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Analysis of sediment variation and influencing factors in the upper Yangtze River in the past 50 years, China

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ABSTRACT

River sediment load has a profound impact on river geomorphology and river ecosystems. We selected sediment load data from 1965 to 2019 from three key hydrological stations in the upper reaches of the Yangtze River: Pingshan, Cuntan, and Yichang. We have used the Mann-Kendall method, t-test, and wavelet analysis to analyze the characteristics of sediment load variation, the Cumulative volume slope rate of change, and the River Impact method to quantitatively assess the degree of sediment variation and the influencing factors. The results show that (1) The annual sediment load at the upper reaches of the Yangtze River at the Pingshan, Cuntan, and Yichang stations all showed a significant decreasing trend, with mutations in 1997, 2003, and 2002, respectively, with the main period of 15 years, 24 years, and 10 years. (2) A series of human activities such as interception of dams, sand mining in river channels, and soil and water conservation measures are the main reasons for the significant reduction of sediment load in the upper reaches of the Yangtze River, with the contribution of human activities exceeding 80% in all cases after the 1990 s and 90% after the 21st century. (3) Under human activities, the annual sediment load at Cuntan station has been highly altered, while serious alterations have occurred at Pingshan and Yichang stations. The results of the study can provide a corresponding reference for ecological protection and restoration in the Yangtze River basin.

Key words: ecological restoration, quantitative evaluation, river impact factor method, sediment, upper Yangtze River

HIGHLIGHTS

- Analyzed the sediment variation in the upper Yangtze River in the past 50 years.
- Quantitatively evaluated the degree of sediment alteration.
- The contribution of climate change and human activities to sediment variation was quantitatively assessed.
- To discuss and analyze the influencing factors of sediment variation and the resulting environmental impact.

1. INTRODUCTION

As an important hydrological factor, river sediment not only has an important influence on the geological, chemical, physical, and ecological processes of rivers (Zheng *et al.* 2018) but also has an important significance for the exchange and migration of materials between sea and land (Bianchi & Allison 2009). Natural river sediment has certain spatial and temporal distribution characteristics influenced by natural conditions such as precipitation, temperature, evapotranspiration, and groundwater (Songzhe *et al.* 2018). However, with human exploitation of rivers (construction of reservoirs, sand mining in rivers) and changes in river environments (soil and water conservation, land-use changes), natural river sediment production and transport processes produce changes in response, which in turn affect the hydrological situation, water quality, geomorphology, and aquatic life of rivers (Yang *et al.* 2018). The changes in river conditions caused by these sediment changes will directly endanger river ecosystem health (Wang *et al.* 2017).

For the study of river system characteristics, a series of indicator systems on river hydrological conditions have been proposed by some scholars since the 1980 s (Sanderson *et al.* 2012). To ensure the independence among hydrological indicators, Richter *et al.* introduced the Range of Variability Approach (RVA), which uses 33 ecologically significant hydrological alteration indicators to quantitatively evaluate the degree of alteration of hydrological conditions of one or more elements under specific activities (Richer *et al.* 1997, 1998). However, this method requires more hydrological indicators of statistical rivers and its results are more complex. Haghighi *et al.* established the Integrated River Impact Assessment

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Index (River Impact, RI) based on the three main characteristics of rivers (intensity, time, and interannual variability) in the IHA method and evaluated the Ebro River as an example, and its results are streamlined and better respond to the characteristics of river changes, which make up for the shortcomings of IHA (Haghighi *et al.* 2014). In addition, the attribution analysis of the change of river characteristics usually attributes the impact factors to climate change and human activities (Zhao *et al.* 2015). In contrast, the cumulative slope method proposed by Wang *et al.* can better separate climate change from human activities and quantitatively evaluate the impact produced by each (Wang *et al.* 2012). In summary, the RI method and the cumulative slope method are used to analyze the changes in river sediment, which can better reflect the change process and its extent.

In the context of global warming and the continuous expansion of human activities, the study of the effects of changing environments on sediment loads has become a current research topic (Jiao *et al.* 2021). Climate change is mainly characterized by global warming, which causes changes in precipitation by altering atmospheric temperature, thus changing the local hydrological cycle and driving changes in hydrological factors such as runoff and sediment (Duan *et al.* 2020). On the other hand, human activities affect sand production in the basin mainly through a combination of reservoir storage and sediment interception, river sand mining, and soil conservation measures (Gu *et al.* 2019). The upstream area of the Yangtze River is the main source area of sediment load of the whole Yangtze River and plays a controlling role in the change of sediment load in its middle and lower reaches (Guo *et al.* 2020). Therefore, it is important to study the effects of climate change and human activities on sediment load for the rational development of water resources in the Yangtze River basin.

Up to now, a large number of scholars have studied the changes in sediment conditions in the Yangtze River, for example, Wang *et al.* (2014a, 2014b) used hydrological data to systematically analyze the variation characteristics of water-sediment dynamics and its causes in the middle and lower reaches of the Yangtze River, Dong *et al.* (2015) preliminarily evaluated the water-sediment characteristics and trends of the Yangtze River mainstream channels, and Ban *et al.* (2014) used the range-of-variation method to quantitatively assess the spatial and temporal changes of water-sediment after the impoundment of the Three Gorges Reservoir. The spatial and temporal changes of water and sand after the impoundment of the Three Gorges Reservoir were quantitatively assessed by Ban Xuan *et al.* In summary, the current study mainly focuses on the interannual variability of sediment in the middle and lower reaches of the Yangtze River, and overemphasizes the impact of the Three Gorges Reservoir on sediment variability. However, there is a lack of assessment of sediment changes in the upper Yangtze River. Therefore, it is necessary to conduct relevant studies on sediment changes in the upper Yangtze River.

The main objectives of this study are: (1) to count the spatial and temporal distribution of sediment in the upper reaches of the Yangtze River over the past 50 years and analyze the main characteristics of changes; (2) to reveal the extent of sediment changes in the upper reaches of the Yangtze River using the RI method; (3) to quantitatively evaluate the effects of climate change and human activities on sediment changes and discuss and analyze the ways of influencing sediment changes. The research results can provide a scientific basis for the sustainable and healthy economic development and ecological restoration of the Yangtze River Economic Zone.

