The variation and attribution analysis of the runoff and sediment in the lower reach of the Yellow River during the past 60 years
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ABSTRACT

The water and sediment regimes of the Yellow River are the basis of decision-making of major projects of the Yellow River. Based on the water and sediment data at the Huayuankou station, Gaocun station, Aishan station, Lijin station in the lower reach of the Yellow River, the Mann-Kendall test, the T-test for differences, wavelet analysis, slope change ratio method and the double cumulative curve method were applied to analyze the runoff and sediment regimes alteration. The results show that the water and sediment of the lower Yellow River have a significant downward trend, and the annual sediment decreases significantly compared with the annual runoff. The annual runoff and sediment of the four hydrological stations changed around the 1980 and 1990s, respectively. The water and sediment of hydrological stations have periodic variations on multiple time scales, but the variation scales are different. Precipitation, human activities and other factors lead to the decrease trend of water and sediment in the lower Yellow River, and their contribution rates to the change of water and sediment are also different. Precipitation contributed 0.15%–8.71% and 0.06%–22.32% to the reduction of runoff and sediment load at hydrological stations, while human activities contributed 91.29%–99.85% and 77.68%–102.21% to the reduction of runoff and sediment load, respectively. Human activity is the main factor of runoff and sediment reduction.

Key words | human activities, runoff, sediment load, the Yellow River

HIGHLIGHTS

- To statistically detect the trend, change-points and periodic relationship of the annual runoff and sediment discharge of the four main hydrological stations in the lower Yellow River.
- To analyze of the contribution of climate change and human activities to runoff and sediment in the lower Reaches of the Yellow River basin.

INTRODUCTION

Rivers are the indispensable and important resource for human survival and development. For most rivers, the impacts of climate change and human activities on water and sediment processes are particularly significant. The change of land use, large-scale drainage and overgrazing have reduced the water holding capacity of the basin, resulting in an increase in the frequency and scale of downstream floods in the wet season, and a serious decrease in river water volume in the dry season (Leopold 1968). The construction and storage of reservoirs obviously changes the hydrological process of rivers, which is the human activity that has the largest impact
on rivers and the most far-reaching disturbance from rivers (Petts 1984).

The Yellow River is the second longest river in China. The complex and intractable crux of the Yellow River lies in the nature of less water and more sand and the inharmonious relationship between water and sand (Wang 2015). With the superposition of natural factors and human activities, the amount of water and sediment in the basin shows an obvious trend of fluctuation, and the historical water and sediment conditions in the lower reaches of the Yellow River are completely different from those in modern times. In the new period, the relationship between water and sediment in the Yellow River has changed, and the sediment inflow in the lower reaches of the Yellow River has decreased sharply (Hu & Zhang 2018). The serious shrinkage of the lower reaches of the Yellow River, the reduction of flood discharge and sediment load capacity, etc., seriously threatens the flood control safety of the basin and seriously restricts the sustainable development of regional economy and society.

The evolution of water and sediment in the Yellow River basin has always been a concern of human beings, and it is also a focus and difficult problem in the Yellow River management. At present, there have been a large number of studies on the changes of water and sediment in the Yellow River, most of which focus on the changes of main sections, branch flows and sediment as well as the middle and upper reaches of the basin, and the characteristics of the water and sediment process are not comprehensive enough (Ouyang et al. 2016; Zhang et al. 2018) and there are relatively few quantitative analyses on the changes of water and sediment along the main stream of the Yellow River and its influencing factors. Then, under the influence of various coupling factors, what will be the characteristics of the water and sediment change of the Yellow River in the last 60 years? How much did each factor contribute to the change?

Therefore, the purpose of this study is (a) to statistically detect the trend, change-points and periodic relationship of the annual runoff and sediment discharge of the four main hydrological stations in the lower Yellow River; (b) to analyze of the contribution of climate change and human activities to runoff and sediment in the lower Reaches of the Yellow River basin; The study will provide scientific guidance for the management of the Yellow River basin.

