Comprehensive analysis of water-sediment variation characteristics at the confluence of the upper reaches of the Weigan River and Heizi River with multiple methods and multiple influencing factors

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ABSTRACT

In-depth analysis of the characteristics of water and sedimentary changes at the confluence of the upper reaches of Weigan River and Heizi River is the prerequisite and basis for studying the future water and sedimentary situation in the Kizil Reservoir. This article analyzes the trend, mutation point and periodicity of the water and sedimentary sequence with multi-methods. The double cumulative curve method and the attenuation analysis method were used to analyze the impact of precipitation and human activities on runoff and sedimentary transport, and other influencing factors were qualitatively analyzed also. The results showed that: (1) In the past 60 years, Kizil Reservoir’s runoff and sedimentary transport have shown an upward trend; the mutation point of the reservoirs’ runoff was in 1994; the annual runoff had a periodicity of 7, 13, and 28 years; the annual sedimentary transport had a periodicity of 4, 12, and 26 years. (2) The impact of precipitation and human activities on runoff were 485.37% and 385.37%, respectively; the impact of precipitation on sedimentary transport was first high and then low, while the impact of human activities on sedimentary transport was first low and then high. Solar activities, ENSO, underlying surface changes and glacier snow melt also contributes to water-sediment changes to some extent.

Key words: attenuation analysis method, double cumulative curve method, human activities, mutation point, periodicity, precipitation, trend

HIGHLIGHTS

• Various analytical methods were used to analyze the changing trends and mutation points, and comprehensively determined the results.
• The ensemble empirical mode decomposition (EEMD) method was used to accurately analyze the periodicity of runoff and sedimentary transport.
• The quantitative and qualitative systematic analysis of the factors which affect water and sedimentary changes were carried out.

1. INTRODUCTION

Under the climate change and human activities, the overall water cycles of various basins are undergoing significant changes (Wang & Jia 2016; Xu et al. 2016). Water and sediment are the two most basic elements in river systems, and their distribution pattern within a year and inter-annually are the essentials for the water conservancy departments to grasp in order to understand the river characteristics. On one hand, the distribution of water and sediment within a year determines the operation and dispatching mode of water conservancy projects and the evolution process of river channels in the upstream and downstream (Xiong et al. 1992); on the other hand, the inter-annual variation of water and sediment reveals the evolution pattern of rivers under the influence of natural and human activities in the long term. Therefore, studying the characteristics of water and sedimentary changes has always had important scientific significance.

In recent years, many researchers have gradually deepened their research on water and sedimentary problems in river basins. For example, Yao et al. (2015) studied the changes in water and sediment in the Yellow River in a period of over a century and found that sediment mainly decreases in the middle reaches and runoff mainly decreases in the upstream. Yang (2020) studied the sediment runoff data at the Shali Station of the Dayang River and found that there

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was a significant downward trend in sedimentary transport, while the decline in runoff was not significant. Zhang et al. (2020) analyzed the characteristics of water and sedimentary changes in the main stream of the Huai River and found that even though the runoff in the basin has no significant fluctuation, the incoming sediment significantly decreased. Ye et al. (2017), based on the 50-year of runoff, sedimentary deposit and precipitation data of the Wuhua River, found that the impact of precipitation on runoff and sediment changes was 73% and 21%, respectively, and the impact of human activities on runoff and sediment changes was 27%, 79%, respectively. Guo et al. (2017) introduced the Archimede-Copulas, which overcome the low accuracy and subjective nature of the traditional double mass curve method, to investigate the precipitation–runoff-relationship and detect mutation points in the Weihai River basin. Yog & Jianting (2020) proposed a new method that combines the two-parameter Budyko equation and an improved double mass curve technique and adapted it to be isolated and removed the effect of climate change from the total changes in the seasonal hydrological drought. Abdollah et al. (2019) used the Mann-Kendall and cumulative rank difference test and the double mass curve method to study the time series of hydro-meteorological variables from 1971 to 2010 in the Tajan River basin in Iran. Lu et al. (2018) used a simple and effective sediment load reduction factor analysis method to analyze the sedimentary transport and attribute the changes in river sediment load to different driving factors. Based on changes in hydrological and meteorological conditions and the impact of direct human activities on runoff, Fu et al. (2020) analyzed their contribution on runoff reduction in different periods. Sun et al. (2019) applied an integrated method combining the non-parametric Mann-Kendall trend test and the double-mass curve to analyze runoff data from 1961 to 2010. Chikita et al. (2012) studied the intra-annual and inter-annual changes of water and sediment in the Yukon River basin, and found that the incoming water and sediment were concentrated in the snow melt season. Hu et al. (2010) analyzed the variation trend of total runoff and total sedimentary transport at representative stations of major rivers in China and found that natural conditions and human activities are the key factors affecting water and sedimentary changes. Zhao et al. (2015) analyzed the characteristics of water and sedimentary changes in the Huangfuchuan River basin and the results showed that human activities are the dominant factor contributing to the water and sedimentary changes. Shi et al. (2012) studied the temporal and spatial distribution characteristics of water and sediment in the Huaihe River basin, and the results showed that the construction of reservoirs in upstream mountainous rivers was the main reason for the decrease in incoming sediment. Jia (2017) analyzed the reasons for the reduction of water and sediment in the Yihe River basin and found that soil and water conservation measures were the main factors.

The characteristics of water and sedimentary change can reflect the changes in climate and human activity in the basin (Stover & Montgomery 2001). Therefore, the study the characteristics in water and sedimentary changes and their influencing factors has always been the focus of many scholars domestic and abroad. The purpose of this paper is to: (1) use long-term data from 1960 to 2017 to analyze the trend in the water and sedimentary sequence in the upper reaches of the Kizil Reservoir; (2) analyze the mutation points of the annual runoff sequence and classify the base period and the change period; (3) analyze the periodicity of water and sedimentary sequence, and perform corresponding analysis with solar activities and ENSO phenomena; (4) separate and quantify the contribution rate of precipitation and human activities to the changes in runoff; consider 10 years as a division scale to quantitatively analyze the contribution rate of precipitation and human activities to the change of sedimentary transport in different periods. The research results of this paper provide certain basic data for the optimal operation of reservoirs, water and sediment prediction and dredging work, and also provide certain research value.