2. MATERIALS AND METHODS

2.1. Study area

With a total length of about 6 300 km, the Yangtze River is the third-longest river in the world and the fourth largest in terms of sediment (Jin *et al.* 2010; Wang *et al.* 2014a, 2014b). The Yangtze River is usually divided into upper, middle, and lower reaches according to different geomorphological environments and hydrological characteristics (Wang *et al.* 2015). The upper reaches of the Yangtze River are 4,500 km long, accounting for about 70% of the total length of the Yangtze River, and its controlling tributaries mainly include the Jinsha, Yalong, Min, and Jialing rivers on the north bank and the Wu River on the south bank (Guo *et al.* 2020) (Figure 1). Among them, the Jinsha River and Jialing River are the main sediment-producing areas. The temporal and spatial variation of precipitation in the Yangtze River Basin is closely related to the monsoon activity, which transports a large amount of water vapor from the East China Sea and the South China Sea to the Yangtze River Basin. However, the distribution of precipitation time is extremely uneven. More than 60% of the annual precipitation occurs in summer, and floods occur frequently (Hong *et al.* 2015). As of 2016, the number of hydropower dams across the Yangtze River increased to about 52,000 and its total storage capacity increased to about 360 billion m^3,

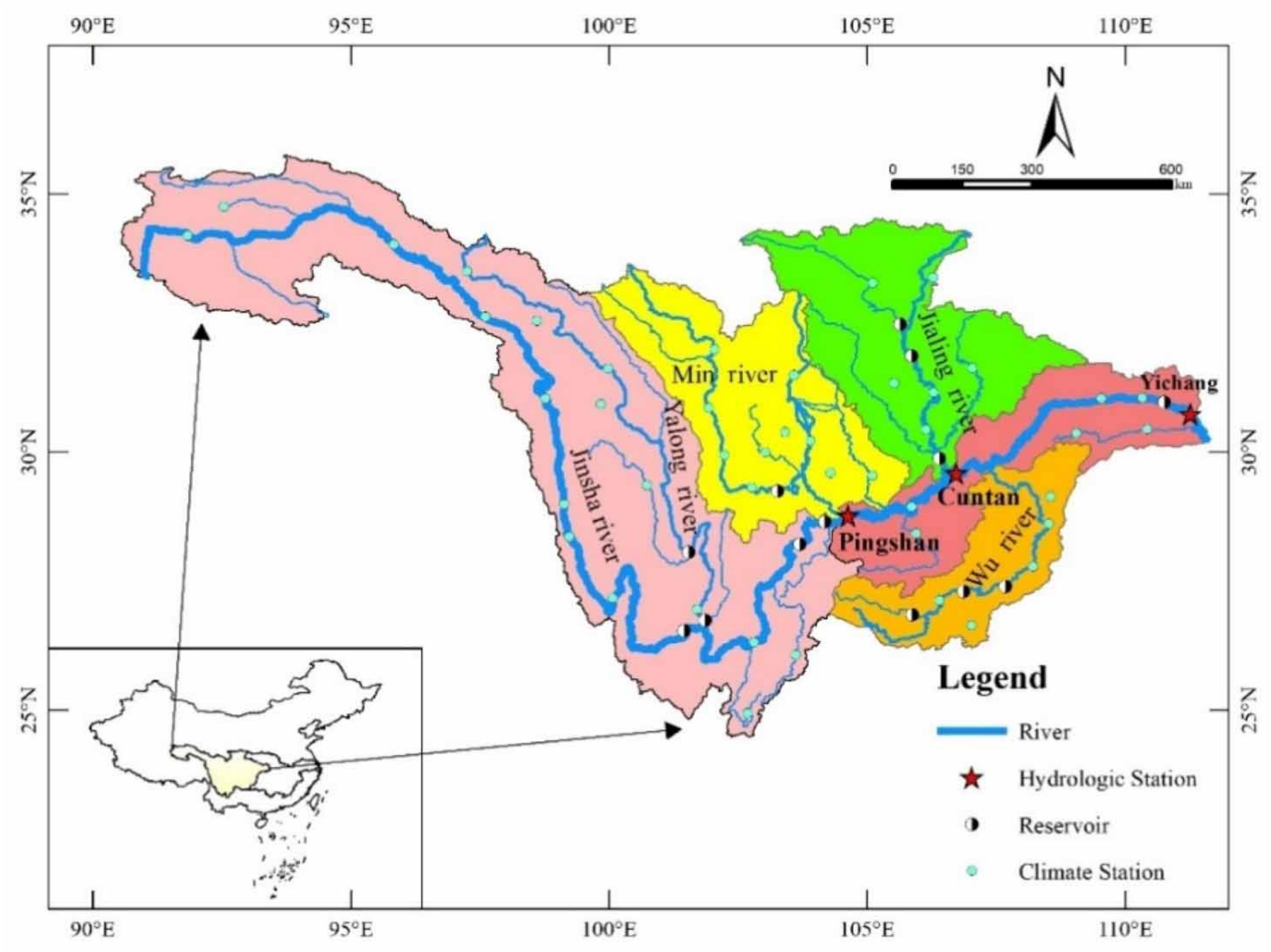

Figure 1 | upper Yangtze River basin map.

ranking it as one of the most heavily dammed large rivers in the world, and since 1989, a series of soil and water conservation projects (named the Chang Zhi Project) have been implemented in the upper reaches of the Yangtze River, and the scope of its human activities continues to expand and enhance, so there is an urgent need to clarify the upper reaches of the Yangtze River water and sand flux changes and evaluation of influencing factors (Peng *et al.* 2019).

2.2. Datasets

We selected daily data of sediment load from 1965 to 2019 at three hydrological stations of the main control stations of the Yangtze River, Pingshan, Cuntan, and Yichang, and data of precipitation at meteorological stations in the basin to study the characteristics of sediment change. The Ping Shan hydrological station is located downstream of the confluence of the Jinsha River and Yalong River, and the station was submerged after the impoundment of Xiangjiaba in 2012, so the Xiangjiaba hydrological station was generally selected instead of the Ping Shan hydrological station. Cuntan hydrological station, located 7.5 km downstream of the confluence of Yangtze River and Jialing River, controls the basic water condition of Minjiang River and Jialing River after they merge into Yangtze River. The Yichang hydrological station, located 44 km downstream of the Three Gorges Dam, is the export control hydrological station for the upper reaches of the Yangtze River mainstream (Yang *et al.* 2006) (Table 1). Considering the stability and reliability of meteorological data, 67 national basic meteorological stations in the upper reaches of the Yangtze River were selected for this study, excluding the missing and relocated stations. The sediment data were obtained from the Hydrological Yearbook of the Yangtze River Basin, and the precipitation data were obtained from China Meteorological Data Network (http://data.cma.cn/).

Table 1 | Composition of sediment areas in the upper reaches of the Yangtze River

	Control area		Average annual sediment load		
Hydrological station	**Value/10^4 km^2**	**Proportion of Yichang/%**	**Value/10^8 t**	**Proportion of Yichang/%**	**Period**
Pingshan	45.86	45.61	2.06	60.95	1965–2019
Cuntan	86.66	86.19	3.20	94.68	1965–2019
Yichang	100.55	100	3.38	100	1965–2019

2.3. Methods

2.3.1. Trend and mutation analysis

We used the Mann-Kendall nonparametric test method and the t-test method to analyze the trend and mutation of the daily sediment load data at Pingshan, Cuntan, and Yichang stations. Among them, Mann-Kendall nonparametric test is a more extensive method for testing the abrupt changes of runoff, but its detection results have great human interference factors, and it also needs to be combined with the t-test method detection method and the actual situation to ensure its accuracy. The specific calculation procedure is described in Refs. (Chen *et al.* 2018; Zhuo *et al.* 2020).