**STUDY AREA AND DATA**

The Yellow River is known as the cradle of Chinese civilization and is a world-famous river with high sand content. The Yellow River Basin is located between 95°53′ to 119°05′E longitude and 32°10′ to 41°50′N latitude. It has a continental climate with a multi-year average annual precipitation of 446 mm. The basin covers an area of 752,443 km², showing a trend of ‘high in the west and low in the east’, descending gradually from west to east. The western section of the Yellow River is located on the Qinghai-Tibet Plateau with an altitude of more than 4,000 m. The middle section is dominated by the Loess Plateau, with an altitude of 1,000 to 2,000 m. The eastern section is located in the North China Great Plain, with the main landforms being plains. The total area of the Yellow River Basin is 795,000 square kilometers, the main stream is 5,464 kilometers in length, and the water drop is 4,480 meters. The main stream has a variable curvature and uneven distribution of tributaries. There are 76 first-level tributaries with a drainage area greater than 1,000 km², among which 13 are the first-level tributaries with a drainage area greater than 10,000 km² or with a sediment inflow of more than 50 million tons. According to the characteristics of the river, with Hekou Town and Taohuayu as the dividing point, the Yellow River is divided into three parts: the upper, middle and lower reaches. The section from Mengjin to Gaocun on the lower Yellow River is a typical wandering section. The section has the characteristics of wide and shallow water flow, unsteady mainstream swing, and drastic changes in river regime. During the operation of the Sanmenxia Reservoir for water storage and sediment interception, the amount of sand entering the downstream river channel was greatly reduced, resulting in strong erosion in the lower Yellow River. During this period, the lower reaches of the Yellow River scoured a total of 2.14 billion m³ of sediment, of which the total scouring of the upper reaches of Gaocun (1.52 billion m³) accounted for 71% of the total erosion of the lower channel. After the operation of the Xiaolangdi Reservoir, the amount of sediment entering the lower reaches of the Yellow River has been greatly reduced, and the riverbed in the lower reaches of the river has been scoured severely.
In order to analyze the temporal changes of runoff and sediment conditions, four major hydrological stations in the lower reaches of the Yellow River, Huayuankou station, Gaocun station, Aishan station, Lijin station, were selected as the case study locations (Figure 1). Hydrological data (annual runoff and sediment load) from the Yellow River Yearbook and China River Sediment Bulletin, as well as annual rainfall series from China Meteorological Data Network (1960–2016) were used in this study. Three missing rainfall data were supplemented by linear interpolation method.

The Huayuankou Hydrological Station, which is the starting point of the suspension of the Yellow River, is about 4,700 km from the source of the Yellow River and 770 km from the mouth of the Yellow River. Its catchment area accounts for 97% of the total area of the Yellow River Basin. As an important flood reporting station for major rivers in China, the Gaocun Hydrological Station is also the first important control station for the Yellow River to enter Shandong. Its cross-section is a compound riverbed with banks and troughs, about 579.1 kilometers away from the mouth of the river. Aishan Hydrological Station is used to monitor and forecast downstream floods. It is located in a narrow river with a section of 384 kilometers away from the mouth of the river, and its control basin area is 749,000 square kilometers. As the last hydrological station of the Yellow River, Lijin Hydrological Station provides important hydrological data in the lower reaches of the Yellow River.

Note: HYK: Huayuankou station, GC: Gaocun station, AS: aishan station, LJ: Lijin station; LYP: Longyangxia Water Conservancy Project, LJX: Liujiaxia Water Conservancy Project, SMX: Sanmenxia Water Conservancy Project, XLD: Xiaolangdi Water Conservancy Project.

**METHODOLOGY**

The Mann-Kendall non-parametric test method (Wang et al. 2014; Liu & Wang 2015) is used to statistically test the long-term change trend of hydrological elements, and quantitatively determine the possible mutation points of the hydrological time series. At the same time, the T-test for differences method (Liu et al. 2007) is used to carry out the possible mutation points test. The wavelet analysis method (Wang et al. 2009) reveals the multiple change cycles of the water
and sediment time series under different time scales. The slope change ratio method (Wang et al. 2012, 2015) was used to quantify the contribution rate of natural factors and human activities to the evolution of water and sediment quantity, and the double cumulation curve method (Mu et al. 2010; Qin et al. 2018; Guo et al. 2019) was used to analyze the stage change characteristics of water and sediment sequence.