2. STUDY AREA

The Kizil Reservoir is the largest controlling reservoir project in the upper reaches of the Weigan River Irrigation District, and it bears important responsibilities not only for downstream agricultural irrigation but also for domestic water use. The water and sediments entering the reservoir mainly comes from the Muzati River and the Heizi River tributary in the Kharktawu Mountains. The main stream of Muzati River was formed under the confluence of Kamuslang River, Telewaichuk River and Karasu River; the location of water systems in the basin is shown in Figure 1. The research data in this paper comes from various hydrological stations located on the main stream of Muzati River and its tributaries, Kamuslang River, Telewaichuk River, Karasu River, and Heizi River. And the measured runoff and sedimentary transport data of the Kizil Reservoir from 1960 to 2017 are selected as the basic data for water and sedimentary changes analysis.
3. RESEARCH METHODS

3.1. Trend analysis

3.1.1. Linear trend estimation method

The linear trend estimation method (Zhou & Guo 2018) is to set \( f(t) \) as a certain variable, \( t \) as time, and \( f(t) \) to establish a linear regression equation with \( t \):

\[
f(t) = C_0 + C_1 t.
\]

\( C_0, C_1 \) are the regression coefficients, and the sign of \( C_1 \) reflects the rising or falling trend, which is called the tendency rate. Using the relationship between the regression coefficient and the correlation coefficient, \( R \) can be obtained. If \( R \) passes the significance test, it indicates that the degree of trend change is significant.

3.1.2. Mann-Kendall rank correlation test

The Mann-Kendall method (Guo et al. 2020) is a rank correlation test on the rank and time series of the observation sequence. Assuming that \( H_0 \) is a time series \( x_1, x_2, \ldots x_n \) subject to \( n \) independent and uniformly distributed samples of random variables, then the calculation formula of the statistical variable \( S \) is:

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij}; \quad a_{ij} = \text{sgn}(x_j - x_i) = \text{sgn}(R_i - R_j) = \begin{cases} 1, & x_i < x_j \\ 0, & x_i = x_j \\ -1, & x_i > x_j \end{cases}
\]

where: \( R_i \) and \( R_j \) are the ranks of \( x_i \) and \( x_j \), respectively. When \( n \) is greater than 8, when the measured data obey the assumption of independence and distribution, the statistical variable \( S \) obeys the normal distribution and its mean and variance satisfy the following formula:

\[
E(S) = 0; \quad \text{Var}_0(S) = \frac{n(n-1)(2n-1)}{18}
\]

where: \( E(S) \) is the mean value; \( \text{Var}_0(S) \) is the variance.
The standard statistical variable Z can be calculated by the following formula:

\[
Z = \begin{cases} 
\frac{(S - 1)}{\sqrt{\text{Var}_0(S)}}, & S > 0 \\
0, & S = 0 \\
\frac{(S + 1)}{\sqrt{\text{Var}_0(S)}}, & S < 0
\end{cases}
\]

After the significance level \( \alpha \) is given, \( Z_{1-\alpha/2} \) is calculated. When \( |Z| < Z_{1-\alpha/2} \), accept the null hypothesis, that is, the upward or downward trend of annual runoff is not significant; otherwise, the trend is significant. When the statistical variable \( Z > 0 \), it indicates that the sequence has an upward trend; when \( Z < 0 \), it indicates that the sequence has a downward trend. In this study, after taking the significance level \( \alpha = 0.05 \), \( Z_{1-\alpha/2} = 1.96 \) was calculated and compared with the standard statistical variable \( Z \) of the time series of annual runoff and annual sediment transport in the upper reaches of the Kizil Reservoir to analyze the trend changes of water and sediment in the area.

3.1.3. R/S analysis

The R/S method (Liu 2012) is an analysis method that was first used by the British hydrologist Hurst to analyze the inflow and outflow between the reservoir and the river. It has few assumptions for the system under study, and it has a very wide range of applications for time series analysis.

For time series \( x_1, x_2, \ldots, x_n \) for any positive integer \( n \geq 1 \), the mean value of the sequence \( \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \); the cumulative deviation \( x(t, n) = \sum_{i=1}^{t} (x_i - \bar{x}), 1 \leq t \leq n \); the range is \( R(n) = \max(X(t, n)) - \min(X(t, n)) \); the standard deviation is \( S(n) = \left[ \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{1/2} \). The expression of Hurst exponent \( H \) is \( \frac{R(n)}{S(n)} = (cn)^H \), where \( C \) is a constant. Take the logarithm of both sides of the equation to get \( H \ln n + H \ln c = \ln[R(n)/S(n)] \).

For a certain time series, the \( H \) value represents its change characteristics. When \( H = 0.5 \), it indicates that the sequence is a random process; when \( 0 < H < 0.5 \), it means that the time series is anti-continuous; when \( 0.5 < H < 1 \), it means that the time series is continuous. When the \( \ln[R(n)/S(n)] \sim \ln n \) relationship diagram shows a non-linear relationship, it indicates that there are mutation points in the time series, and the turning points are the mutation points.

3.2. Mutation analysis

3.2.1. Ordered clustering method

The essence is to find the optimal segmentation point, seeking for the smaller sum of squared deviations between classes, and the larger sum of squared deviations between classes as possible interference points. For the sequence \( x_1, x_2, \ldots, x_n \), if the segmentation point is \( \tau \), the sum of squared deviations before and after the mutation can be expressed as:

\[
V_{\tau} = \sum_{i=1}^{\tau} (x_i - \bar{x}_\tau)^2 V_{n-\tau} = \sum_{i=1+\tau}^{n} (x_i - \bar{x}_{n-\tau})^2
\]

where, \( \bar{x}_\tau, \bar{x}_{n-\tau} \) are the mean values of the two parts before and after the dividing point \( \tau \), respectively.