2.3.2. Wavelet analysis

The complex Morlet wavelet was used to analyze the periodicity and variation tendency in sediment load at the three 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:

$$\psi_{a,b}(t) = |a|^{-1/2}\varphi\left(\frac{t-b}{a}\right) \quad (a, b \in R, \ \ a \neq 0) \tag{1}$$

$$W_f(a, b) = |a|^{-1/2}\int_R f(t)\overline{\varphi}\left(\frac{t-b}{a}\right)dt \tag{2}$$

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 (Guo *et al.* 2019a, 2019b).

In this study, the complex Morlet wavelet function is applied to distinguish temporal 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.

2.3.3. Cumulative curve method

We use the cumulative curve method to calculate the sediment load cumulatively and study the change of the sediment load according to the change of the cumulative curve. When the accumulation curve makes an obvious turn at a point, it indicates a shift in sediment characteristics; when the slope of the accumulation curve is biased toward the axis of accumulated sediment load (or the horizontal axis), it indicates an increase in sediment load (or decrease). (Guo *et al.* 2019a, 2019b).

2.3.4. RI method

The RI method mainly considers the interannual variation of sediment load, the time variation of extreme values, and the intra annual variation of sediment load, and quantifies the three types of impact factors as M_{IF} (magnitude impact factor), T_{IF} (timing impact factor), and V_{IF} (variation impact factor). M_{IF}'s impact is equivalent to the combined effect of T_{IF} and V_{IF}. The river impact factor is calculated as:

$$RI = M_{IF} \times (T_{IF} + V_{IF}) \tag{3}$$

where M_{IF} is calculated by the following equation:

$$M_{IF} = F_{post}/F_{pre} \tag{4}$$

where:

F_{post} is the annual sediment load before river alteration;
F_{pre} is the annual sediment load after river alteration.
V_{IF} can be calculated by the following equation:

$$V_{IF} = (50 - 0.5I_{RR})/100 \tag{5}$$

Among them:

$$I_{RR} = \frac{|RRI_{pre} - RRI_{post}|}{RRI_{pre}} \times 100 \tag{6}$$

$$RRI = \sum_{k=1}^{12} MRRP(k) \tag{7}$$

where: RRI is the coefficient of variation of the hydrological regime of the river; RRI_{pre} and RRI_{post} are the hydrological regimes before and after the change of the river, respectively; $MRRP(k)$ is the monthly hydrological regime of the river (Torabi & Klve 2013; Liu *et al.* 2016).

The time impact factor T_{I_F} mainly considers the change in the time of appearance of the maximum, minimum, and median values and is calculated as shown below:

$$T_{IF} = (50 - 0.274 \times T_F)/100 \tag{8}$$

$$T_F = \frac{|DT_{Max}| + |DT_{Min}| + |DT_{Median}|}{3} \tag{9}$$

where: T_F is the time-invariant index; DT_{Max} is the amount of change in the time of appearance of the maximum value; DT_{Min} is the change of minimum value appearance time; DT_{Median} is the change of median value occurrence time. Considering that the median occurrence time selection is limited by the statistical method of hydrological data, this study streamlines Equation (9) by removing DT_{Median} as a parameter in the original method, i.e., the modified formula for calculating the time variable index is.

$$T_F = \frac{|DT_{Max}| + |DT_{Min}|}{2} \tag{10}$$

where RI of 0.75~1 is low change, 0.5~0.75 is moderate change, 0.25~0.5 is a high chance, and 0~0.25 is severe change (Haghighi *et al.* 2014).

2.3.5. Cumulative volume slope rate of change

This method was proposed by Wang *et al.* (2012), which can be used to quantitatively assess the degree of contribution of climate change and human activities to river sedimentation. The method assumes that the slope of the cumulative curve of precipitation and sediment load with year varies in the same multiplicative ratio if the annual change in sediment load is influenced by precipitation only. The combination of all influencing factors of the variable is defined as 1, and the degree of their influence on the variable is deduced from the ratio of the cumulative slope of various influencing factors over time to the rate of change of the cumulative slope of the variable (Wang *et al.* 2015). Assuming that the cumulative sediment load changes with time at an inflection point in a certain year, the slopes of the variables before and after the inflection point are Y_{Sa} and Y_{Sb}, and the slopes of the cumulative precipitation before and after the inflection point are Y_{Pa} and Y_{Pb}, respectively.

The rate of change of accumulated sediment slope, K_S (%), is:

$$K_S = \frac{Y_{sa} - Y_{sb}}{Y_{sa}} \times 100 \tag{11}$$

The rate of change of cumulative precipitation slope, K_P (%), was:

$$K_P = \frac{Y_{Pa} - Y_{Pb}}{Y_{Pa}} \times 100 \tag{12}$$

Then the contribution of climate change to sediment change, C_P (%), is expressed as:

$$C_P = |K_P/K_S| \times 100 \tag{13}$$

And the contribution of human activities to sediment change C_H (%) is:

$$C_H = 100 - C_P \tag{14}$$

It should be noted that climate change mainly includes precipitation, evapotranspiration, temperature, and groundwater in the basin (Wang *et al.* 2012; Zhao *et al.* 2015). However, the influence of evapotranspiration on sediment load is relatively small, and it is difficult to obtain evapotranspiration data; the influence of temperature on river sediment load is not obvious, and the change of groundwater is mainly reflected in intra-annual distribution, and the influence on inter-annual variation is negligible (Wang *et al.* 2019), so the climate change in this study is mainly attributed to the change of precipitation, and the influence of climate change on river sediment situation is studied by analyzing the relationship between precipitation and sediment load.

3. RESULTS

3.1. Intra-annual and inter-annual distribution characteristics of sediment

Figure 2 shows the intra-annual distribution of sediment load in the upper reaches of the Yangtze River. From the information in the figure, it can be seen that the intra-annual distribution of the multi-year monthly average sediment load at the three

