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Temporal variations and influencing factors of river runoff and sediment regimes in the Yangtze River, China

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ABSTRACT

The Yangtze River is the largest river in China. Based on data from the Cuntan, Yichang, Hankou, and Datong hydrological stations, the temporal variations and influencing factors of river runoff and sediment regimes were examined in the Yangtze River basin over the past 60 years. The Mann-Kendall nonparametric test, Morlet wavelet method, and double cumulative curve were employed to analyze the long-term runoff and sediment data measured at the four hydrological stations. The results indicated that the annual variations in flow discharge were relatively stable and that the sediment load showed a significantly decreasing trend at a 99% confidence level at the four hydrological stations. The annual runoff and sediment load exhibited an abrupt change in 1992 and 2003. The effect of an abrupt change in monthly runoff and sediment load in the flood season is obvious. The first, second, third and fourth dominant periodicities of the runoff were 13, 26, 5 and 8 years at the Cuntan and Hankou stations, and the first three dominant periodicities of the runoff were 26, 12, 5 years at the Yichang and Datong stations, whereas the first three dominant periodicities of the sediment load were 26, 13, and 5 years. The relationship between water and sediment changed in different stages under the influence of human activities. A significant reduction in the annual sediment load has mainly been attributed to reservoir impoundment and sediment retention over the past six decades. The results of the study will provide a reference for promoting effective watershed management and sustainability in the Yangtze River basin.

Keywords: Runoff; Sediment load; Temporal variation; Human activities; Yangtze River

1. Introduction

Rivers are the major pathways of runoff, sediment load, and other terrestrial materials from headwaters into the sea [1–3]. The runoff and sediment are the fundamental drivers of river conditions, affecting water quality, thermal regime, habitat and aquatic communities, river stability, and natural hazards [4]. During the past century, global rivers have been seriously impacted by climate change and human activities [3,5,6]. In particular, human activities, such as damming, water diversion, land-use change, and agricultural irrigation, have significantly altered the flow and sediment regimes of rivers around the world [7,8]. Rivers such as the Nile River in Egypt, the Mississippi River in America, the Indus River in India, and the Yangtze River, Yellow River and Pearl River in China have experienced changes in the flow and sediment regimes due to human activities [9–12]. Therefore, a better understanding of flow and sediment regime variations and their potential effects is crucial for the environmental management of river systems [4,13]. As the largest and longest river in China, the Yangtze River supplies fresh water for approximately 400 million people,

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accounting for approximately 6.6% of the world's population. With the exploitation and development of the Yangtze River, more than 50,000 water reservoirs have been constructed, especially the impoundment of the Three Gorges reservoir. The runoff and sediment of the Yangtze River have been altered by the influences of human activities [14]. The Yangtze River has become one of the most highly impacted rivers in the world [7]. The reservoirs not only bring great economic benefits but also disrupt river continuity and unavoidably induce alterations in the flow and sediment regimes. The alterations of flow and sediment regimes have had a fundamental impact on river morphology and geomorphology and the ecosystem health and stability of the Yangtze River [15,16]. In recent decades, increasing attention has been paid to the negative effects of changes in the flow and sediment in the Yangtze River basin. At the same time, a large number of scientific documents have appeared in China, studying the impact of human activities on the water and sediment regimes of the Yangtze River. Wang et al. [17] systematically analyzed the various characteristics and the causes of flow and sediment regimes in the main tributaries in the middle and lower reaches of the Yangtze River. Dong et al. [18] have preliminarily evaluated the characteristics and variation trends in water and sediment in the mainstream of the Yangtze River. Ban et al. [19] employed the range of variability approach to quantitatively evaluate the temporal and spatial variation in water and sediment after the impoundment of the Three Gorges Reservoir. Zhang et al. [20] analyzed the impact of the Three Gorges Dam (TGD) on runoff and sediment in the middle and lower reaches of the Yangtze River, showing that TGD did not seem to exert a significant influence on streamflow occurring at three stations and that changes in streamflow can be mainly attributed to the streamflows of tributaries [20]. Zhao et al. [21] analyzed the changes in water discharge and sediment load in the main channel and tributaries of the Yangtze River, showing that the water discharge and sediment load of the Yangtze River are changing substantially under the impacts of climate change and human activities. Previous studies have documented variations in the flow and sediment regime characteristics of the Yangtze River and their influencing factors. However, few of these studies were able to discuss the variations in the relationship between flow and sediment of the whole Yangtze River basin. Also, a more detailed assessment is required on the alteration of flow and sediment regimes due to reservoir construction based on the latest hydrological data. More importantly, quantifications of the relationship between the cascade reservoir construction and the sediment load of the Yangtze River have also received little attention in previous studies.

Therefore, the objectives of this study are (a) to statistically detect trends and change-points in annual runoff and sediment discharge at four key hydrological stations along the Yangtze River mainstream; (b) to analyze the correlation between the runoff and sediment in the Yangtze River; and (c) to quantify the impacts of the cascade reservoirs construction on the sediment load reduction. The study will provide scientific guidelines for river management of the Yangtze River.

2. Study area and data

The Yangtze River is one of the most important rivers in the world. The river lies between 91–122°E and 25–35°N. The Yangtze River is the third-longest river and has the ninth largest catchment basin. The Yangtze River (Fig. 1) originates from the Qinghai-Tibetan Plateau at an elevation of 6,600 m above sea level, and it flows eastward 6,300 km through eleven provinces before discharging into the East China Sea [22]. The Yangtze River is generally considered in three sections. The upper reaches, from the headwater to Yichang, are more than 4,500 km long; the middle reaches, from Yichang to Hukou, are 950 km long; and the lower reaches, from Hukou to the river mouth about 930 km long [23]. The catchment basin covers an area of 1,808,500 km^2 and has a population of more than 400 million.