The sum of squared deviations is: \( S_{\tau}(\tau) = V_{\tau} + V_{n-\tau} \)

When satisfies \( S = \min_{2 \leq \tau \leq n-1} (S_{\tau}(\tau)) \), \( \tau \) is the optimal cut point, denoted as \( \tau_0 \), which is the most likely mutation point.

3.2.2. Mann-Kendall statistical test method

In the original hypothesis \( H_0 \): when there is no change in the climate sequence, let this sequence be \( x_1, x_2, \ldots, x_n \), \( m_i \) represents the cumulative number of the \( i \)th sample \( x_i \), greater than \( x_j \) (\( 1 \leq j \leq i \)).

Define a statistic: \( d_k = \sum_{i=1}^{k} m_i \)

Under the assumption of random independence of the original sequence, the mean and variance of \( d_k \) are respectively:

\[
\begin{align*}
E[d_k] &= \frac{k(k-1)}{4} \\
\text{Var}[d_k] &= \frac{k(k-1)(2k+5)}{72} \quad (2 \leq k \leq n)
\end{align*}
\]
Standardize $d_k$: $u(d_k) = (d_k - E[d_k]) / \sqrt{\text{Var}[d_k]}

Here $u(d_k)$ is the standard normal distribution. The probability $\alpha = \text{prob}(\mid u \mid > \mid u(d_k) \mid)$ can be obtained by calculation or look-up table. Given a significance level $\alpha_0$, accept the null hypothesis at that time $\alpha_1 > \alpha_0$, and reject the null hypothesis at that time $\alpha_1 < \alpha_0$. It indicates that this sequence will have a strong increase or decrease trend, all of which will form a curve UF, and through the reliability test, we can know whether it has a trend of change.

Introducing this method to the reverse sequence, it means that the i-th sample $x_i$ is greater than the cumulative number of $x_j$ $(1 \leq j \leq i)$.

When $i' = N + 1 - i$, if $\overline{u} = m_F$, then the reverse sequence $\overline{u}(d_i)$ is given by

$$\begin{cases} \overline{u}(d_i) = -u(d_i) & (i, i' = 1, 2, \ldots, N) \\
 i' = n + 1 - i 
\end{cases}
$$

Among them: Denoted $\overline{u}(d_i)$ by UB in the figure.

When the curve UF exceeds the confidence line, it means that there is an obvious trend of change. If the intersection of the curves UF and UB is between the confidence line, this point is the beginning of a sudden change. If the intersection of two curves lies outside the confidence line, the intersection is not necessarily a mutation point. If the values of UF and UB are greater than 0, it indicates that the sequence shows an upward trend, and if the value is less than 0, it indicates a downward trend. When they exceed the critical value, it indicates a significant upward or downward trend.

### 3.2.3. Sliding t-test method

Divide the continuous hydrometeorological sequence point by point into two sub-sequences $X_1$ and $X_2$, the capacities are $n_1$ and $n_2$, the mean values are $\overline{u}_1$ and $\overline{u}_2$, the variances are $S_1^2$ and $S_2^2$, respectively, to construct a statistic

$$T = \overline{u}_1 - \overline{u}_2 / S \sqrt{1/n_1 + 1/n_2},$$

where $S = \sqrt{n_1 S_1^2 + n_2 S_2^2 / n_1 + n_2 - 2}$. $T$ obeys the t distribution of degrees of freedom $v = n_1 + n_2 - 2$; given the significance level $\alpha = 0.05$, if $|T| > t_\alpha$ (critical value), it is considered that a sudden change occurs at the split point, otherwise it is considered that there is no significant difference between the two sequence means before and after the split point (Wang et al. 2020).

### 3.3. Periodic analysis

#### 3.3.1. Ensemble empirical mode decomposition method

The ensemble empirical mode decomposition (EEMD) method (Wu & Huang 2009) is suitable for nonlinear and non-stationary sequence signal analysis, and can well extract trend and period information. The original signal sequence to be analyzed is superimposed with a white noise sequence of a given amplitude; the signal after adding white noise was subjected to EMD decomposition (decomposed into intrinsic function IMFs), and the IMFs obtained after multiple decompositions were then aggregated and averaged. The white noises cancel each other out, and it was used as the final decomposition result:

$$C_j(t) = \frac{1}{N} \sum_{i=1}^{N} C_{ji}(t)
$$

where: $C_j(t)$ is the j-th IMF component obtained after the original signal was decomposed and transformed using EEMD; $N$ is the increase in white noise; $C_{ji}(t)$ is the j-th IMF component decomposed after adding white noise for the i-th time. Morlet wavelet analysis is performed on each IMF component obtained above. Then, the period of each IMF component was determined by drawing the contour map of the real part of the wavelet coefficients and the wavelet variance map.

#### 3.3.2. Wavelet analysis method

The wavelet analysis method has been put forward for more than 40 years. In view of its time-domain characteristics when analyzing time series (Todd 2002), it has been widely used in the periodic analysis of various long series such as in hydrology research. The Wavelet functions in wavelet analysis could be divided into real wavelet functions and complex wavelet functions. Compared with real wavelet functions, complex wavelet functions can better reflect the time-scale periodicity of hydrological series and the time-scale periodicity in the time domain. The Morlet complex wavelet function was used as the analysis method to study the water and sedimentary periodicity.
The function of Morlet wavelet is: \( \psi(t) = \pi^{-1/4} e^{i\omega_0 t} e^{-t^2/2} \)

Where, \( \omega_0 \) is a constant and \( i \) is the imaginary part.