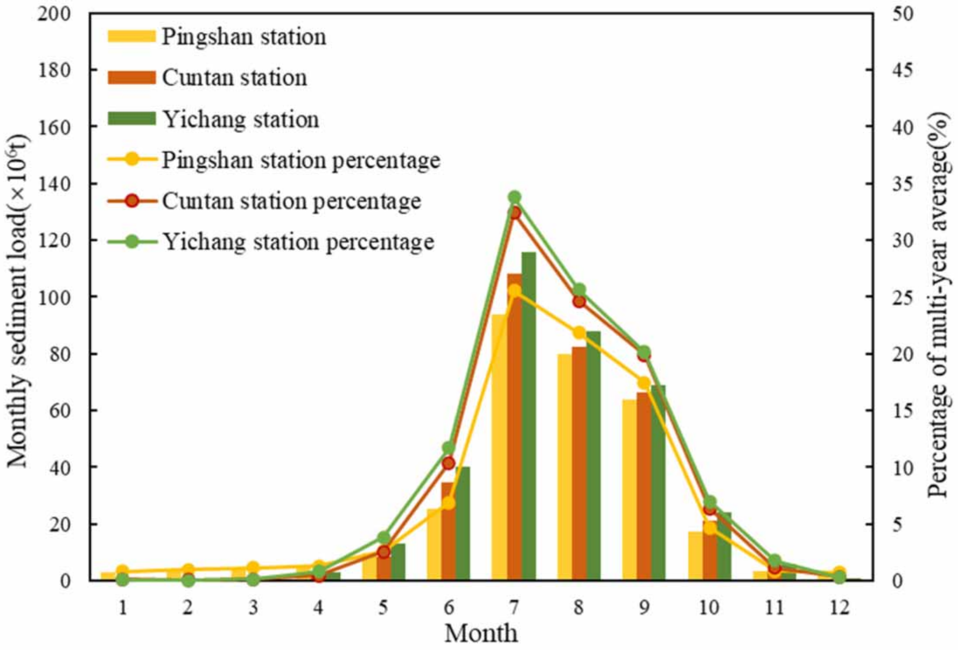

Figure 2 | Intra-year distribution of sediment load in the upper Yangtze River.

stations of the upper Yangtze River mainstem from 1965 to 2019, Ping Shan, Cuntan, and Yichang, is basically the same, and May to October of the mainstem flood season is the concentrated period of sediment production, and the total sediment load at the three stations of Ping Shan, Cuntan and Yichang from May to October accounts for 93, 98, and 97% of the multi-year average sediment load at each station, respectively. It can be seen that the intra-annual distribution of sediment in the upper Yangtze River is influenced by precipitation, and the intra-annual distribution of sediment load is basically matched with precipitation, which is more concentrated in the flood season (May-October) (Liu *et al.* 2021).

The inter-annual process of sediment load at each major hydrological station in the upper reaches of the Yangtze River is shown in Table 2, and it can be seen that the inter-annual variation of sediment is large. In the 1990s, with the successive construction of large and medium-sized reservoirs in the upper reaches of the Yangtze River, the effect of reservoirs in intercepting sand was gradually obvious (Xu & Dong 2012). Compared with the pre-1990s, the annual sediment load at the Pingshan, Cuntan, and Yichang stations has decreased significantly, with the average annual sediment load at the Yichang station decreasing from 5.33×10^8 t per year before 1990 to 1.31×10^8 t per year in the 2000 s, and the average annual sediment load from 2011 to 2019 has been less than $2{,}000\times10^4$ t, indicating that reservoir storage in the upper Yangtze tributaries has a significant impact on the sediment load of the Yangtze River, especially after the 2000s.

3.2. Trend and mutation analysis

To reveal the multi-year sediment variation trend in the upper Yangtze River mainstream, we plotted the annual sediment load variation curve at each hydrological station (Figure 3). As can be seen from Figure 3, there is no obvious trend in the multi-year sediment transport at the Ping Shan station, while the multi-year sediment transport at the rest of the hydrological stations shows an obvious decreasing trend during the study period. It mainly shows no obvious trend change before the 1990s, a certain decreasing trend from 1990 to the 2000s, and an obvious decreasing trend after 2000s. Among them, Yichang station has the most significant trend of sediment transport reduction, and this change is analyzed to be related to climate change and human activities, and a large amount of sediment retained by the Three Gorges impoundment in 2003 is one of the important reasons for the significant reduction of sediment transport in Yichang station (Ma *et al.* 2008). We used Mann-Kendall non-parametric test and t-test to test the trend and mutation of sediment at each hydrological station in the upper Yangtze River mainstream (Table 3), and the results showed that the Z_c of M-K trend test were -4.21, -5.33, and -6.65 at Pingshan, Cuntan, and Yichang stations, respectively, and their absolute values were greater than 2.58, indicating that the sediment amount in the upper Yangtze River was on a significant downward trend. M-K mutation test in 1997, 2003, 2002, and the t-test value is greater than 0.05 t_α, that is, each hydrological station in these years shows a mutation in the amount of sediment load. Among them, the Ertan Reservoir built in the tributary of Jinsha River in 1998 has a storage capacity of 20×10^8 m^3, which has a great impact on the sediment load of Jinsha River Control Station-Pingshan Station; The impoundment of the Three Gorges Reservoir shows that the impoundment of the Three Gorges will have an important impact on the sediment load at Cuntan Station before entering the reservoir and the change in the sediment load at Yichang Station after leaving the reservoir (Chi *et al.* 2020).

3.3. Sediment periodic analysis

Morlet wavelet analysis of annual sediment load at three hydrological stations in the upper Yangtze River was used to plot contour plots of the real part of wavelet coefficients (Figures 4(a)–6(a)) and variance plots (Figures 4(b)–6(b)), which represent

Table 2 | Interannual distribution characteristics of sediment load in the upper Yangtze river

	Sediment load ($\times10^8$ t)			
Period	**Pingshan**	**Cuntan**	**Yichang**	**Precipitation ($\times10^3$ mm)**
1965–1970	2.89	4.89	5.81	1.03
1971–1980	2.21	3.77	4.75	1.00
1981–1990	2.57	4.76	5.49	1.03
1991–2000	2.97	3.61	4.20	0.99
2001–2010	1.78	2.15	1.31	0.97
2010–2019	0.22	0.97	0.20	1.00

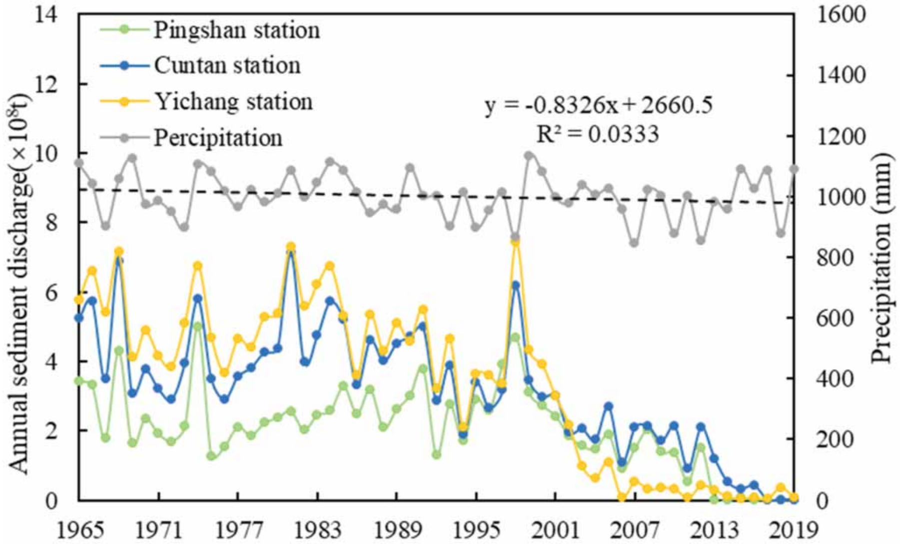

Figure 3 | Sediment changes in the upper reaches of the Yangtze River from 1956 to 2019.