**Mann-Kendall test**

**Mann-Kendall trend test**

The Mann-Kendall test is the rank-based nonparametric test used in hydrological trend detection studies. The Mann-Kendall test statistic \( S \) is calculated as follows:

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)
\]

(1)

where \( x_i \) and \( x_j \) are the date values of \( x \) in years \( i \) and \( j \), and \( n \) indicates the length of the date values. When \( n > 40 \), the statistic \( S \) is approximately normally distributed with the mean, and the variance is given by the following:

\[
\text{Var}(S) = \frac{n(n-1)(2n + 5)}{18}
\]

(3)

Based on \( S \) and \( \text{Var} \), the standardized Mann-Kendall statistics \( Z \) is computed as follows:

\[
Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{Var}(S)}}, & S > 0 \\
0, & S = 0 \\
\frac{S + 1}{\sqrt{\text{Var}(S)}}, & S < 0 
\end{cases}
\]

(4)

The standardized Mann-Kendall statistic \( Z \) follows the standard normal distribution with a mean of zero and variance of one. In the test for a trend, if \(|Z| > Z_{\alpha/2}\), where \( Z \) is asymptotically normally distributed and \( Z_{\alpha/2} \) is the critical value of the standard normal distribution with a probability \( \alpha/2 \), the trend of the sequence will be significant. A positive value of \( Z \) denotes an increasing trend, and the opposite corresponds to a decreasing trend.

The ability of M-K test to detect trends can be influenced by autocorrelation in the data. Given this, the ‘trend-free prewhitening’ (TRPW) technique was applied before the M-K test to avoid this issue in this paper. More details of calculation procedures about the TRPW technique can be obtained from Yue et al. (2002) and Shahid et al. (2020). If the statistical value is small enough, it can be directly tested by the traditional Mann-Kendall trend test method without preprocessing.

**Mann-Kendall abrupt change test**

The Mann-Kendall test was also applied to determine the abrupt changing year for time series. The statistic \( S_k \) of the abrupt change test was given by:

\[
S_k = \sum_{i=1}^{k} r_i
\]

(5)

\[
r_i = \begin{cases} 
1, & (x_i - x_j) \\
0, & (x_i - x_j) \\
-1, & (x_i - x_j)
\end{cases}, \quad j = 1, 2, \ldots, i
\]

(6)

Calculate the parameter UF using the following expression

\[
E(S_k) = \frac{K(K - 1)}{4}
\]

(7)

\[
\text{Var}(S_k) = \frac{k(k - 1)(2k + 5)}{72}
\]

(8)

\[
UF = \frac{s_k - E(S_k)}{\sqrt{\text{Var}(S_k)}}
\]

(9)

The Mann-Kendall mutation test calculates the normalized variable UF of time series data and compares it with a critical variable at a certain confidence level \( \alpha \) (taken as 0.01). When UF is greater than 0, it indicates an upward trend, and when it is less than 0, it indicates a downward trend; When UF exceeds a critical value, it indicates a significant upward or downward trend. At the same time, the same statistical calculation is performed on the inverse sequence of the original time series, so that UB = −UF. If the two curves
appear at the intersection point within the 99% confidence level, it indicates that the mutation occurred at this time point.

**T-test for differences**

Define the sequence mutation index of the sample length $N$ as $AI$, and use the method of continuously moving the base year to calculate the time series of mutation index $AI$. $Sp$ is the joint sample variance. The statistic $t$ follows the $t$ distribution with degrees of freedom $M_1 + M_2 - 2$. When a certain significant level $a$ is given, such as $t < t_a$, at the significant level of $a$, the mean values of $M_1$ and $M_2$ on both sides of the reference total there are obvious differences, that is, a sudden change occurs at the reference point. The calculation formula is given by:

$$AI = \frac{(X_{1p} - X_{2p})}{(s_1 + s_2)}$$  \hspace{1cm} (10)

$$t = \frac{(X_{1p} - X_{2p})}{[Sp(1/M_1 + 1/M_2)^{1/2}]}$$  \hspace{1cm} (11)

$$Sp^2 = \frac{[(M_1 - 1)s_1^2 + (M_2 - 1)s_2^2]}{(M_1 + M_2 - 2)}$$  \hspace{1cm} (12)

Among them: $X_{1p}$ are the average and standard deviation of $M_1$ years before the baseline; $X_{2p}$ and $S_2$ are the mean and standard deviation of the $M_2$ years after the baseline. $M_1$ and $M_2$ are the sample lengths of the two sequences before and after the benchmark.