The wavelet variance is often used to determine the main period of the time series, and its changes over time is called the wavelet variance graph, and its calculation formula is: \( \text{Var}(a) = \int_{-\infty}^{\infty}|W(a, b)|^2 db \)

Where, \( a \) is the scale factor reflecting the length of the wavelet period; \( b \) is the time factor reflecting the time shift; \( W(a, b) \) is called the wavelet coefficient.

### 3.4. Double cumulative curve method

The theoretical basis of the double cumulative curve method (Yang et al. 2020) is that there should be a proportional relationship between the two elements or variables to be analyzed. The establishment of the curve can show the significance of the tested variable being affected by other factors (or variables) in addition to the influence of the benchmark variable. The specific analysis method is:

1. The mutation year obtained by the Mann-Kendall mutation test divides the entire time series into two stages, with time series 1 as the base period and time series 2 as the change period;
2. Linear regression calculation was performed on the annual cumulative precipitation \((\sum P)\) and runoff \((\sum Q)\) in the reference period to obtain the fitting equations of \(\sum P\) and \(\sum Q\) in the reference period: \(\sum Q = a \sum P + b\);
3. Substitute \(\sum P\) into the fitting equation to calculate the simulated value of \(\sum Q\) in the change period. \(\sum Q\) is considered to be the runoff that hasn’t been affected by human activities under the same conditions as the underlying surface in the reference period;
4. Based on the annual cumulative runoff simulation value \(\sum Q\), the annual runoff depth simulation value \(Q'\) is inversely calculated. The difference between the measured runoff and the average value of the simulation value during the change period is the impact of human activities on the runoff.

### 3.5. Attenuation analysis method

Watershed precipitation was the dynamic condition for surface sedimentary production, and its temporal and spatial distribution has a direct impact on watershed aquatic and sedimentary production; while human activities such as water and soil conservation, rainwater storage, and land use always alters the underlying surface of the basin, and changes the runoff mechanism. Therefore, changes in soil and water conservation and precipitation are the fundamental and direct causes of changes in water and sedimentary volume. In order to eliminate the influence of precipitation, let

\[ E = \frac{W_s}{P} \]

where, \( E \) is called the erosion rate (or sediment yield coefficient) (t/mm), \( W_s \) is the amount of sedimentary transport \((10^4 t)\), \( P \) is the amount of precipitation (mm), then \( W_s = E \times P \). Let the average sedimentary transport in the base period be \( W_s1 \), precipitation \( P_1 \) and erosion rate \( E_1 \), and the average sedimentary transport in each time period as \( W_s2 \), precipitation \( P_2 \) and erosion rate \( E_2 \). Take the full differential of the sedimentary transport and express it in the form of difference as:

\[ \Delta W_s = W_{s1} - W_{s2} = \frac{(P_1 - P_2)}{2}(E_1 - E_2) + \frac{(E_1 - E_2)}{2}(P_1 - P_2) = P \cdot \Delta E + E \cdot \Delta P \]

If the precipitation \( P \) remains, then the difference \( \Delta W_s = P \cdot \Delta E \) between the base period and each time period can be counted as the impact of human activities, if the erosion rate \( E \) does not change, then \( \Delta W_s = E \cdot \Delta P \) can be counted as the impact of precipitation.

### 4. RESULTS AND DISCUSSION

#### 4.1. Analysis of water and sedimentary characteristics

##### 4.1.1. Trend analysis results

In this study, the linear trend estimation method was first used to analyze the long-term trend of runoff and sedimentary transport sequence in the upstream of Kizil Reservoir, and then the Mann-Kendall rank correlation test method was used to identify the trend of hydrological time series. And the variation of hydrological time series in the future were analyzed with the R/S analysis method. Because there is contingency in a single analysis method, three methods were used to...
accurately determine its trend, and each method can mutually confirm the accuracy of the obtained conclusions. According to the collected water and sediment time series (1960–2017), the statistical results are shown in Table 1.

It can be seen from Table 1 that the multi-year runoff has an overall upward trend based on the linear trend analysis method, and the increase rate of the annual runoff is $1.165 \times 10^8$ m$^3/10$ a. The Mann-Kendall rank correlation test method was used to determine the significance of the runoff trend. The increasing trend of runoff is considered significant, because the Z value is 4.0583 and is greater than 1.96. The calculated H value is 0.9082 based on the R/S analysis method, which is between 0.5 and 1. The time series is continuous, and the future trend is a continuous increase. The main source of runoff in this basin is glacier snow melt water. With the gradual intensification of global climate warming, the annual ablation of glaciers has gradually increased, leading to an upward trend in river runoff, which is consistent with the analysis results.

It can be seen from Table 1 that the annual sediment delivery volume has shown an upward trend in general based on the linear trend analysis method, and the increase rate of the annual sediment delivery volume is $104.3 \times 10^4$ t/10 a. The Mann-Kendall rank correlation test method was used to determine the significance of the sedimentary transport trend, and the increasing trend of sedimentary transport was not significant, because the Z value is 1.8313 and is less than 1.96. Calculated using the R/S analysis method, the H value is 0.2653, between 0 and 0.5, the time series shows anti-continuity, and the future trend is downward. The sedimentary content of the river is related to the local land use types. The land use types in this area are gradually increasing, and the problem of soil deflection has become particularly prominent, resulting in an increase in the amount of sediment entering the river. At the same time, the frequency of floods has also increased in recent years. The floods scour the surface and carried away a large amount of loose soil into the rivers, causing the river’s sediment load to increase.

