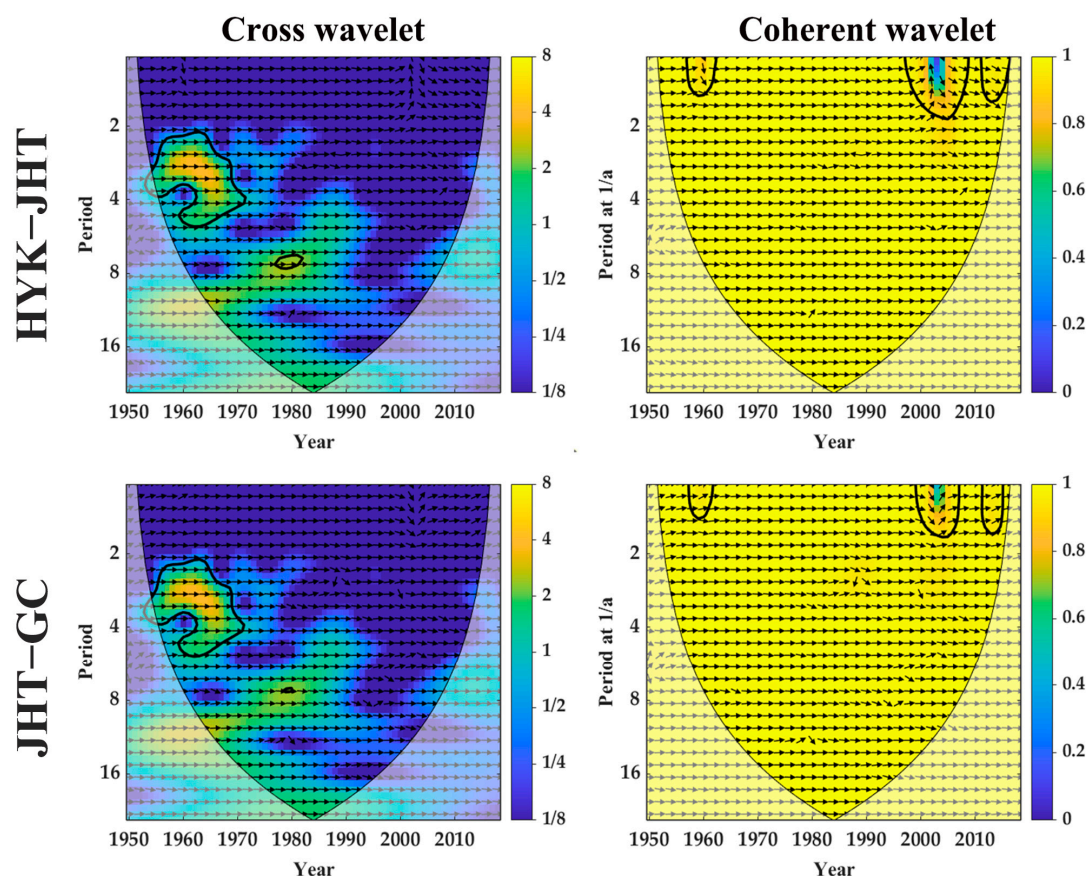


Figure 10. Resonance period characteristics.

Furthermore, the coherence wavelet analysis reveals that HYK–JHT and JHT–GC exhibit significant positive correlations across most timescales, indicating synchronized runoff variations between them. However, around the year 2000, both combinations exhibited a negative correlation at the one-year scale. This anomaly may be attributed to the completion of the Xiaolangdi Multipurpose Dam Project in 2001 and the implementation

of unified water resources management in the Yellow River since 2000. Dam construction can significantly alter the natural flow patterns of rivers, such as changes in water levels, discharges, and flow velocities, thereby influencing runoff variations upstream and downstream. Additionally, water conservancy projects may have profound impacts on river ecosystems through water allocation regulation and riverbed morphology alterations. Studies have shown that the Xiaolangdi Reservoir has a significant impact on the hydrological regime of the Yellow River Basin; for example, the Xiaolangdi Reservoir leads to about a 75–72% annual reduction, 81–86% reduction in flood season, and 86–90% reduction in non-flood season [39]. Before and after the operation of Xiaolangdi Reservoir, the coefficients of variation of runoff were 0.28–1 and 0.38–0.83, respectively. The distribution of runoff was more uniform, and the percentage of runoff in flood season decreased from 51.51% to 39.89% [40].