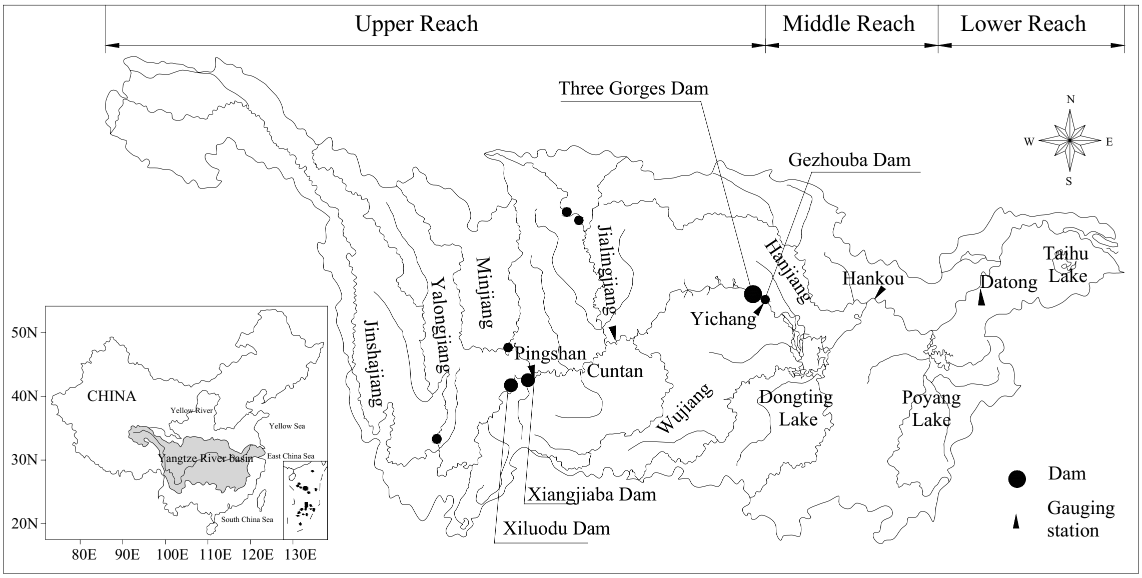


Fig. 1. Location of the study area and hydrological stations.

The characteristics of the runoff and sediment in the Yangtze River basin are different, which reflect the characteristics of the water and sediment heterogeneity [24]. The distribution of the annual average runoff and sediment load at the main hydrological stations of the Yangtze River is shown in Table 1. With the Yichang station as the boundary point between the upper and middle reaches of the Yangtze River, the upstream sediment load accounts for 108.84% of the annual sediment discharge at the Datong station. It can be seen that the sediment volume in the middle and lower reaches of the Yangtze River mainly comes from the upper reaches, and a small part of the sediment load is supplied by river channel erosion as well as tributaries and lakes, such as the Hanjiang River, the Dongting Lake, and the Poyang Lake. The upstream runoff accounts for 47.98% of the total runoff at Datong station, and the middle and lower reaches provide 52.02% of the total basin runoff. On the whole, the upper reaches of the Yangtze River are the main sources of water and sediment in the basin, and the annual runoff and annual sediment discharge show an obvious gradual increase from upstream to downstream in the Yangtze River.

To analyze the temporal variations in runoff and sediment regimes, the four major hydrological stations of Cuntan, Yichang, Hankou, and Datong along the Yangtze River were selected as case study sites (Fig. 1). The hydrological data (monthly and annual water discharge and sediment load) used in this study, which cover the period from 1954 to 2016, were measured at the Yichang, Hankou, and Datong gauging stations in the Yangtze River. The hydrological data at the Cuntan gauging station cover the period from 1965 to 2016. These data were obtained from the Changjiang Water Resources Commission, China (http://www.cjw.com.cn/). The monthly and annual sediment loads were calculated by multiplying the sediment concentrations by the water discharge.

3. Methodologies

In this study, the Mann-Kendall trend test, double cumulative curve analysis, and correlation analysis are used to understand the changes in runoff and sediment load in the Yangtze River.

3.1. Mann-Kendall trend test

The Mann-Kendall test is the rank-based nonparametric test for assessing the significance of a trend and has been widely used in hydrological trend detection studies [25–27]. The Mann-Kendall test statistic (S) is calculated as follows:

$$S = \sum_{i-1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

$$\operatorname{sgn}\theta = \begin{cases} 1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{2}$$

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

$$\operatorname{Var}\left(S\right) = \frac{n\left(n-1\right)\left(2n+5\right)}{18} \tag{3}$$

Based on S and Var, the standardized Mann-Kendall statistics Z is computed as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{Var}\left(S\right)}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{Var}\left(S\right)}} & S < 0 \end{cases} \tag{4}$$

The standardized Mann-Kendall statistic Z follows the standard normal distribution with a mean of zero and variance of one. In the test for a trend, if $\left|Z\right| > Z_{\alpha/2}$, where Z is asymptotically normally distributed and $Z_{\alpha/2}$ is the critical value of the standard normal distribution with a probability $\alpha/2$, the trend of the sequence will be significant. A positive value of Z denotes an increasing trend, and the opposite corresponds to a decreasing trend. In this paper, a significant level of $\alpha = 0.01$ is used. When $\left|Z\right| \geq 2.58$, it means that the sequence has passed the significance level test of 0.01, that is, the rising or falling trend is significant.

3.2. Double cumulative curve

The theory of the double cumulative curve is based on the fact that a plot of two cumulative quantities during the

Table 1
Distribution of the annual average runoff and sediment load in the Yangtze River

Station	Basin area		Runoff		Sediment discharge		Periods
	10^4 km^2	Proportion of Datong%	10^{11} m^3	Proportion of Datong%	10^8 t	Proportion of Datong%	
Cuntan	86.66	50.81	3.38	37.89	3.38	93.37	1965~2016
Yichang	100.55	58.96	4.28	47.98	3.94	108.84	1954~2016
Hankou	148.80	87.25	7.05	79.04	3.33	91.99	1954~2016
Datong	170.54	100.0	8.92	100	3.62	100	1954~2016

same period exhibits a straight line so long as the proportionality between the two remains unchanged, and the slop of the line represents the proportionality [28]. However, a break in the slope within a double cumulative curve indicates that a change in the constant of proportionality occurred [29,30]. In this study, double cumulative curves of runoff vs. sediment are plotted to estimate the relative effects of human activities.