4.1.2. Results of mutation analysis
In this study, the Mann-Kendall parameter test method was used to analyse the mutation of the upstream runoff sequence, then the ordered clustering method and the sliding t test method were used to test the mutation of the runoff sequence, and the three determination methods were combined to finally determine the mutation point. The ordered clustering method was used to analyse the abrupt changes of the annual runoff sequence, estimate the segmentation point of the annual runoff sequence, and calculate the relationship curve between the total square deviation of the annual runoff sequence and the segmentation point $\tau$, as shown in Figure 2(b), preliminary analysis of the variation points of annual runoff, the smallest is in 1995, and the second smallest is in 1993; in order to further analyse the significance of the variation points, the non-parametric test method Mann-Kendall was used to confirm the significance of the variation points. The results are shown in Figure 2(a), the time of mutation is in 1994; finally, the sliding t test method was used to test the mutation points, as shown in Figure 2(c), the time of mutation is in 1994; combined with the above analysis data, the mutation year of the Kizil Reservoir’s annual runoff sequence was determined to be 1994.

4.1.3. Periodic analysis results
The runoff and sedimentary transport in the upper reaches of the Kizil Reservoir are non-stationary series, which have a certain fluctuation period. The traditional wavelet analysis method and the wavelet analysis method based on EMD decomposition have room for improvement. EEMD decomposition is proposed on the basis of EMD decomposition in this paper. In order to accurately analyze the qualitative influence of solar activity and El Niño-Southern Oscillation

### Table 1 | Results of trend analysis of annual runoff and annual sediment discharge in the upper reaches of Kizil Reservoir

| Type          | Statistical period | Linear trend method | M-K rank correlation test | R/S analysis method |
|---------------|--------------------|---------------------|---------------------------|---------------------|
| Runoff        | 1960–2017          | $y = 0.1165x – 206.1053$ | Z value = 4.0583, Significant upward trend | H value = 0.9082, Continuously rising |
| Sediment transport | 1960–2017          | $y = 10.4306x – 19,764.217$ | Z value = 1.8313, The upward trend is not significant | H value = 0.2653, Future decline |
(ENSO) phenomenon on sedimentary transport and runoff, this paper adopts the wavelet decomposition method based on EEMD decomposition to obtain the periods of two non-stationary series.

(1) From 1960 to 2017, the runoff sequence in the upstream watershed of the Kizil Reservoir can be decomposed into 4 IMF components with different fluctuation periods and one Res trend component, as shown in Figure 3. Which reflects the complexity of the runoff changes in multiple time scales in the upstream watershed of Kizil Reservoir.

(2) The first eigenmode function IMF1 has the largest amplitude, the highest frequency and the shortest wavelength. The amplitudes of the IMF2, IMF3 and IMF4 components gradually decreases, the frequency gradually decreases, and the wavelength gradually increases.

(3) The Res component shows the overall change trend of annual runoff, and it can be seen that there has been a clear upward trend over the years.

In order to further study the accurate periodic characteristics of each IMF component, on the basis of EEMD decomposition to obtain the IMF component, Morlet wavelet analysis is performed on each component. The wavelet variance diagram of each IMF component is obtained through matlab software programming, as shown in Figure 4.

It can be seen from Figure 4 that the IMF1 component has two peaks, the time scale is 6a–9a, and the quasi-period is 7a. The IMF2 component has a higher peak, and the time scale is 11a–15a, and the quasi-period is 13a. The IMF3 component has
one peak, time scale is 26a–30a, quasi-period is 28a. There is no obvious peak in IMF4 component. The results indicate that the complex multi-time scales natures of the annual runoff changes in the upper reaches of the Kizil Reservoir. This conclusion can provide scientific guidance for future water resources allocation, flood control and disaster mitigation, and drought resistance studies in the Kizil Reservoir.

(1) The sedimentary transport sequence in the upstream of Kizil Reservoir from 1960 to 2017 can be decomposed into four IMF components with different fluctuation periods and one Res trend component, as shown in Figure 5. Which reflects the complexity and multi-time scales nature of the sedimentary transport changes in the upper reaches of the Kizil Reservoir;
(2) The first eigenmode function IMF1 has the largest amplitude, the highest frequency and the shortest wavelength. The component amplitudes and the frequency of IMF2, IMF3 and IMF4 gradually decrease, and the wavelength gradually increases;
(3) The Res component shows the overall change trend of the annual sedimentary transport. It can be seen that at first the sedimentary transport increases for many years, and then decreases in the future time series.

Figure 3 | EEMD decomposition diagram of annual runoff series in the upstream basin of Kizil Reservoir.

Figure 4 | Wavelet variance diagram of EEMD component of annual runoff.
In order to obtain more accurate periodic characteristics of each IMF component, on the basis the IMF component obtain through EEMD decomposition, Morlet wavelet analysis was performed on each component. The wavelet variance diagram of each IMF component was obtained through matlab software programming, as shown in Figure 6.

It can be seen from Figure 6 that the IMF1 component has two obvious peaks, the time scale is 2a–5a, and its quasi-period is 4a. The IMF2 component has an obvious peak, the time scale is 10a–15a, and its quasi-period is 12a. The IMF3 component has an obvious peak, the time scale is 25a–28a, and its quasi-period is 26a. There is no obvious peak in IMF4 component. The results indicate the complex and multi-time scales of the annual sedimentary transport changes in the upper reaches of the Kizil Reservoir. This conclusion can provide help for the optimized operation of the Kizil Reservoir and the desilting and dredging of the reservoir to extend the life of the reservoir.

4.2. Analysis of influencing factors

The soil type, land use type and vegetation coverage in the study area are the main factors that affect the river water and sand conditions in different periods. Soil types (see Figure 7) mainly include dry soil, desert soil, alpine soil, etc. These soil types are
prone to water and soil erosion, soil erosion and other problems. Its water and soil conservation measures were not properly planned, resulting in serious soil erosion and increased sand content in the river. The population density in this area is small. It can be seen from Figure 8 that the area of arable land is on the rise, and the changes in other land use types are not obvious. The vegetation coverage is measured by the NDVI index in Figure 9. Through the specific values (0.692-0.92-0.78), it can be seen that from 2000 to 2010, human activities have a significant impact on the runoff and sediment transport in the region.