4.3. Characteristics of Land Use Transformation in the Yellow River Basin

The influence of human activities on runoff is mainly reflected by underground changes [41]. An analysis of historical land use data in the Yellow River Basin between 1980 and 2020 (Figure 11) reveals a significant expansion trend in cultivated land area, with an increasing annual agricultural land footprint, predominantly in the central plains and hilly regions. This expansion is primarily attributed to the growing rural population and subsequent surge in demand for agricultural land. In contrast, the eastern coastal regions, particularly the mountainous and island areas in the south, once boasted lush forests. However, due to recent deforestation and human activities, the forest area in the Yellow River Basin has gradually declined, resulting in a lack of effective soil and water conservation and ecological protection during flooding events.

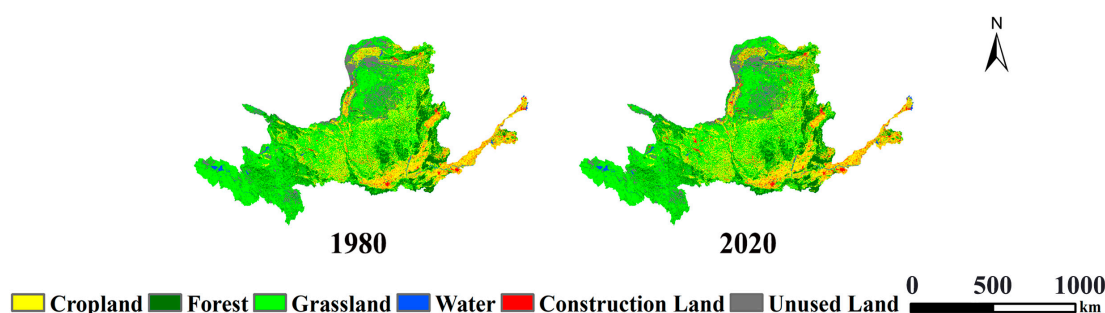


Figure 11. Land use spatial distribution map of the Yellow River Basin in 1980 and 2020.

Concurrently, with rapid population and economic growth, waterfront cities and industrial areas have rapidly expanded along the Yellow River's banks. Among all land use categories, construction land has witnessed the fastest growth, primarily concentrated in eastern coastal cities such as Beijing, Tianjin, Zhengzhou, Nanjing, Wuhan, and Shanghai. Over the past 40 years, a total of 750,000 km² of land in the Yellow River Basin has undergone land use conversion, with land primarily transitioning from cultivated land, grassland, and construction land. The primary incoming land use categories are cultivated land, grassland, and construction land, accounting for 16.42%, 28.09%, and 31.50% of the total converted area, respectively.

Specifically, 57.8% of the converted forest area originated from grassland and 36.6% from cultivated land, primarily due to the implementation of the Grain for Green Program in the Yellow River Basin, which gradually created vast areas of reforestation and grassland restoration. Additionally, 69.6% of the converted construction land area came from cultivated land, primarily driven by a series of land use policies introduced by the government since 2000. Among the outgoing cultivated land area, forestland, grassland, and construction land accounted for 12.49%, 50.99%, and 30.17%, respectively, reflecting the encroachment of cultivated land by forest restoration and urban development. The largest area of grassland converted to cultivated land was 13.544 million km², primarily

due to the enhanced efforts in ecological protection and restoration. The increase in human activities and constructed land is also a significant contributor to the changes in basic surface parameters [42].

5. Conclusions

1. The runoff at the three hydrological stations in the lower Yellow River Basin—Huayuankou (HYK), Jiahetan (JHT), and Gaocun (GC)—all exhibit significant downward trends on an annual scale. The year of abrupt change for all three stations is 1985, which is further validated by the results of the cumulative departure method and the Mann–Kendall test.
2. Before and after the abrupt change, the mean annual runoff decreased significantly, and after the year of abrupt change, the rate of decline slowed down and began to increase gradually. The runoff in June showed an upward trend at all three stations, while October was the month with the most significant decline in runoff, indicating the fastest rate of runoff decrease in autumn.
3. The runoff series at the HYK, JHT, and GC stations all exhibit similar periodic fluctuations, with major cycles of 5 and 7 years. During the pre-abruption period, there was a clear 5-year primary cycle for runoff at all three stations. However, there were no significant periodic patterns observed during the post-abruption period.
4. The hydrological situation in the lower Yellow River Basin experiences a high degree of change, and the degree of flow alteration tends to decrease gradually as the downstream distance increases.
5. During period A, the variation in runoff was primarily driven by climatic factors. In period B, however, the change in runoff was primarily influenced by human activities, which increased progressively along the river basin.

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