**Wavelet analysis**

The complex Morlet wavelet was used to analyze the periodicity and variation tendency in runoff and sediment load at the four stations. The continuous wavelet transform (CWT) is defined as the sum over time of the real signal, $f(t)$, multiplied by the scaled (stretched or compressed) shifted versions of the wavelet function, $\psi(t)$ as follows:

$$\psi_{a,b}(t) = |a|^{-1/2} \psi\left(\frac{t-b}{a}\right)$$  \hspace{1cm} (13)

$$W_f(a,b) = |a|^{-1/2} \int_R f(t)\psi\left(\frac{t-b}{a}\right) dt$$  \hspace{1cm} (14)

where the wavelet coefficients, $W$, are the result of the CWT of signal $f(t)$. The function, $\psi(t)$, can be real or complex, playing the role of a convolution-kernel. The scale or dilation parameter, $a$, scales a function by compressing or stretching it, whereas $b$ is the translation of the wavelet function along the time axis.

In this study, the complex Morlet wavelet function is applied to distinguish temporal runoff and sediment load oscillations. Using the wavelet transform, wavelet coefficients and their variances are calculated. Wavelet power spectra and multiscale periodicity features are obtained with wavelet coefficients.

**Slope change ratio**

The change rate of cumulative slope is used to quantitatively assess the contribution of human activities and climate change to river runoff and sediment. The sum of all the influencing factors of the variable was defined as 1, and the influence degree on the variable was calculated according to the ratio of the cumulative slope of various influencing factors over time to the change rate of the cumulative slope of the variable. Assuming that the cumulative runoff changes over time and there is an inflection point in a given year, the slopes of the variables before and after the inflection point are $Y_{Rp}$ and $Y_{Ra}$ respectively, and the slopes of the cumulative precipitation before and after the inflection point are $Y_{Pp}$ and $Y_{Pa}$ respectively. The formula of $K_p$, $K_R$, $C_R$, $C_H$ are given as:

$$K_R = \frac{(Y_{Rp} - Y_{Ra})}{Y_{Rp}} \times 100$$  \hspace{1cm} (15)

$$K_p = \frac{(Y_{Pp} - Y_{Pa})}{Y_{Pp}} \times 100$$  \hspace{1cm} (16)

$$C_p = \frac{K_p}{K_R} \times 100$$  \hspace{1cm} (17)

$$C_H = 1 - C_p$$  \hspace{1cm} (18)

$K_p$, $K_R$, $C_R$, $C_H$ stand for Change rate of cumulative runoff slope, Cumulative precipitation slope change rate, the contribution of climate change, the contribution rate of human activity.
Double cumulative curve

The double cumulative curve is a commonly used method, which tests the consistency of the relationship between two parameters and their changes. The double cumulative curve is the continuous cumulative value of one variable and the continuous cumulative value of another variable during the same period plotted by a relationship line in a rectangular coordinate system. If the curve has a significant turn at a certain point, that is, the abrupt change in the slope of the curve has changed (Mu et al. 2010). In this study, double cumulative curves of runoff vs sediment are plotted to estimate the relative effects of human activities.

RESULTS AND DISCUSSION

Analysis of variation characteristics

Trend analysis of the runoff and sediment

The annual runoff and sediment load of each hydrological station is shown in Figure 2. During this period, generally speaking, the annual runoff and sediment load show a downward trend.

In Table 1, the mean Mann-Kendall values of annual runoff at the HYK, GC, AS and LJ station were −3.99, −4.17, −4.71, −5.44, respectively, which absolute value greater than 1.96, there were obvious downward trend at the four stations (p < 0.01); the mean Mann-Kendall values of sediment load at the HYK, GC, AS and LJ station were −6.51, −7.03, −6.68, −6.47, respectively, which absolute value greater than 1.96, there were obvious downward trend at the four stations (p < 0.01).