The impact of human activities and climate change on river sediment content can be judged by the suspended load sediment particle curve in the river. The Figure 10 show the particle gradation curves of Muzati River and Heizi River at a certain particle size. Suspended sediment in the Muzati River is mainly composed of silt and sand, of which fine silt less than 0.007 mm accounts for 4.6%, coarse silt soil between 0.007 mm and 0.05 mm accounts for 45.3%, and medium and fine sand between 0.05 mm and 0.5 mm accounts for 50%. Suspended sediment in the Heizi River is mainly composed of silt, of which fine silt less than 0.007 mm accounts for 19.3%, and coarse silt soil with 0.007 mm to 0.05 mm accounts for...
80.7%. The suspended load particle size is finer than that of the Muzati River. The finer particle size of suspended sediment has a lot to do with the soil type in the study area. At the same time, human adjustments and changes in land use types and vegetation coverage directly affect the sediment content of rivers.

### 4.2.1. The impact of human activities and precipitation on runoff

In order to distinguish the effects of human activities and precipitation on the changes in water and sediment in the upper reaches of the Kizil Reservoir. Firstly, the annual runoff mutation test in the upper reaches of the Kizil Reservoir from 1960 to 2017 was carried out, and the period before the mutation year was regarded as only under influence of rainfall, the period after the mutation year was regarded as the period with the combined effect of human activities and rainfall, as shown in Figure 11. As shown in the previous calculation results, the sudden mutation year in the upstream runoff of Kizil Reservoir from 1960 to 2017 was 1994. Secondly, the precipitation-runoff double accumulation curve was used to simulate the regression analysis of the contribution of human activities and rainfall on runoff, as shown in Table 2. A calculated value was obtained through the precipitation-runoff double accumulation curve fitting equation, and the difference between the calculated value and the measured value was the contribution of human activities, as shown in Table 3.

From 1960 to 2012, compared with the calculated cumulative runoff, the measured cumulative runoff decreased by $72.73 \times 10^8$ m$^3$. After the sudden runoff mutation year, the measured cumulative runoff increased by $0.82 \times 10^8$ m$^3$. The differences were significant.
contribution rate of human activities to the increase of upstream runoff accounted for \( 385.37\% \), while the contribution rate of precipitation to the increase of runoff accounted for 485.37%. The results show that after the year of sudden change in the upstream runoff of the Kizil Reservoir, the impact of precipitation on the runoff is greater than that of human activities. The population density in the upper reaches of the Kizil Reservoir is not very high. Near the end of the river is the source of glaciers; it is difficult for people to survive, and human activities are still very few. The runoff here is obviously affected by precipitation, and precipitation is the main influencing factors in this area.

### 4.2.2. The impact of human activities and precipitation on sediment transport

In order to accurately analyse the impact of precipitation and human activities in different periods on the changes in sediment transport in the upper reaches of the Kizil Reservoir, the statistical data series are divided into periods every 10 years, and the attenuation analysis method was used to analyse the degree of influence of precipitation and human activities on sedimentary transport in each period. If the precipitation \( P \) does not change, the difference between the base period and each time period is counted as the impact of human activities. If the erosion rate \( E \) does not change, it is counted as the impact of precipitation. The calculation result is shown in Table 4.

From 1960 to 1969, the proportion of the influence of precipitation on the amount of sedimentary transport is 24.13%, and the proportion of the influence of human activities on the amount of sedimentary transport is 75.87%. This is mainly because before the 1970s, the annual precipitation in the upper reaches of the Kizil Reservoir was relatively small, so the proportion of precipitation relative to human activities on sedimentary transport was small.

### Table 3 | Contribution rate of precipitation and human activities before and after the mutation year in the upper reaches of Kizil Reservoir

| Time       | Runoff | Runoff increase | Precipitation impact | Human activity |
|------------|--------|-----------------|----------------------|---------------|
|            | Measured value | Calculated | Increments | Percentage | Increments | Percentage | Increments | Percentage |
| 1994       | 27     | 30.98           | 0.82                 | 3.04%        | 3.98      | 485.37%    | −3.16      | −385.37%    |
| 1995–2012  | 27.82  | 30.98           | 0.82                 | 3.04%        | 3.98      | 485.37%    | −3.16      | −385.37%    |

### Table 4 | Calculation results of Kizil Reservoir’s sedimentary transport

| Time period | 1960–1969 | 1970–1979 | 1980–1989 | 1990–1999 | 2000–2009 | 2010–2012 |
|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
| \( W_s \) (10^4t) | 597.25    | 778.84    | 1,143.10  | 936.19    | 1,420.94  | 886.52    |
| \( P \) (mm)    | 87.68     | 93.79     | 122.66    | 129.85    | 141.77    | 95.96     |
| \( E = W_s/P(10^4t/mm^{-1}) \) | 6.81      | 8.30      | 9.32      | 7.21      | 10.02     | 9.24      |
| \( \Delta W_s \) (10^4t) | 181.59    | 545.85    | 338.94    | 823.69    | 289.27    |           |
| \( \Delta P \) (mm)    | 6.11      | 34.98     | 42.17     | 54.09     | 8.27      |           |
| \( \Delta E(10^4t/mm^{-1}) \) | 1.49      | 2.51      | 0.40      | 3.21      | 2.43      |           |
| \( E\times \Delta P \) (10^4t) | 41.62     | 290.45    | 392.99    | 389.93    | 82.94     |           |
| \( \Delta W_s = E\times \Delta P \) (10^4t) | 130.85    | 235.20    | 48.83     | 417.03    | 344.10    |           |
| \( E\times \Delta P \) (%) | 24.13%    | 55.26%    | 88.95%    | 48.32%    | 19.42%    |           |
| \( \Delta W_s \) (10^4t) | 75.87%    | 44.74%    | 11.05%    | 51.68%    | 80.58%    |           |
From 1970 to 1979, the impacts of precipitation and human activities on sedimentary transport were relatively equal. The proportions of precipitation and human activities on sedimentary transport were 55.26% and 44.74%, respectively. This stage follows the annual precipitation in the upper reaches of the Kizil Reservoir. As the amount of precipitation increases, the proportion of precipitation that affects the amount of sediment is gradually increasing.