Table 3 | Trend and mutation test results of annual sediment load in the upper Yangtze River

Hydrological elements		**Pingshan**	**Cuntan**	**Yichang**
Sediment load	Z_c	−4.21	−5.33	−6.65
	Test discrimination	$\lvert Z_c\rvert > 2.58$	$\lvert Z_c\rvert > 2.58$	$\lvert Z_c\rvert > 2.58$
	Trends	Significant reduction	Significant reduction	Significant reduction
	Mutation year	1997	2003	2002
	Mutation point statistic t-value	2.5	7.3	14.41
	Mutation discrimination	$t > t_\alpha$	$t > t_\alpha$	$t > t_\alpha$

Note: Z_c is the M-K trend test statistic; t is the value of the t-test statistic; t_α is the value of the t-test at the significance level of 0.05 with a value of 2.032.

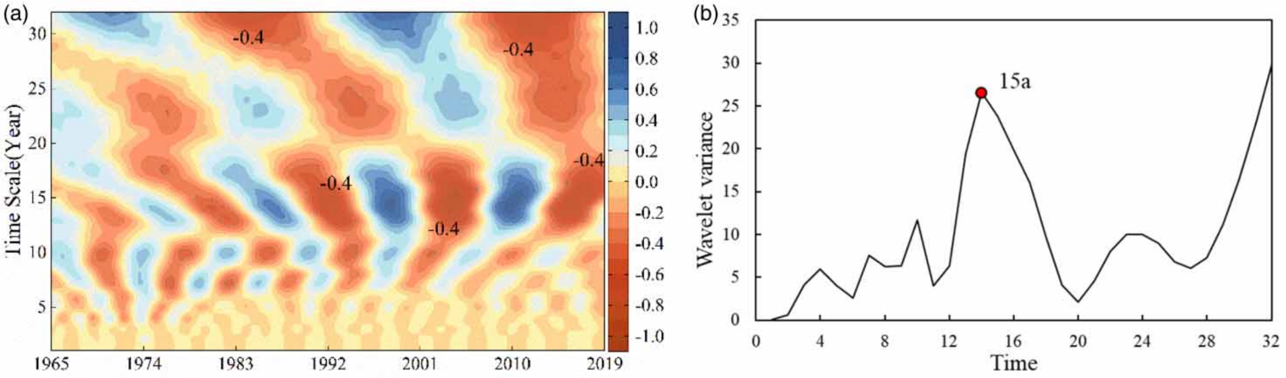

Figure 4 | Wavelet isogram (a) and wavelet variance map (b) of sediment load at Pingshan station.

the magnitude of periodic fluctuations in the time series. The sediment series of the upper Yangtze River include several different periods, and the sediment series of these three stations show significant interannual variability.

The results show that there are four-cycle scales for the Ping Shan and Cuntan stations and three cycle scales for the Yichang station (Figures 4–6). Among them, the wavelet variance at Pingshan station has 2 obvious peaks, and the largest peak is consistent with the 15-year time scale, i.e., the strongest cycle oscillation around 15 years, which is the first main

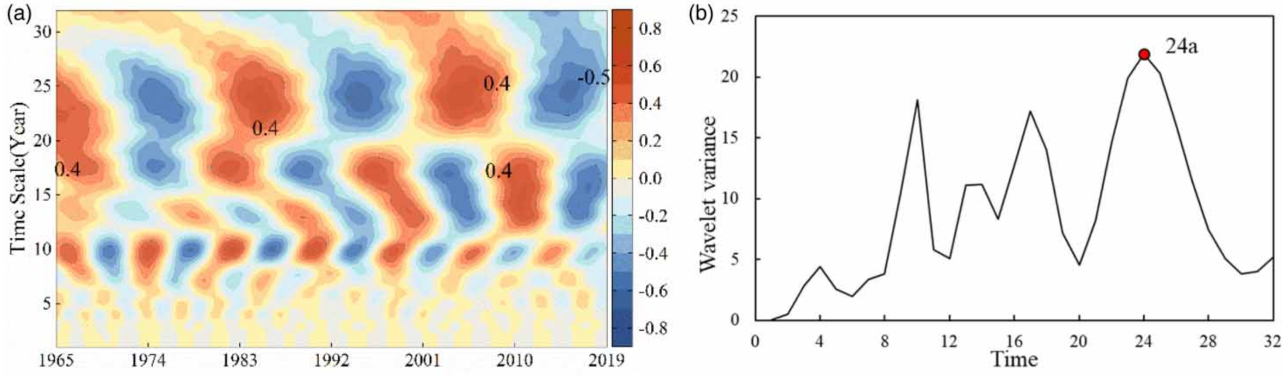

Figure 5 | Wavelet isogram (a) and wavelet variance map (b) of sediment load at Cuntan station.

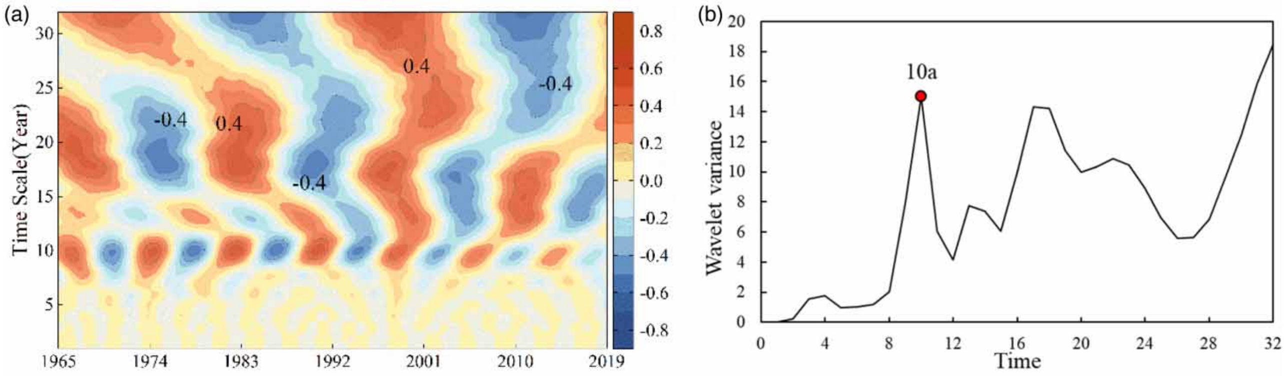

Figure 6 | Wavelet isogram (a) and wavelet variance map (b) of sediment load at Yichang station.

cycle of sediment load variation at Pingshan station (Figure 4(b)). The Cuntan station has the most obvious oscillation around 24 years on the scale of 5 cycles, i.e., 24 years is the first major cycle of Cuntan station (Figure 5(b)). Yichang station, on the other hand, has 10 years as the major cycle among the three major variance peaks (Figure 6(b)). The reason for the multi-scale cycle variation of sediment load in the upper Yangtze River is related to the storage of upstream reservoirs. Among them, the presence of smaller-scale cycle variations at the Pingshan and Yichang stations is associated with the frequent construction of large reservoirs in the Jinsha and Yangtze River mainstems after 2000, while the Cuntan station is associated with the concentrated construction of large reservoirs in the Jialing River in the 1980 s (Xu & Dong 2012).