Abrupt changes analysis of the runoff and sediment

The Mann-Kendall test was used to analyze the abrupt change of annual runoff and sediment load of the four hydrological stations in the lower Yellow River. The statistical results of Mann-Kendall were shown in Figure 3. In the past 60 years, the changes of multi-year runoff and sediment load at the four hydrological stations are divided into two stages, that is, the trend of first increasing and then decreasing. The annual runoff and sediment load of the four hydrological stations all had obvious mutation, but the occurrence time was different, and the mutation year was shown in Table 2. The abrupt transition points of the annual runoff series of HYK, GC and AS hydrological stations all passed the confidence test of 0.05, while the abrupt transition points of the annual runoff series of LJ

![Figure 2](image-url)
Hydrological Stations all passed the confidence test of 0.01. The abrupt transition points of the annual sediment load sequence of HYK, AS and LJ hydrological stations all passed the 0.01 confidence test. The intersection point of the detection curve of the annual sediment load sequence of GC Station is outside the critical limit of 99% of the confidence level, which indicates that the annual sediment load sequence of GC Station has no high reliability of abrupt change in 1996. The annual runoff sequence of each station changed in the early and mid-1980s, which was mainly related to the implementation of a series of soil and water conservation measures in the middle reaches of the Yellow River. The sequence of annual sediment load occurred abrupt change in the middle and late 1990s. Since the 1990s, water conservancy facilities in the Yellow River basin have been built and put into use one after another, resulting in a significant decrease in the sediment load of the Yellow River compared with the previous period, resulting in abrupt change in sediment load. The impoundment of the reservoir has held back a lot of sediment and reduced the sediment load quantity of the Yellow River. After entering the 20th century, with the increase of human activities, the capacity of sediment load further decreased.

The Mann-Kendall non-parametric test may have multiple mutation points or low mutation credibility in the test process, so the T-test of mean difference was used to verify the mutation results. In this paper, the critical value is $t = 2.704$ and the significance level 0.01, and the statistical

**Figure 3** Mann-Kendall Statistics for the annual runoff (left) and sediment load (right) at each station. (continued.)
results are shown in Table 3. The abrupt transition points of annual runoff of AS station are 1980, 1981 and 1985, among which the fluctuation range of 1980 and 1981 is relatively small and the time series from 1980 to 1985 is short, so the abrupt transition points of annual runoff of AS Station are all attributed to 1985.

### Periodicities in the runoff and sediment load

The Morlet wavelet analysis of annual runoff and sediment load at four hydrological stations in the lower Yellow River was used to draw the real part isolines of the wavelet coefficients (Figure 4) and the variance (Figure 5), which represented the periodic changes of the sequence at different time scales and their distribution in the time domain. The positive and negative values of the real part of the small wave coefficients in the contour map reflect the
water and sediment in the Yellow River Basin (Ma et al. 2014; Shi et al. 2014; Yan et al. 2015; Gao et al. 2020). The rainfall-sediment correlation model is a commonly used method to analyze the causes of sediment change in rivers. According to the occurrence time of the abrupt point, the time series was divided into stages and the results were shown in Table 5. According to the characteristics of hydrological abrupt transitions, the relationship curves of rainfall and runoff, rainfall and sediment load accumulation before and after abrupt transitions of the four stations were drawn as shown in Figure 6. The determination coefficient $R$ of the fitting relation in each stage is above 0.95, and the fitting degree is good.

### Natural factors

The contribution rate of precipitation and human activities to the variation of water and sediment volume of the four hydrological stations is calculated quantitatively by the cumulative slope change rate method. See Tables 6 and 7. The influence of rainfall on the yield of water and sediment mainly lies in the size and amount of rainfall in the region. When the rainfall is too much, it will even lead to the damage of water conservancy and water conservation projects with low standards and cause the change of water and sediment quantity. In recent years, the magnitude and frequency of heavy rain and heavy rain have decreased. According to statistics, since the 1980s, the average number of heavy rain days and heavy rain days in the middle and upper reaches of the Yellow River have decreased, and the number of heavy rain days and heavy rain days has decreased more, which directly affects the sediment inflow into the Yellow River (Shi & Zhang 2013; Zhai et al. 2020). The contribution of precipitation in the lower Yellow River basin to the reduction of water and sediment volume of the four hydrological stations is different. Compared with the period of $T_b$ and $T_a$, the contribution of precipitation to the reduction of runoff volume of the four hydrological stations is 3.89%, 5.52%, 8.71% and 0.15% respectively, and the contribution of precipitation to the reduction of sediment volume is $-2.21\%$, $-0.06\%$, $22.32\%$ and $-0.04\%$ respectively. It can be concluded that the change of water and sediment quantity mainly depends on the influence of human activities.