3.3. Wavelet analysis

The complex Morlet wavelet was used to analyze the periodicity and variation tendency in runoff and sediment load at the four stations. The continuous wavelet transform (CWT) is defined as the sum over time of the real signal, *f*(*t*), multiplied by the scaled (stretched or compressed) shifted versions of the wavelet function, ψ(*t*) [31] as follows:

$$\psi_{a,b}(t) = |a|^{-1/2} \varphi\left(\frac{t-b}{a}\right) \quad (a,b \in R, \mathrm{a} \neq 0) \tag{5}$$

$$W_f(a,b) = |a|^{-1/2} \int_R f(t) \overline{\varphi}\left(\frac{t-b}{a}\right) dt \tag{6}$$

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

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

3.4. Correlation analysis

Correlation analysis is a statistical method to study the correlation between random variables. The correlation analysis of hydrological variables reveals the degree of closeness between different factors by calculating the correlation coefficient. The expression formula for the correlation coefficient between the two groups of random variables x_i and y_i ($i = 1,2,\ldots,n$) is defined as follows:

$$R = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2 \sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}} \tag{7}$$

where $\bar{x}$ is the average value of x_i, and $\bar{y}$ is the average value of y_i. When $|R| \geq 0.8$, it is expressed as highly correlated; when $0.5 \leq |R| < 0.8$, it is expressed as moderately correlated; when $0.3 \leq |R| < 0.5$, it is expressed as low correlated; when $|R| < 0.3$, it is expressed as extremely low correlated.

4. Results and discussion

4.1. Alternations in annual runoff and sediment load

4.1.1. Trend analysis of the runoff and sediment

The Mann-Kendall nonparametric test results of the annual runoff and sediment discharge of the hydrological stations along the Yangtze River are illustrated in Table 2. The Mann-Kendall statistics of the runoff from the Cuntan station to the Datong station are –1.03, –1.89, –0.09, and 0.31, which are all lower than the critical value 1.96 at the significance level of $\alpha = 0.05$, indicating that the annual runoff of the Yangtze River has no significant variation trend (Fig. 2). The Mann-Kendall statistics Z_c of the annual sediment discharge series at the Cuntan, Yichang, Hankou, and Datong hydrological stations are all less than 0, and the absolute values of the statistics Z_c are all above the critical value of 2.58 when the significance level of $\alpha = 0.01$. The results all passed the 99% significance test, which showed that the sediment discharge at most stations has a significant decreasing trend (Fig. 2). Therefore, the annual runoff of the Yangtze River has no significant trend, and the annual sediment discharge shows a significant decreasing trend.

4.1.2. Annual variation of runoff and sediment load

The annual runoff and sediment discharge of the main hydrological stations in the Yangtze River basin are shown in Table 3. The annual variation in the runoff is relatively stable, and the ratio of the maximum runoff to the minimum runoff at each hydrological station is 1.08~1.18, which shows a decreasing trend on the whole. However, the range of variation does not exceed 10% of the average runoff in many years. The sediment transport volume varies dramatically between years, mainly concentrated in the middle and lower reaches of the Yangtze River. With the completion of large and medium-sized reservoirs in the upper reaches of the Yangtze River in the 1990 s [32], the role of sediment retention by reservoirs becomes increasingly obvious. Compared with those before the 1990s, the annual sediment discharge at the Yichang station has been greatly reduced from 533 million tons before 1990 to 131 million tons in the 2,000 s and less than 20 million tons per year since 2011. The results show that the upstream reservoir impoundment has a significant influence on the sediment discharge

Table 2
Mann-Kendall trend test of the runoff and sediment discharge in the Yangtze River Station

	Runoff/10^{11} m^3/s			Sediment load/10^8 t		
	Z	Tr	P	Z	Tr	P
Cuntan	–1.03	↓	–	–5.33	↓	**
Yichang	–1.89	↓	–	–6.65	↓	**
Hankou	–0.09	↓	–	–6.77	↓	**
Datong	0.31	↑	–	–7.64	↓	**

Notes: Tr: trend; ↓ indicates decreasing trend; ↑ indicates increasing trend; P: confidence value; ** indicates significant trend at the 0.01 confidence level.

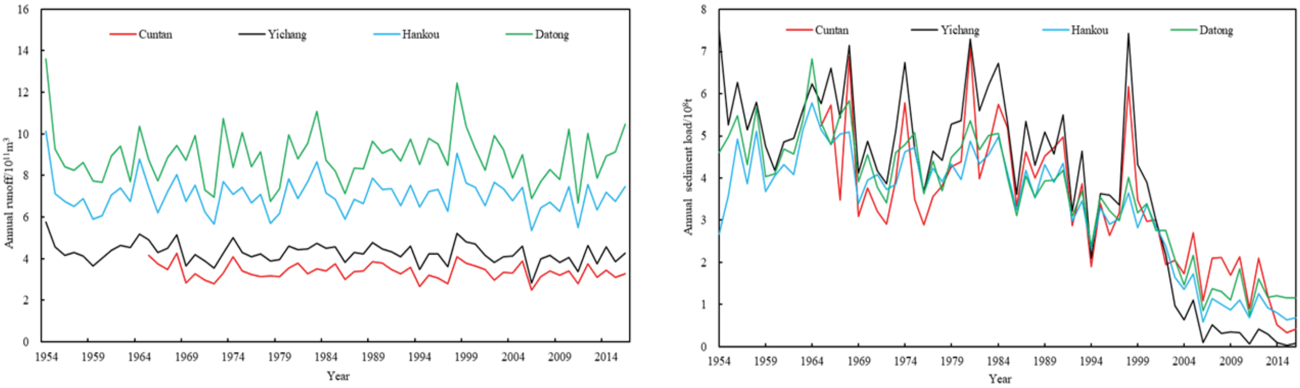


Fig. 2. Trend of the runoff and sediment load of four hydrological stations in the Yangtze River.