From 1980 to 1989, the proportions of precipitation and human activities on sedimentary transport were 88.95% and 11.05%, respectively; from 1990 to 1999, the proportions of precipitation and human activities on sedimentary transport were 48.32% and 51.68%, respectively; From 2000 to 2009, the proportions of precipitation and human activities affecting sedimentary transport were 19.42% and 80.58%, respectively. The impact of precipitation on sedimentary transport was first high and then low, and the impact of human activities on sediment transport was first low and then high. The main reason for this phenomenon might be related to the construction of Kizil Reservoir. The effect is that the precipitation of the unbuilt reservoir has a large impact on the sedimentary transport, and the human activities has a large impact on the sediment transport during and after the construction of the reservoir.

4.2.3. The impact of solar activity on runoff and sediment transport

The main indicator of solar activity changes is the fluctuation of the number of sunspots, which is a non-stationary sequence. In order to accurately analyze the period of solar activity, the EEMD decomposition period method based on the wavelet analysis method used above is used to solve the wavelet variance of each component and draw the wavelet variance analysis diagram of the solar activity. It can be seen from the Figure 12 that the fluctuations of the IMF1 component and the IMF2 component were similar and have obvious peaks with a quasi-period of 16a; the IMF3 component has no obvious peak; and the IMF4 component has an obvious peak with a quasi-period of 31a.

The annual runoff in the upstream of the Kizil Reservoir has major cycles of 7a, 13a, and 28a, and the first major cycle is 28a. On the 11–15a and 26a–30a scales, the annual runoff and the relative number sequence of sun black have similar main periods, but the two periods are different in a short time scale. The 7a cycle shown by the annual runoff change has little to do with sunspot activities, while the 13a and 28a cycles should be mainly affected by sunspot activities and are closely related to sunspot activities. The increase in runoff will affect the sediment carried in the river, and further affect the amount of sediment transported into the Kizil Reservoir. The periodic fluctuation of the amount of sedimentary transport is closely related to the runoff, and the change of runoff is affected by solar activity. The amount of sedimentary transport is also affected by changes in runoff.

4.2.4. Analysis of the impact of ENSO on runoff and sediment transport

El Niño-Southern Oscillation (ENSO) is the most significant ocean-atmosphere coupling signal in the tropical Pacific. The warm and cold phases are represented by El Niño and La Niña events, respectively (Hu et al. 2017). The periodicity of ENSO events in southern Xinjiang is: 6a periodicity before 1980 and the late 1990s, quasi-4a periodic change from the 1980s to the mid-1990s, and this long trend periodic change is after 1995. This is consistent with the 6–9a short period of

![Figure 12](http://iwaponline.com/ws/article-pdf/22/2/1275/1009104/ws022021275.pdf)
water and sediment change in the Kizil Reservoir. It can be inferred that the water and sediment in the Kizil Reservoir are regulated by ENSO signals. Analyzing the relationship between the two, it can be found that the water-sediment change cycle is 3–4 years later than the ENSO event. This is because the impact of ENSO on the rainfall in the rainy season in Xinjiang is obviously lagging, and this impact is not an accidental phenomenon. Because there is a physical teleconnection relationship between Xinjiang precipitation and ENSO (Liu & Yang 2008).

4.2.5. The impact of changes in underlying surface on runoff and sediment transport

After entering the 1980s, human activities were the main reason for the increase in sediment in the reservoir. The entire Weigan River basin is distributed in a fan shape. From north to south, it covers the high mountain belt above 3,200 m, the middle mountain belt 2,400–3,200 m and the low mountain belt below 2,400 m. The high mountain belt has steep terrain, sharp peaks, and is covered with snow and ice for many years; the middle mountain belt has large annual rainfall, high air humidity, and relatively good vegetation coverage. It is the main runoff producing area of the Weigan River basin; the low mountain belt has a relatively dry climate with bare rocks, vertical and horizontal gullies, and sparse vegetation, it is the main sand-producing area in the Weigan River basin. The location of the Kizil Reservoir has a fragile ecological environment (Wang & Xi 2016), the vegetation coverage in the upper reaches of the reservoir is easily affected by human activities, and the degree of fragmentation in the interlaced zone and desert area is relatively large (Cao et al. 2016), and along with the Weigan River irrigation area in the lower reaches of the reservoir The area of arable land has increased year by year, which has caused changes in the use of water resources, reduced groundwater replenishment, and the groundwater level has dropped below the ecological water level, resulting in the degradation of natural vegetation around the Wei reservoir oasis (Du et al. 2015), thus leading to an increase in the amount of sediment transported into the reservoir.

4.2.6. The degree of influence of glacier snow melt water on runoff and sediment transport

By consulting the ‘Chinese Glacier Catalog’, there are a total of 853 continental glaciers in the upper reaches of the Kizil Reservoir, with a total area of 1,784 km², as shown in Table 5. It can be seen from Table 5 that the proportion of glacial meltwater in the Muzati River is 56.8%, and the proportion of glacial meltwater in the Kamuslang River is 44.8%. The glacial meltwater is the main component of the runoff of the Kizil Reservoir. In recent decades, under the environment of global warming and accelerating water cycle, the amount of glacier ablation and runoff in the central and western mountainous areas of the Tianshan Mountains in Xinjiang has increased year by year (Huang et al. 2003). From 1961 to 2010, the temperature increase rate of the Tianshan Mountains in Xinjiang was 0.54°C/10a. After 1997, the temperature increased significantly (Mao et al. 2012); the average annual temperature increase rate of Weigan River in the past 40 years from 1961 to 2000 was about 0.17°C/10a. The rate of decrease in volume is about 149 mm/10a (Mansuer et al. 2008). As the temperature gradually increases, the monthly ablation energy also increases significantly. The glacier meltwater runoff also has the same changing trend. The sensitivity of runoff to temperature in May and June is significantly lower than that in July–September. Comparing to the change curve of the annual runoff of the Kizil Reservoir, it can be found that the runoff reached its peak in 2001. This shows that with the warming of the climate, the rate of glacier melting has accelerated, and the runoff of the reservoir will inevitably increase, accompanied by the annual increase in sediment into the reservoir.