| Station | Variable | Year | Base year | Mutation Index | Statistics |
|---------|----------|------|-----------|----------------|------------|
| HYK     | Runoff   | 1986 | 27        | 0.772          | 5.869      |
|         | Sediment | 2000 | 41        | 1.421          | 7.321      |
| GC      | Runoff   | 1986 | 27        | 0.801          | 6.049      |
|         | Sediment | 1996 | 37        | 1.318          | 7.745      |
| AS      | Runoff   | 1985 | 26        | 0.843          | 6.351      |
|         | Sediment | 1997 | 38        | 1.18           | 6.842      |
| LJ      | Runoff   | 1979 | 20        | 0.713          | 5.538      |
|         | Sediment | 1995 | 36        | 1.13           | 6.873      |

*Test significant level $\alpha = 0.01$, critical value $t_{\alpha} = 2.704$. 

### Analysis of influencing factors of water and sediment change

The change of runoff and sediment load relationship is affected by natural disasters, underlying surface conditions, climate change, human activities and other factors (Guo et al. 2020), among which climate change and human activities are the main driving factors leading to the change of...
Figure 4 | Contour maps of the real parts of wavelet coefficients for the annual runoff (left) and sediment load (right) at each station.
The variation of water and sediment quantity in the lower Yellow River basin is closely related to human activities. With the passage of time, human activities are increasing, and its contribution to the reduction of water and sediment quantity in the lower Yellow River basin is dominant. The response degree of each station to the contribution rate of human activities to the variation of water and sediment volume is different. Compared with the Td and Tc period, the contribution rate of human activities to the runoff reduction of the four hydrological stations is 96.11%, 94.48%, 91.29% and 99.85% respectively, and the contribution rate of human activities to the sediment load reduction is 102.21%, 100.06%, 77.68% and 100.04% respectively.

**Human activity factors**

When the slope of the double accumulation curve is inclined to the cumulative runoff axis or the cumulative sediment load axis, it can be expressed as the decrease or increase of hydrological variables respectively. The double accumulation curves of runoff and sediment load in HYK, GC, AS and LJ are shown in Figure 7. The double cumulative slope of the four hydrological stations all deviated towards the cumulative runoff, indicating that the cumulative sediment load tended to decrease. There were two turning points on the double accumulation curve of runoff and sediment load, so the accumulation curve was divided into three stages, and the linear fitting equation of sediment load and runoff accumulation was established. The results of stage sediment reduction and annual sediment reduction are shown in Table 8.

The variation of water and sediment quantity in the lower Yellow River basin is closely related to human activities. With the passage of time, human activities are increasing, and its contribution to the reduction of water and sediment quantity in the lower Yellow River basin is dominant. The response degree of each station to the contribution rate of human activities to the variation of water and sediment volume is different. Compared with the Td and Tc period, the contribution rate of human activities to the

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**Table 4** Multi-periodicities of the annual runoff and sediment load

| Stations | Annual runoff | Annual sediment load |
|----------|---------------|----------------------|
|          | Multiple time scale periodicity (a) | Dominant periodicity (a) | Multiple time scale periodicity (a) | Dominant periodicity (a) |
| HYK      | 11, 7, 4      | 11                   | 20, 8, 4                             | 20                   |
| GC       | 11, 7, 4      | 11                   | 21, 12, 4                            | 21                   |
| AS       | 11, 7, 4      | 11                   | 22, 13, 5                            | 22                   |
| LJ       | 11, 7, 4      | 11                   | 23, 13, 5                            | 23                   |

**Table 5** Runoff and sediment stage division at each station

| Station | Runoff | Sediment load |
|---------|--------|---------------|
|         | The First period (T_a) | The Second period (T_b) | The first period (T_c) | The second period (T_d) |
| HYK     | 1960–1986 | 1987–2019 | 1960–2000 | 2001–2019 |
| GC      | 1960–1986 | 1987–2019 | 1960–1996 | 1997–2019 |
| AS      | 1960–1985 | 1986–2019 | 1960–1997 | 1998–2019 |
| LJ      | 1960–1979 | 1980–2019 | 1960–1995 | 1996–2019 |

Figure 5 | Wavelet variance graphs for runoff (left) and sediment load (right) at each station.
respectively every year, which is closely related to the large-scale water conservancy and water conservation project implemented since the end of 1970s and the project of returning farmland to forest and grassland in the late 1990s.