Table 3
Average annual runoff and sediment load in the Yangtze River

Period	Runoff/10^{11} m^3				Sediment discharge/10^8 t			
	Cuntan	Yichang	Hankou	Datong	Cuntan	Yichang	Hankou	Datong
1950 s	–	4.43	7.23	9.32	–	5.79	3.97	4.85
1960 s	3.70	4.53	7.17	8.77	4.87	5.49	4.68	5.09
1970 s	3.25	4.14	6.73	8.51	3.77	4.75	4.11	4.24
1980 s	3.49	4.45	7.24	8.99	4.76	5.49	4.21	4.35
1990 s	3.37	4.31	7.28	9.60	3.72	4.24	3.27	3.43
2000 s	3.29	4.04	6.81	8.43	2.14	1.31	1.70	1.92
2011~2016	3.27	4.08	6.90	9.05	1.09	0.19	0.87	1.27

at the Yichang station, especially after 2000, and the sediment discharge noticeably decreases. The annual variation in sediment discharge at the Hankou and Datong stations are similar to those at the Yichang station, but the decreasing range is obviously smaller than that of the Yichang station, which can be attributed to the fact that most of the sediments in the middle and lower reaches comes from the upper reaches [33].

4.1.3. Double cumulative analysis of runoff and sediment

The runoff and sediment discharge of the rivers are generally positively correlated, and the double cumulative curve of runoff and sediment transport is a straight line. If the characteristics of water and sediment change, there will be an obvious turning point in the double cumulative chart of water and sediment. That is the slope of the cumulative curve noticeably increases or decreases [34]. By analyzing the double cumulative curves of the annual runoff and the annual sediment transport at the four hydrological stations, the trend changes in water and sediment of the Yangtze River are analyzed. The double cumulative curves at the four hydrological stations in the Yangtze River are shown in Fig. 3.

It can be seen from Fig. 3 that two abrupt change-points are occurring on the double cumulative curve of runoff and sediment at the Cuntan hydrological station in the upper reaches in the Yangtze River, of which the abrupt change-points appeared in 1992 and 2003. The Cuntan hydrological station was basically in a straight line before 1992, and the slope began to decrease after 1992, which was mainly affected by the continuous development of the hydropower projects in the upper reaches of the Jialing River basin. Since the 1990 s, 20 large and medium-sized hydropower stations have been built in the Jialing River basin, with a total storage capacity of more than 4 billion m^3 [35]. The reservoir impoundments blocked a large amount of sediment, resulting in a decrease in sediment transport after the Jialing River flows into the Yangtze River. After entering the 20th century, the sediment transport capacity at the Cuntan station is further reduced with the increasing human activities along the main tributaries.

The double cumulative curves of runoff and sediment load at the Yichang, Hankou and Datong hydrological stations show obvious abrupt change-points in 1992 and 2003 (Fig. 3). The slope of the cumulative curve changed relatively smoothly after the first abrupt point in 1992. The first abrupt change is related to human activities such as soil and water conservation and water conservancy project construction in the upper reaches of the Yangtze River [36]. After the second abrupt point in 2003, the slope showed an obvious declining trend, which indicated that the Three Gorges Reservoir impoundment had an important influence on the change in sediment discharge in the middle and lower reaches of the Yangtze River over the past ten years. It can be seen from Fig. 3 that the slopes gradually weakened from the Yichang station to Datong station after

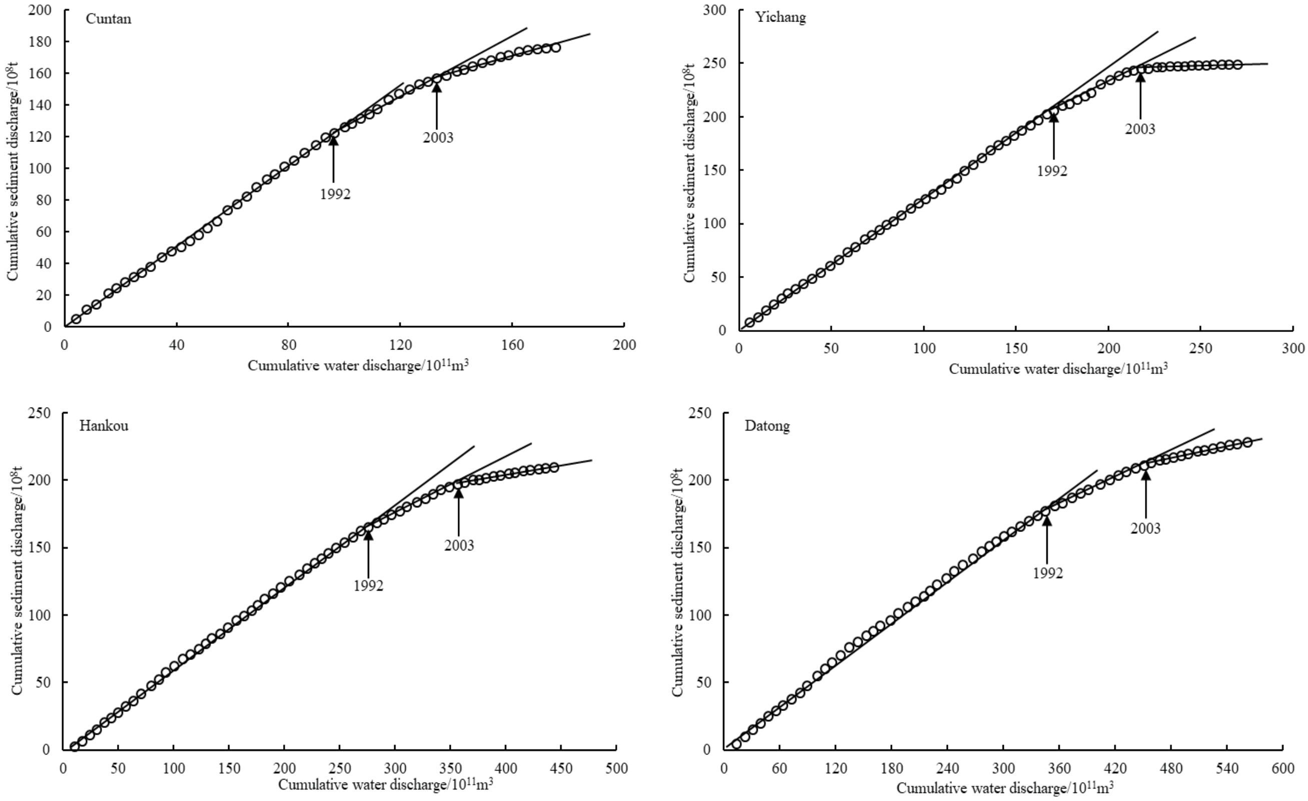


Fig. 3. Double cumulative curves of runoff and sediment load in the Yangtze River.

the abrupt point in 2003, indicating that the change in sediment discharge also decreased with distance from the Three Gorges Reservoir.