3.4. Analysis of sediment change phases

Figure 7 shows the sediment accumulation curve. When the cumulative curve turns significantly at a certain point, it indicates that the mud-sand properties have changed. According to the analysis of the figure, it can be concluded that the three stations in the upper reaches of the Yangtze River were all deflected to different degrees in the 1990 and 2000s. The two deflections indicate that due to the influence of human activities such as the Baozhusi Reservoir and Wujiangdu Reservoir built in the 1990s, and the water and soil conservation measures carried out in the Yangtze River Basin, the amount of sediment load has continued to decrease significantly. Large reservoirs such as Tantan, Caojie, and the Three Gorges further affect the sediment load (Li & Zhang 2015). In addition, the sediment load at Pingshan station was deflected again around 2013, which is presumed to be related to further sediment interception by large reservoirs such as Xiluodu, Guanyingyan, Jinping levels, and Xiangjiaba built successively in the Jinsha River basin in the 2010s (Yang *et al.* 2018). According to the above staged analysis and mutation test results, the long-term sediment sequence of each hydrological station is divided into stages, and T_a is the first stage of sediment change, T_b is the second stage of sediment change, and T_c is the first stage of sediment change. There are three stages, and the classification results are shown in Table 4. According to the division results of annual sediment load,

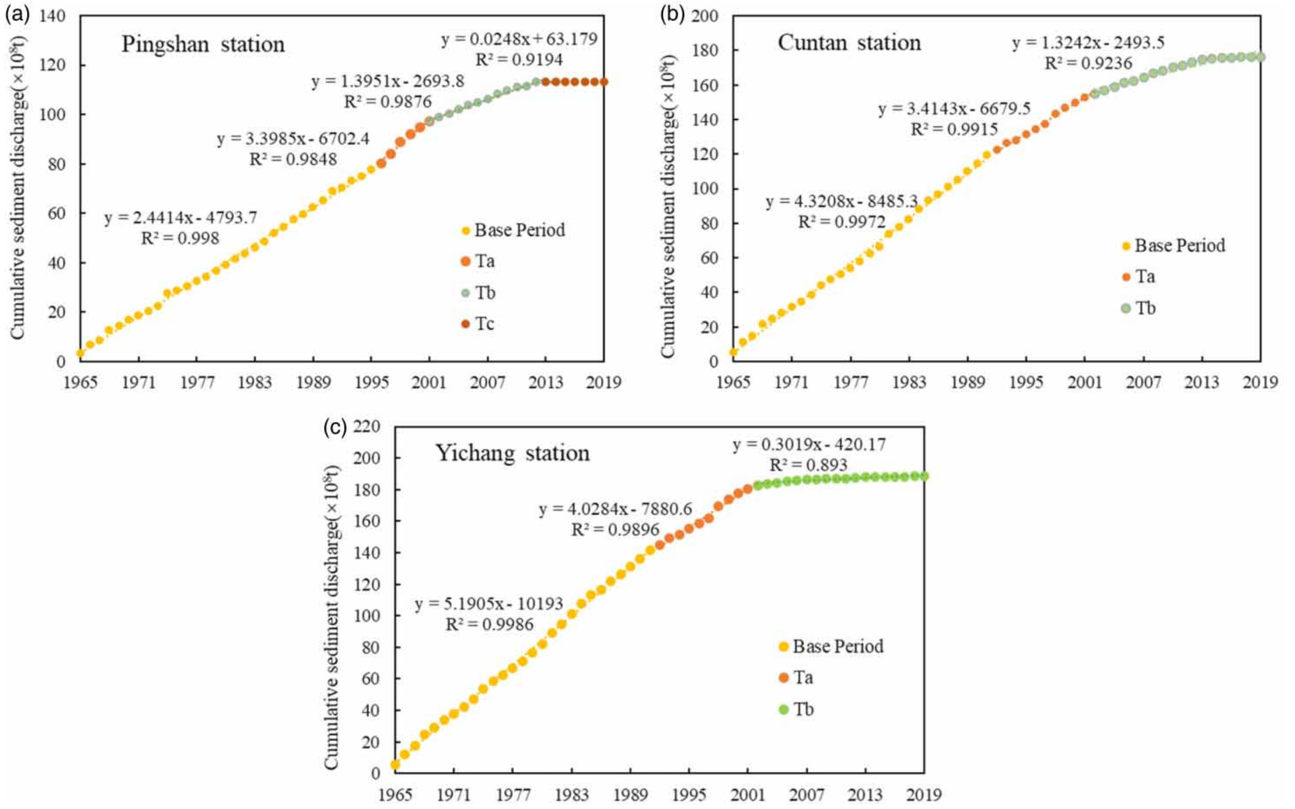

Figure 7 | Variation of cumulative sediment discharge in the upper reaches of Yangtze River.

Table 4 | Classification of sediment stages at each hydrological station in the upper Yangtze river

Hydrological stations	Period	Base Period	T_a	T_b	T_c
Pingshan	1965–2019	1965–1996	1997–2001	2002–2013	2014–2019
Cuntan	1965–2019	1965–1991	1992–2002	2003–2019	–
Yichang	1965–2019	1965–1991	1992–2002	2003–2019	–

Note: T_a is the first stage of sediment change, T_b is the second stage of sediment change, and T_c is the third stage of sediment change.

combined with the precipitation in different stages, we use the cumulative slope change rate method to quantitatively evaluate the sediment changes in the Yangtze River due to climate change and human activities.