The implementation of soil and water conservation activities, the construction of water conservancy projects, and the continuous expansion of irrigation area from Yellow River are the main human factors affecting the variation of water and sediment in the lower Reaches of the Yellow River, which not only change the hydrological cycle process and the temporal and spatial distribution law, but also have a significant impact on the runoff and sediment yield conditions of the Yellow River.

Soil and water conservation is one of the main influencing factors. The loess Plateau began soil erosion control in the 1950s. Researchers have carried out a variety of rapid dam-building technology exploration, such as water pouring in water, water pouring in soil and directional blasting. In 1957, the application of hydraulic filling damming technology promoted the construction of warping dam to a great extent and accelerated the progress of comprehensive treatment of small watershed. Since 1960, soil and water conservation on the Loess Plateau has been transformed into comprehensive control and comprehensive planning, instead of the former state of disordered control. At the end of 1970s, the key method to reduce sediment flow into the Yellow River was defined as strengthening...
the construction of dam and reservoir for water storage in the upper and middle reaches of the Yellow River. All above are the initial stage of implementing soil and water conservation measures, which cannot play a significant role. In the 1980s, warping dam became the ‘backbone project’ in the comprehensive management mode and the key measures of soil erosion control for small watershed in the middle reaches of the Yellow River (Zuo et al. 2010). From 1980 to 1985, soil and water conservation measures played an important role in the period, and it was a stage of comprehensive treatment with small watershed as a unit. Therefore, the annual runoff of the lower Yellow River has a sudden change.

### Table 6: Contribution rates of precipitation and human activities to runoff in different periods

| Time | Station | Runoff ($Y_a$) | Precipitation ($Y_p$) | Precipitation ($C_p$) | Human activity ($C_h$) |
|------|---------|----------------|-----------------------|-----------------------|-----------------------|
| $T_a$ | HYK     | 434.97         | 648.37                | –                     | –                     |
| $T_b$ | AS      | 226.38         | 636.59                | 5.52%                 | 94.48%                |
| $T_a$ | GC      | 416.2          | 653.02                | –                     | –                     |
| $T_b$ | AS      | 407.97         | 564.99                | –                     | –                     |
| $T_a$ | AS      | 203.61         | 540.35                | 8.71%                 | 91.29%                |
| $T_b$ | AS      | 416.21         | 617.97                | –                     | –                     |
| $T_a$ | AS      | 164.2          | 560.32                | 0.15%                 | 99.85%                |

Figure 6 | Continued.
The construction of water conservancy projects is another important reason for water and sand changes (Li 2008). Since 1960, a series of water control projects have been built in the upper main stream of the Yellow River, such as Qingtongxia, Liujixia and Longyangxia water control projects. Since 1986, the combined action of Longyangxia and Liujiang reservoir has blocked most of the sediment above Lanzhou Station, and the water volume of the upper reaches of the Yellow River in flood season is 54% less than that of the Liujiang reservoir. Therefore, this is also the reason for the abrupt change of annual runoff in the lower Yellow River. After the completion of

| Time | Station | Sediment load (YR) | Precipitation (YP) | Precipitation (CP) | Human activity (CH) |
|------|---------|--------------------|-------------------|-------------------|-------------------|
| Tc   | HYK     | 9.8677             | 633.8             | –                 | –                 |
| Td   |         | 0.922              | 646.47            | –2.21%            | 102.21%           |
| Tc   | GC      | 9.2571             | 629.4             | –                 | –                 |
| Td   |         | 1.4061             | 659.73            | –0.06             | 100.06%           |
| Tc   | AS      | 8.7686             | 537.4             | –                 | –                 |
| Td   |         | 1.483              | 569.05            | 22.32%            | 77.68%            |
| Tc   | LJ      | 8.2977             | 552.87            | –                 | –                 |
| Td   |         | 1.3482             | 571.48            | –0.04%            | 100.04%           |

Figure 7 | Double cumulative curves of runoff and sediment load at each station.
Xiaolangdi Water Control Project in 1999, the control of downstream water and sand was further strengthened. In December 1996, the lower sluice of Lijiaxia stored water. Under the joint action of the two, the sediment load volume of the lower Yellow River has hydrological variation.