4.2. Alternations in monthly runoff and sediment

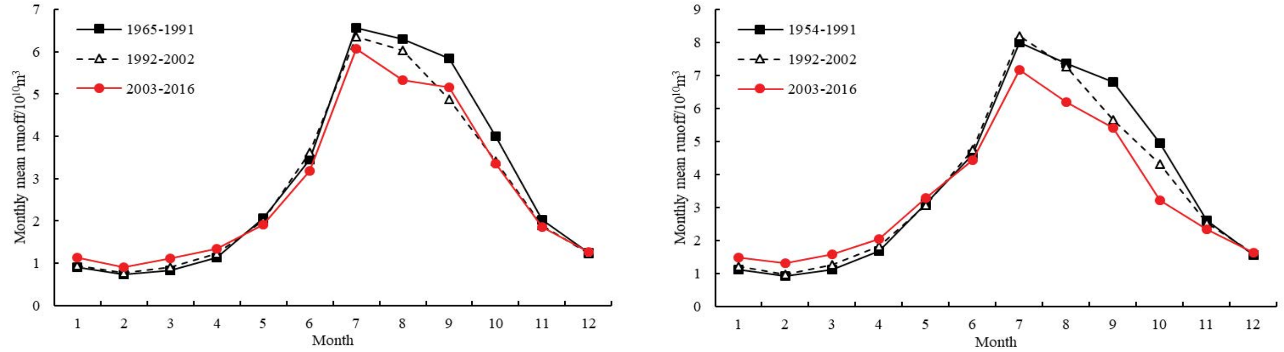
Figs. 4 and 5 illustrate the analysis of the monthly distribution of runoff and sediment load at the Cuntan, Yichang, Hankou and Datong stations. From Figs. 4 and 5, it can be seen that the runoff and sediment distribution in the Yangtze River is closely related to precipitation. The flood season of the mainstream between June and October is the concentrated period for the production of runoff and sediment. The distribution of monthly sediment discharge is matched with the runoff, but the sediment discharge is more concentrated in the flood season.

From Fig. 4 the monthly runoff changes are most obvious from August to October of the flood season at the Cuntan station from 1992 to 2002 and 2003 to 2016, both showing a decreasing trend. The monthly runoff increased from December to April is the dry season and from July to August in the flood season from 1992 to 2002 at the Yichang, Hankou and Datong stations, and the monthly runoff increased most significantly in August at the Datong station. After the impoundment of the TGD, the monthly runoff showed that the runoff decreased in the wet season and increased in the dry season at the Yichang, Hankou and Datong stations, making the annual distribution of the monthly runoff more even. At the same time, the change in the monthly runoff at the Hankou and Datong stations is not as obvious as that at the Yichang station. This is because Hankou and Datong stations are far from the TGD, and the runoff from the local subbasins played a relatively important role in the monthly runoff at the Hankou and Datong stations.

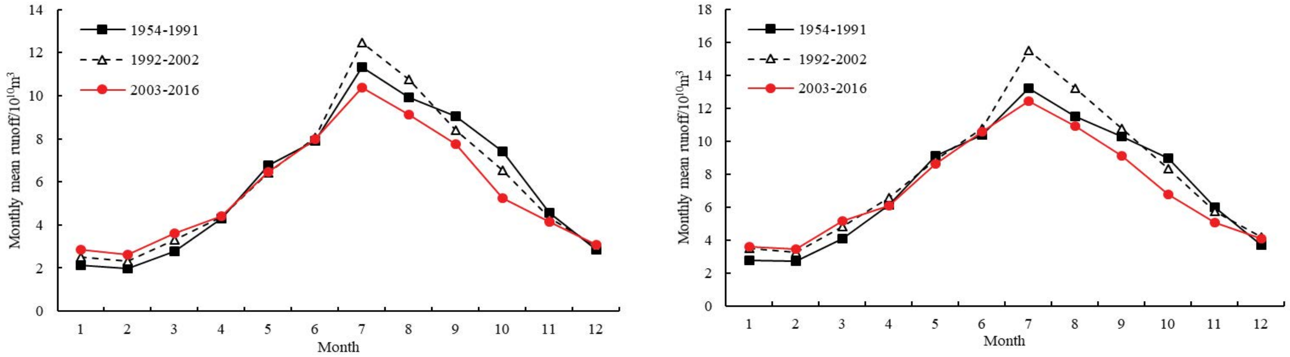
From Fig. 5, since the implementation of the water and soil conservation projects (WSCP), the monthly sediment load decreased in the Yangtze River, but the proportion of monthly sediment load has not changed significantly. After the impoundment by the TGD, the operation of the reservoir intercepts a large amount of sediment, resulting in the significant reduction of sediment load at the Yichang, Hankou and Datong stations, with the most significant reduction during the flood season from June to October. Due to the operation mode of "storing clear water and releasing turbid water", the proportion of the monthly sediment load at the Yichang station increased significantly from July to September. Because of interval storage, the proportion of the sediment load decreased in the flood season at the Hankou and Datong stations. This indicates that the operation of the reservoir has a certain influence on the reduction in sediment load and the annual distribution is also related to the distance from the reservoir.