3.5. Evaluation of sediment alteration degree

The RI method was used to quantitatively study the change of sediment load at each hydrological station in the upper reaches of the Yangtze River, and the results of each RI index are shown in Table 5 and Figure 8. The change of sediment load at different stages was obvious, and each hydrological station showed a similar pattern, that is, the values of M_{IF}, V_{IF}, T_{IF}, and RI were decreasing and the change was increasing. In the T_a stage, M_{IF} values are close to 0.7, V_{IF} values are close to 0.48, T_{IF} values are 0.3~0.5, that is, soil and water conservation measures and reservoir construction in this stage mainly affect the extreme values and intra-annual changes of sediment load, and finally the RI values of Ping Shan, Cuntan the and Yichang stations are 0.74, 0.7, and 0.65 respectively, which are all in moderate change; compared with the T_a stage, M_{IF} decreases significantly in T_b stage Compared with the $T_a$stage, the M_{IF} in the T_b stage decreases significantly to 0.07 at the Yichang station, i.e., the impoundment of the Three Gorges Reservoir built in 2003 mainly affects the intra-annual changes, and the final RI values at the Pingshan, Cuntan, and Yichang stations are 0.53, 0.31, and 0.04, respectively, with

Table 5 | Change degree of sediment discharge in the upper reaches of Yangtze River by RI method

Hydrological stations	Period	M_{IF}	T_{IF}	V_{IF}	RI	Degree
Pingshan	T_a	0.73	0.5	0.49	0.74	Moderate
	T_b	0.59	0.46	0.44	0.53	Moderate
	T_c	0.15	0.27	0.36	0.09	Serious
Cuntan	T_a	0.73	0.47	0.48	0.7	Moderate
	T_b	0.34	0.49	0.43	0.31	Height
Yichang	T_a	0.71	0.31	0.48	0.65	Moderate
	T_b	0.07	0.43	0.08	0.04	Height

Note: T_a is the first stage of sediment change, T_b is the second stage of sediment change, T_c is the third stage of sediment change; M_{IF} is Magnitude Impact Factor, T_{IF} is Timing Impact Factor, and V_{IF} is Variation Impact Factor; RI is the river impact index.

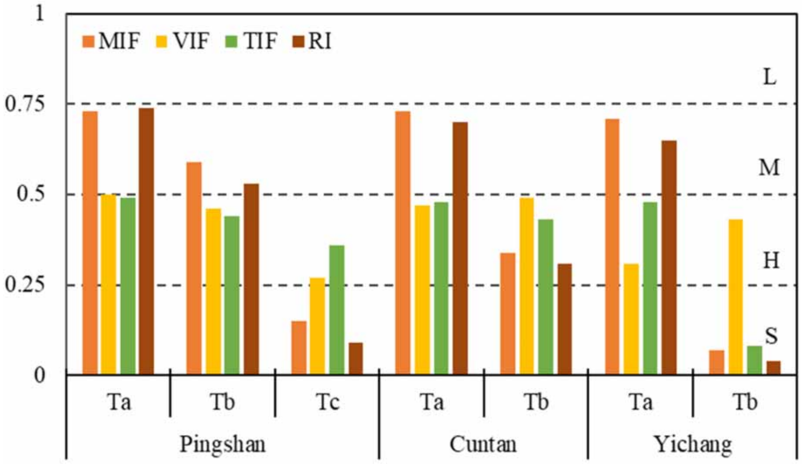

Figure 8 | Degree of sediment variation in the upper Yangtze River (S is severe alternation; H is high alternation; M is moderate alternation; L is low alternation).

moderate changes at Pingshan, high changes at Cuntan, and severe changes at Yichang; both the M_{IF} and RI values at the Pingshan station are in severe changes in the T_c stage, indicating that the Jinsha River was further changed in 2010. The large reservoirs built before and after 2010 further deepened the extreme change of sediment load and the change of intra-annual distribution. It can be seen that the sediment variation has changed to a large extent in the inter- and intra-annual distributions, respectively.

To sum up, the sediment load at Pingshan station is influenced by the Jinsha River basin reservoir group, and the large reservoirs such as Xiluodu, Xiangjiaba, and Guanyingyan, which were built one after another in the 2010s, have further influenced the extreme value and intra-annual distribution of its sediment load, resulting in a serious change in sediment load (Guo *et al.* 2020); the sediment load at Cuntan station is influenced by the Minjiang River Zipingpu, Jialing River Baozhuji, Tingzikou, etc., which were built one after another in the 1980s, resulting in medium and high changes (Guo *et al.* 2020); while the sediment load at Yichang station is mainly influenced by the group of graded reservoirs in the upper watershed, resulting in high changes, even after the completion of the Three Gorges Reservoir in 2003 (Guo *et al.* 2020).

3.6. Quantitative evaluation of sediment change influence factors

In this study, assuming that the change of sediment load is only influenced by precipitation, the contribution of climate change and human activities to the change of sediment load in the upper Yangtze River main stream is calculated by the rate of change of cumulative volume slope, and the results are shown in Figure 9 and Table 6. The change of sediment load is mainly related to the reservoir storage and sediment interception, in addition, the change of precipitation is inseparable from the change of sediment load. When there is too much precipitation, it will lead to damage to dams with lower standards and prompt changes in water and sand volume. At the same time, changes in extreme weather such as heavy

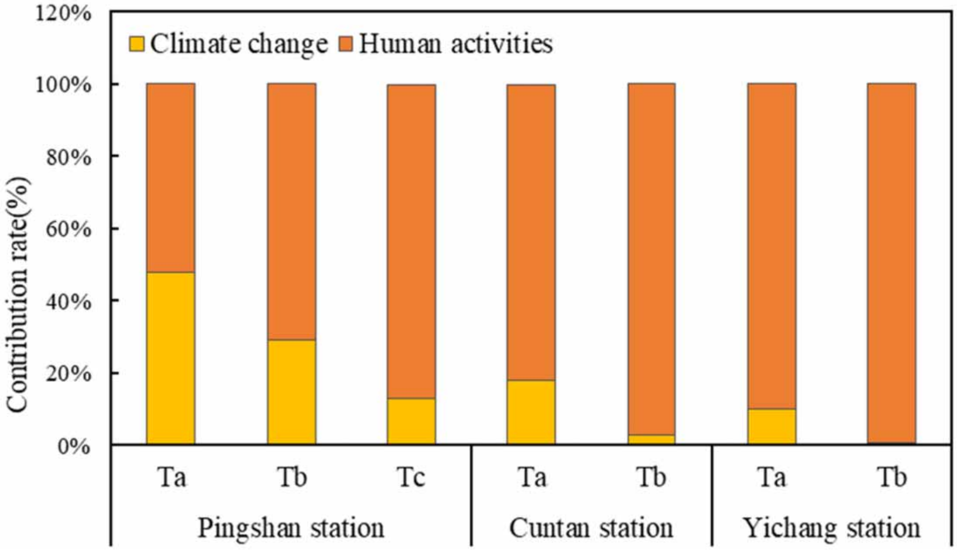

Figure 9 | Effects of precipitation and human activities on sediment changes in the upper Yangtze River.