The irrigation project along the Yellow River main stream is another main aspect that causes the change of water and sediment. Most of the irrigation works along the main stream of the Yellow River are carried water. It is mainly located in the lower Reaches of the Yellow River and the Ningxia-Inner Mongolia reaches, accounting for 52.4% and 44.5% of the total irrigation area respectively, among which the lower reaches of the Yellow River has many irrigated areas and a large irrigation area. Since the 1990s, industry and agriculture have developed rapidly, and the water drawn along the Yellow River is still mainly used for agriculture. The agricultural water of the lower Yellow River accounts for 90% of the total water supply of the lower Yellow River, and the water consumption is 115.619 billion m³ (Li 2008). Therefore, the irrigation project along the Yellow River is another main factor that causes the change of water and sediment.

Discussion

Sediment problem has always been an important problem in the control and development of the Yellow River. In the qualitative description of the causes of water and sediment in the Yellow River, researchers agree that climate conditions, changes in the environment of the Yellow River basin, the construction of water conservancy projects in the main and tributary streams, the excessive exploitation of resources and other factors together promote the change of water and sediment conditions in the Yellow River basin.

The contribution rate of climate change and human activities to runoff and sediment change is analyzed synthetically by hydrologic method in this paper. It should be pointed out that the contribution of climate factors to precipitation factors is mainly quantified. Climate change mainly includes precipitation and temperature in the basin, among which the change of precipitation directly affects the change of yield and discharge, while the change of temperature leads to the change of evapotranspiration, which will also lead to the change of yield and discharge. However, evapotranspiration has little influence on runoff and data acquisition is difficult. Therefore, this study does not consider the influence of air temperature on runoff and sediment in the basin, and climate change only considers the influence of precipitation change on water and sediment change.

The environment for aquatic and sediment production in the Yellow River Basin is extremely complex, and the impact mechanisms of natural factors such as human activities and rainfall on water and sediment changes are different. In this study, only the comprehensive effects of the two factors on water and sediment on a longer time scale were considered. There is no research on the internal relationship between the variation of rainstorm, extreme climate phenomenon, the influence of large-scale human activities on the tributary channel and the change of water and sediment. In addition, it is of greater guiding significance to explore the influence of human activities on the future changes of water and sediment in a short time.

CONCLUSION

Based on the hydrological data of four hydrological stations in the lower Reaches of the Yellow River, a variety of statistical methods were used to analyze the variation trend, abrupt year, period, influencing factors and their contribution rates to the variation of runoff and sediment volume. The major findings can be summarized as follows:

(1) With the passage of time, the annual variation of runoff and sediment discharge of the Yellow River from 1960 to 2019 showed an obvious decreasing trend, and the decreasing trend of annual sediment discharge was more obvious than that of annual runoff.

| Station | The second stage | The third stage | The annual average |
|---------|-----------------|----------------|-------------------|
| HYK     | 31.35           | 90.53          | 3.81              |
| GC      | 30.07           | 56.00          | 2.69              |
| AS      | 12.86           | 58.75          | 2.24              |
| LJ      | 1.16            | 24.36          | 0.672             |
(2) There were abrupt changes in runoff and sediment load at all hydrological stations, among which the abrupt changes in runoff occurred in the 1980s and in the 1990s.

(3) There are multi-time scale periodic changes in the water-sediment series of hydrological stations, and the cycle changes of runoff are the same, while the variation scales of sediment discharge are slightly different.

(4) Since the 1980s, the abrupt change of annual runoff and sediment is caused by the combined action of precipitation and human activities, and human activities are the main reason for the change of runoff and sediment in the lower reaches of the Yellow River.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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