4.3. Periodicities in the runoff and sediment load

The multiple-timescale periodicities of the runoff and sediment loads were obtained from complex Morlet wavelet analyses. The real parts of the wavelet coefficient are shown in the contour maps of Figs. 6 and 7 show a wavelet variance, indicating the magnitude of periodic fluctuation within the

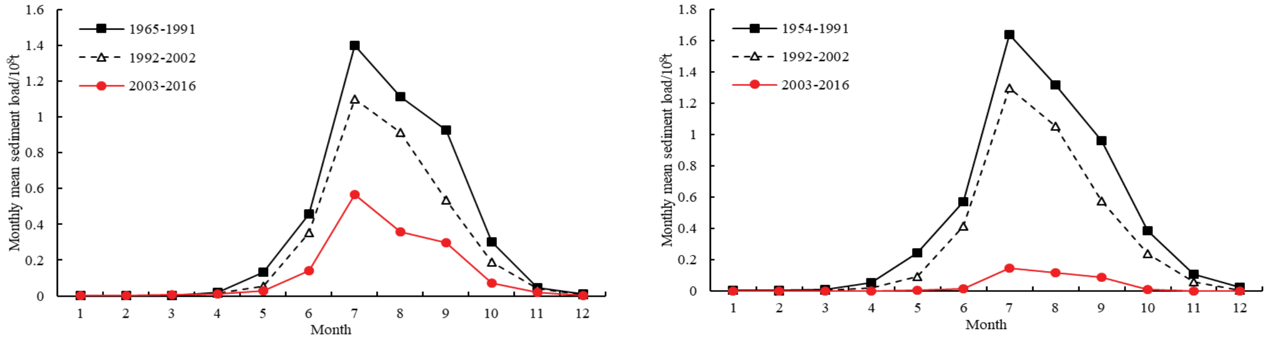


(a) Cuntan (b) Yichang

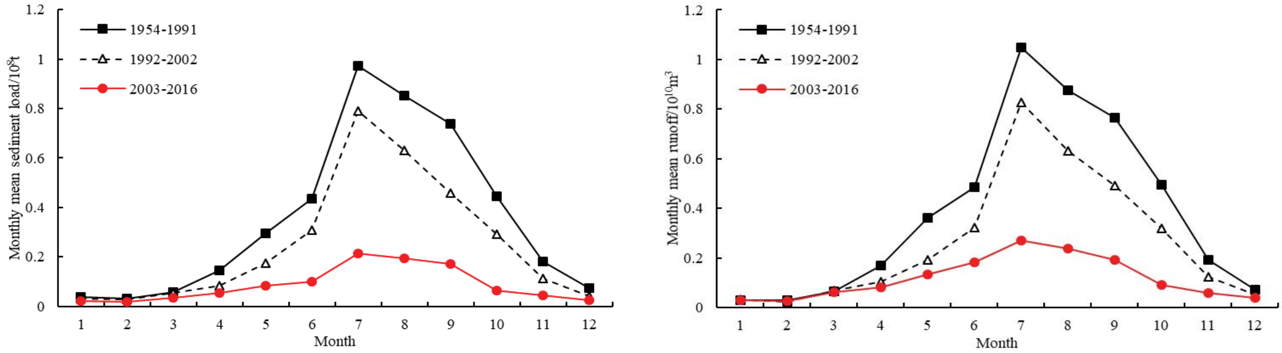


(c) Hankou (d) Datong

Fig. 4. Comparison of monthly runoff in the Yangtze River.