Table 6 | Contribution of precipitation and human activities to changes in sediment load

Period	**Station**	**sediment load (Y_S)**	**Precipitation (Y_P)**	**Climate (C_P)**	**Humanity (C_H)**
Base period	Pingshan	2.44	840.23	–	–
T_a		3.17	992.68	60.65%	39.35%
T_b		1.42	803.63	10.42%	89.58%
T_c		13.88	885.95	1.16%	98.84%
Base period	Cuntan	4.32	923.48	–	–
T_a		3.41	888.26	18.11%	81.89%
T_b		1.55	886.02	6.33%	93.67%
Base period	Yichang	5.26	1,020.4	–	–
T_a		4.03	998.5	9.17%	90.82%
T_b		0.32	966.12	5.66%	94.34%

rainfall and very heavy rainfall also have a greater impact on sediment entry into the river (Wang *et al.* 2021). According to Table 6, a comprehensive analysis shows that the human contribution rate of different hydrological stations has been increasing in different periods, and the human contribution rates of Cuntan station in the T_a and T_b stages all exceed 80%; the precipitation in the T_a stage of Pingshan station has a greater influence on water and sand, while Human activities are gradually obvious with the completion of Ertan, Xiluodu, and Xiangjiaba reservoirs; Yichang station, as the control hydrological station in the upper reaches of the Yangtze River. Human contributions all exceeded 90%, indicating that human activities in the upper reaches of the Yangtze River have a significant and increasingly important influence on the change of sediment load. The factors of human activities that affect the significant decrease of sediment load in the Yangtze River mainstream mainly include a combination of reservoir storage and sand retention, river sand mining and soil and water conservation measures, and this study focuses on the effects of reservoir storage and sand retention, river sand mining, and soil and water conservation measures on the annual sediment load in the Yangtze River basin (Ban *et al.* 2014).

4. DISCUSSION

4.1. Analysis of influencing factors of sediment change

Sediment change has always been an important issue in the management and development of the Yangtze River (Wang *et al.* 2013). In this study, we used hydrological methods to examine the interannual and intraannual distribution of sediment loads in the upper reaches of the Yangtze River and quantitatively assess the contribution of climate change and human activities to its variability, the results further supporting the view of Guo *et al.* (2020). At the same time, we quantitatively assessed the degree of sediment variability in the upper reaches of the Yangtze River, which will provide a reference for assessing the health of the Yangtze River.

The factors affecting the significant decrease of sediment load in the Yangtze River mainstream include a combination of reservoir storage and sediment retention, river sand mining, and soil conservation measures (Guo *et al.* 2021). This study focuses on the effects of reservoirs, sand storage, sand mining in rivers, and soil conservation measures on annual sand transport in the Yangtze River basin. Yang *et al.* analyzed that 60% of the reduction in sediment volume at Yichang Station since the mid-1980s was due to the construction of hydraulic projects, while 65% of the total sediment volume reduction since 2003 was due to the Three Gorges Dam (Yang *et al.* 2018). The construction time of tributary reservoirs in the upper reaches of the Yangtze River was mainly concentrated in the 1970s, 1990s, and 2000s. For example, Gongzui Reservoir was built on the Minjiang River in the 1970s, Ertan Reservoir was built on the Jinsha River in the 1990s, and Three Gorges Dam was built on the mainstream of the Yangtze River in the 2000s (Wang *et al.* 2013). The water and sediment retention effect of these water conservancy projects after the operation will lead to the decrease of sediment in the upper Yangtze River, so the sediment in the upper Yangtze River is mostly concentrated during these periods (Figure 7).

Most of the sand mining in the upper reaches of the Yangtze River began in the late 1970s. With the rapid development of the economic level of both sides of the Yangtze River, the demand for sand for construction is increasing (Wang & Jiang 2015). Since the 1990s, sediment mining in the Yangtze River has become more and more serious. Sand mining in the upper reaches of the Yangtze River is mainly concentrated in the Yibin, Luzhou, and Chongqing reaches (Wang *et al.* 2014a, 2014b). According to statistics, the total amount of sand mining in Chongqing reaches 9.1 million tons in 2004 (Wu 2006). The impact of sand transport is mainly reflected in the reduction of the amount of sediment transport.

Soil and water conservation projects are one of the main reasons for the reduction of sediment transport in rivers (Wang & Zhou 2018). Among them, the earliest soil and water conservation project in the Yangtze River basin started in 1989, and after the implementation of this important soil and water conservation project, the area of soil erosion in the 'four major areas' (the lower reaches of the Jinsha River, the middle and lower reaches of the Jialing River, the Shaanxi area, and the Three Gorges Reservoir area), where soil erosion is most serious in the upper reaches of the Yangtze River, has been reduced to different degrees (Liao *et al.* 2010). In summary, under the combined influence of human activities, the sediment load of the upper Yangtze River has been significantly reduced.

4.2. Effects of sediment change

The reduction of river sediment has an important impact on the changes in hydrology and geomorphology, which in turn has serious damage to the stability of the river ecosystem. After analyzing the changes of sediment volume in the upper reaches of the Yangtze River, we found that in the 1990s and around 2000, the sediment volume dropped sharply, and the degree of decline reached a high degree of change. In this context, the amount of sediment in the main stream of the middle and lower reaches of the Yangtze River has changed from the original depositional state to the erosion state along both banks of the river, and the consequence of the erosion and scour of the riverbank is the collapse of the riverbank (Han *et al.* 2017). According to the investigation of CWRC (2003–2017), there were more than 920 stages of the collapse of different degrees in the middle and lower reaches of the Yangtze River, and the collapsed length exceeded 693 km (CWRC 2003–2017).

In addition, the reduction of sediment will change the water ecological environment in the river, which will have a greater impact on the habitat environment of aquatic organisms. Carric *et al.* have shown that river sediment content and dissolved oxygen concentration are important factors for fish death (Garric *et al.* 1990). According to the 'Three Gorges Project Ecological and Environmental Monitoring Bulletin', the number of the four major fish and Chinese sturgeon in the middle reaches of the Yangtze River has decreased year by year, and the spawning scale has become smaller and smaller (Zhang *et al.* 2020). Especially after the impoundment of the Three Gorges Reservoir in 2003, the four major domestic carp and their breeding scale decreased significantly, while the number of Chinese sturgeon breeding populations was less than 250, and less than 100 after 2014 (Zhang *et al.* 2016). Therefore, in the following research, it is necessary to further analyze the relationship between sediment changes in the upper reaches of the Yangtze River and fish reproductive response.

5. CONCLUSIONS

(1) The annual sediment load in the mainstream of the upper Yangtze River is decreasing, and the decreasing trend is more obvious; the main period of annual sediment load changes in the Pingshan, Cuntan, and Yichang stations are 15 years,

24 years, and 10 years respectively; the abrupt change points of annual sediment discharge at Pingshan station, Cuntan station, and Yichang station are 1997, 2003, and 2002 respectively. In general, the abrupt change time of sediment was concentrated in the late 1990s and before and after the operation of the Three Gorges Dam.

(2) The annual sediment transport changes at each hydrological station in the upper Yangtze River are dominated by human activities. The contribution rate of human activities after the 1990s is more than 80%, and that of human activities after the 21st century is more than 90%.

(3) The RI values of Pingshan station, Cuntan station, and Yichang station before and after the completion of the Three Gorges Dam in the 1990s were 0.74, 0.7, and 0.65, respectively, which were in moderate change. After the operation of the Three Gorges Reservoir, the RI value of the Cuntan station was 0.31, which was a high chance. The RI values of the Pingshan station and Yichang station were 0.09 and 0.04, respectively, which were in serious change. It shows that the sediment change in the upper reaches of the Yangtze River is gradually serious.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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