| Table 5 | Glaciers in the upper reaches of Weigan River |
|---------|---------------------------------------------|
| River name | Catchment area/m² | Glacier area/km² | Glacier coverage/% | Glacier melt/10⁶ m³ | Glacier melt water proportion/% |
| Muzati River | 2,845.00 | 1,219.23 | 42.65 | 12.09 | 56.80 |
| Camus Langhe | 1,834.00 | 298.73 | 16.28 | 3.36 | 44.80 |
| Telwaichuk | 1,072.00 | 157.62 | 9.62 | ... | ... |
| Karasu River | 1,350.00 | 65.62 | 5.89 | 0.74 | 29.30 |
| Kizil River | 3,342.00 | 42.66 | 1.28 | 0.48 | 12.40 |
| total | 10,443.00 | 1,783.86 | ... | 16.66 | ... |
5. DISCUSSION

(1) Predecessors have conducted related studies on the Weigan River Basin, such as: Zhang (2008) analysed the temperature, precipitation, runoff, and flood changes characteristics based on the observation data from the representative hydrological station in the area. Qin et al. (2016) used the Kruskal-Wallis stage conversion test, R/S analysis, EEMD and other methods to study the characteristics of the annual and inter-annual changes in runoff and its influencing factors based on monthly runoff data and daily meteorological data from the area. Li et al. (2016) adapted the data samples from Langan Station, Heizi Reservoir Station, and Qianfodong Reservoir Station in the area, to analyse the defects of R/S and Mann-Kendall methods, and proposed that the combination of these two methods could much accurately analyse the changing trend of hydrological time series. Liu et al. (2018) used the cumulative anomaly method, MK mutation test method, and wavelet analysis method to analyse and study the changing trend, abrupt characteristics and periodic evolution of the inbound water and sediment sequence; attenuation analysis method was used to analyse the impact degree of rainfall and human activities on the water and sedimentary changes in the reservoir.

(2) Most previous studies only use a single analysis method, which lacked comparative verification. Based on the collected data from the Heizi Reservoir hydrological station at the dam site, this paper uses the linear trend estimation method, the Mann-Kendall rank correlation test method and the R/S analysis method to analyse the trend of the water and sedimentary sequence, and the ordered clustering method, Nonparametric test method and sliding t test method were used to analyse the abrupt change of runoff, and wavelet analysis method based on EEMD decomposition was used to analyse the periodicity of water-sediment series. The analysis of trend and suddenness is mutually confirmed by a variety of methods, and the periodic analysis is improved by improving the traditional cycle analysis method, and the results obtained are more accurate and more convincing than previous studies.

(3) This research also has certain limitations. The origin of the research data, there are multiple hydrological stations in the Weigan River Basin, which provides substantial data from different hydrological stations. The researcher can analyse the variation characteristics of the water and sedimentary sequence of different hydrological stations, detect their mutual effect and then a comprehensive analysis of the synergy relationship of the entire region can be concluded. As for the research method, there is still room for improvement in the various basic methods adopted in this article. In future studies there can be more application of cutting-edge methods in the computer field and the latest theories in the field of mathematics. In the improvement of basic methods, interdisciplinary research is proven to be very important. Relying on the advantages of other disciplines to solve the bottleneck problems of current analysis methods, and to provide simple and efficient research methods for researcher is also the trend of future research development.

6. CONCLUSION

(1) The runoff of the Kizil Reservoir site shows an increasing trend and will continue to increase in the future. At present, the sedimentary discharge shows an increasing trend while further analysis revealed that the sedimentary discharge would decrease in the future. The year when the runoff at the Kizil Reservoir site had abruptly changes was 1994. There are three time scales for runoff, namely 6a–9a, 11a–15a, 26a–30a, and its quasi-period is 7a, 13a, 28a; there are also three time scales for annual sedimentary transport, namely 2a–5a, 10a–15a, 25a–28a, the quasi-period is 4a, 12a, 26a. The 7a cycle shown in the annual runoff change has little to do with sunspot activity, while the 13a and 28a cycles shown to be mainly affected by sunspot activity and are closely related to sunspot activity.

(2) The double cumulative curve method was used to analyse the influence of precipitation changes and human activities on runoff. The results showed that the measured cumulative runoff increased by $0.82\times10^8$ m$^3$, the contribution rate of human activities on the increase in runoff accounted for $385.37\%$, and the contribution rate of precipitation on the increase in runoff accounted for $485.37\%$. The attenuation method was used to analyze the impact of precipitation and human activities on sedimentary transport. The results showed that the impact of precipitation on sedimentary transport is first high and then low, and the impact of human activities on sedimentary transport is first low and then high. The main reason for this phenomenon is due to the construction of Kizil Reservoir.

(3) The water and sediment deposit in the Kizil Reservoir are regulated by ENSO signals, and the impact of ENSO obviously has a significant lag effect on rainfall in Xinjiang. And it goes to prove that there is a physical teleconnection relationship between rainfall and ENSO in Xinjiang. The vegetation in the upstream area is affected by human activities, the changes
in water resources utilization method, the reduction of the amount of groundwater replenishment, the degradation of natural vegetation around the oasis, are all direct reasons for the increase in sediment deposited into the reservoir. With the climate warming, the rate of glacier melting has accelerated, and the runoff of the reservoir will inevitably increase, accompanied by the increase of the sediment deposit into the reservoir year by year.

DATA AVAILABILITY STATEMENT

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

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