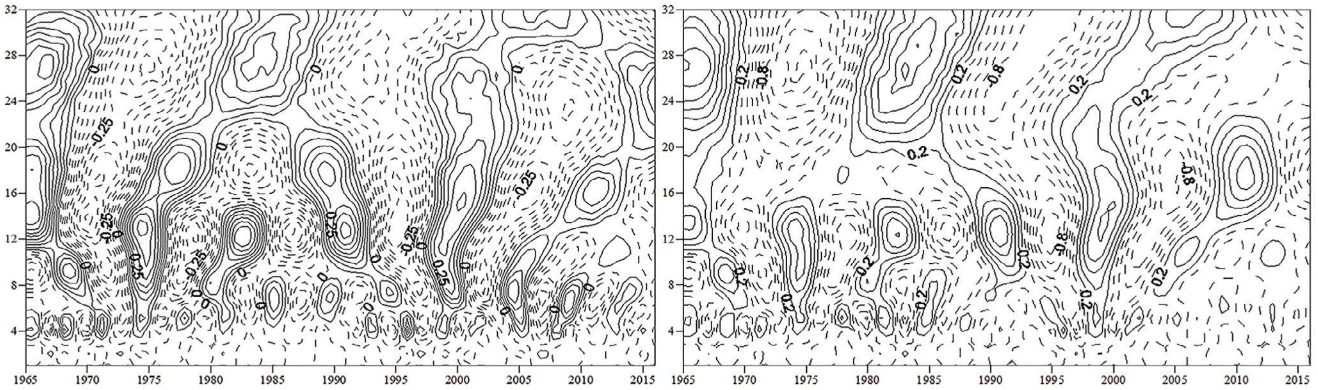


(a) Cuntan (b) Yichang

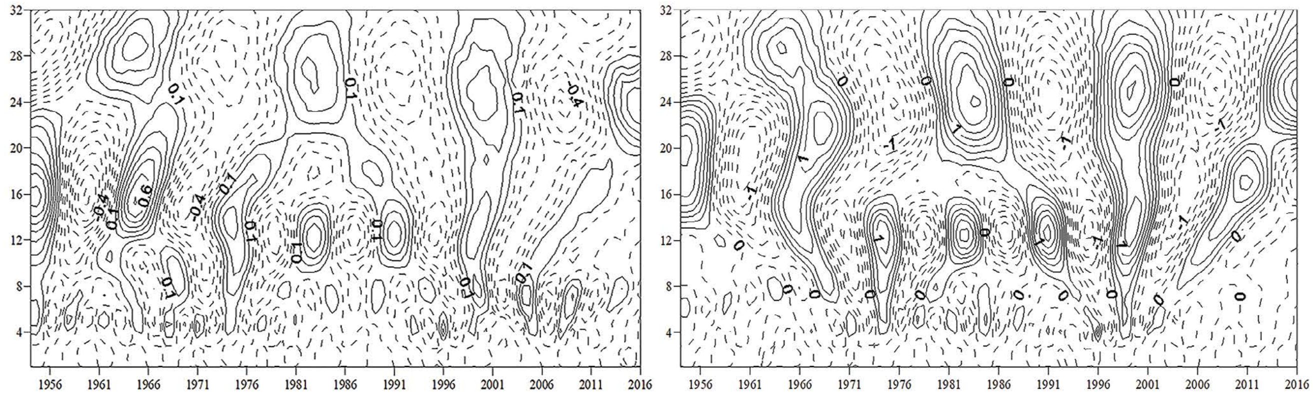


(c) Hankou (d) Datong

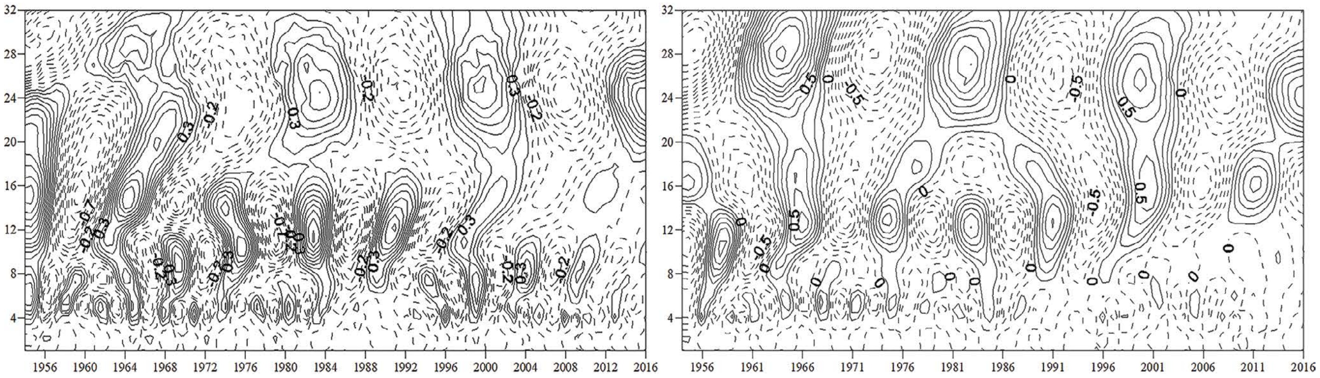
Fig. 5. Comparison of monthly sediment in the Yangtze River.



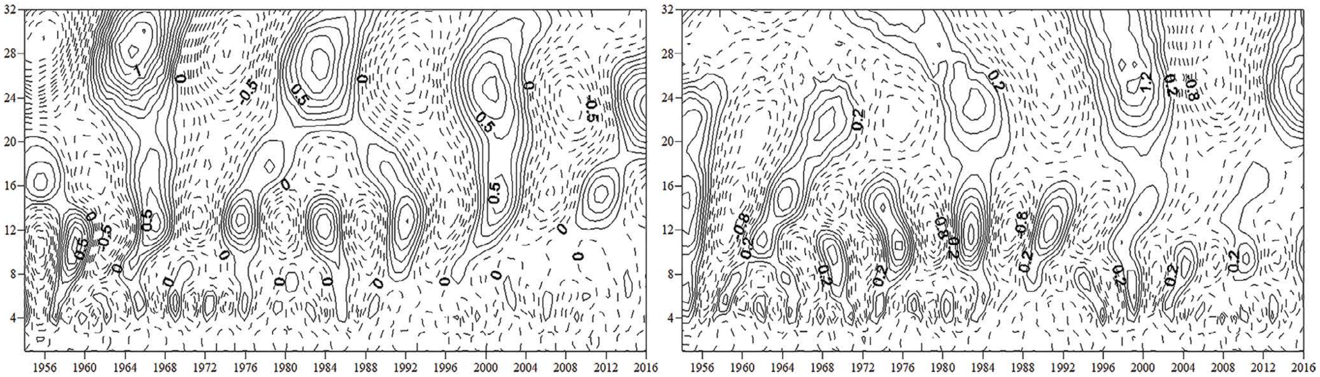
Cuntan Station: runoff (left) and sediment load (right)



Yichang Station: runoff (left) and sediment load (right)



Hankou Station: runoff (left) and sediment load (right)



Datong Station: runoff (left) and sediment load (right)

Fig. 6. Contour maps of the real parts of wavelet coefficients for the annual runoff (left) and sediment load (right) in the Yangtze River.

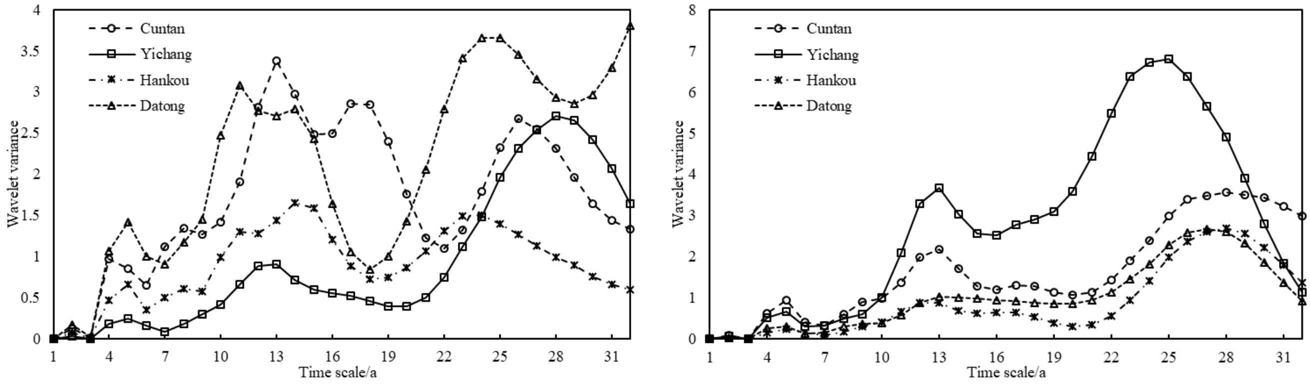


Fig. 7. Wavelet variance graphs for runoff (left) and sediment load (right) in the Yangtze River.

time series. The series of runoff and sediment loads in the Yangtze River comprised several periods at different time scales. Furthermore, the oscillation centers of various time scales formed interlacing positive and negative contours. Thus, the magnitudes (positive or negative) of the real part of the wavelet coefficient in the contour maps reflect the plentiful or low flow areas within the time scale [37]. The runoff and sediment load series from the four stations exhibit obvious inter-year and interdecadal changes.

According to Figs. 6 and 7, the periodic behaviors and durations are identified in Table 4. In the recorded period, the annual runoff of the Yangtze River showed 5-a, 8-a, 11-a, 13-a, 24-a, 26-a, and 28-a. The dominant runoff periodicity was 23-a for the Cuntan and Hankou stations, 28-a for the Yichang station, and 25-a for the other stations. The annual sediment load showed periodicities of 5-a, 13-a, 25-a, and 28-a, with the dominant periodicity of 25-a for the Yichang station and 28-a for the other stations. The periodical variation in sediment transport is similar, but the variation in runoff is different in the Yangtze River. The runoff periodic performance of the Cuntan station and the Hankou station is different from that of the Yichang station and Datong station. The main reason for this difference is that the Yangtze River upstream of the Cuntan station is influenced by the inflow of the Jialing River, Minjiang River, Tuo River, and Chishui River, and the Hankou station is affected by the inflow of the Han river. These tributaries flow into the mainstream and affect the annual runoff. The Yichang station and the Datong station are the control stations of the middle reaches of the Yangtze River and the mainstream of the Yangtze River, respectively. The periodic change has little influence on the regulation and storage of the interval.

4.4 *Relationships between the runoff and sediment load*

4.4.1. *Interannual correlation of water and sediment*

The correlations between multiyear runoff and sediment discharge at four hydrological stations in the Yangtze River were analyzed. The correlation coefficients of a multiyear runoff between the Cuntan station and the Yichang station, the Yichang and the Hankou station, and the Hankou station and the Datong station were 0.92, 0.84, and 0.94, respectively. The correlation coefficients between the annual sediment discharges are 0.94, 0.92, and 0.97, respectively. The relationships between runoff and sediment at the four hydrological stations are all highly correlated, which indicates that there is a good correlation between the runoff and sediment along the middle and lower reaches of the Yangtze River in recent decades. By analyzing the correlation between the multiyear runoff and sediment discharge, the correlation coefficients of annual runoff and sediment discharge between the upstream and downstream hydrological stations are 0.63, 0.57, 0.21, and 0.24. The correlation between water and sediment was the best at the Cuntan station, followed by the Yichang station.

4.4.2. *Stage variation in the water and sediment relationship*

There is a correlation between runoff and sediment discharge, which can be expressed as $W_s = KW_Q^{\alpha}$, where

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

Stations	Annual runoff		Annual sediment load	
	Multiple time scale Periodicity (a)	Dominant periodicity (a)	Multiple time scale Periodicity (a)	Dominant periodicity (a)
Cuntan	5, 8, 13, 26	13	5, 13, 28	28
Yichang	5, 13, 28	28	5, 13, 25	25
Hankou	5, 8, 13, 24	13	5, 13, 28	28
Datong	5, 11, 25	25	5, 13, 28	28

W_s: annual sediment discharge; W_Q: annual runoff; K: coefficient; and α: power exponent. The formula can refer to the references [38] and [39]. Based on the analysis of the double cumulative curve of runoff and sediment, the Cuntan station is divided into three stages: 1965–1991, 1992–2002, and 2003–2016. Similarly, the Yichang, Hankou and Datong stations are divided into three stages: 1954–1991, 1992–2002 and 2003–2016. The correlation diagrams of the runoff and sediment discharge at the four hydrological stations in different periods are illustrated in Fig. 8.

It can be seen from Fig. 8 that the regression curves of the annual runoff and sediment discharge at three stages of the Cuntan station are gradually dispersed (R^2 values are 0.55, 0.21, and 0.14, respectively), which indicates that the relationship between water and sediment is weakening gradually, and the power exponent α is not changing much, but the coefficient k is decreasing. It shows that the annual sediment discharge corresponding to the same annual runoff decreases gradually, which further indicates that the human activities in the upper reaches of the Yangtze River have a certain influence on the sediment discharge at the Cuntan station.

Fig. 8 shows that the fitting degrees R^2 of Yichang during 1954–1991 and 1992–2002 are noticeably higher than those of the Hankou station, indicating that the Yichang station has better homology of water and sediment than the Hankou and Datong stations. The fitting degree of the Yichang station reached the minimum value of 0.18 after 2002, while the fitting degree R^2 of the Hankou station reached the maximum value of 0.48, suggesting that the Three Gorges Reservoir impoundment has a certain negative effect on the relationship between the water and sediment at the Yichang station. From the analysis of the coefficient k, we can see that the value of k at the same stage becomes larger, which indicates that the annual sediment discharge increases, while the power index α of the Yichang station is larger than that of the Hankou station. The sediment load at the Yichang station is larger than that at the Hankou station when the runoff varies to the same extent. The values of k at the Datong station continue to decrease, indicating that the annual sediment discharge showed a decreasing trend. The power index α increases, indicating that the capacity of sediment transport is constantly enhanced. It should be noted that after the Three Gorges Reservoir impoundment in 2003, the runoff and sediment regression curves are different from those of the previous two stages, which indicates that the Three Gorges Reservoir impoundment has a certain influence on the relationship between the water and sediment and the sediment transport capacity.

4.5. Analysis of the influencing factors of water and sediment variations

The main factors affecting runoff and sediment load in the basin include land surface conditions, natural disasters, climate, human activities [40]. Among them, rainfall and human activities have a greater impact on the runoff and sediment in the basin. The average annual precipitation in the Yangtze River basin from the Cuntan station to the Datong station has decreased slightly over the past 60 y, and the yield of diverted water from the Yangtze River Divert has increased slightly, but the variations are not significant [41,42]. At the

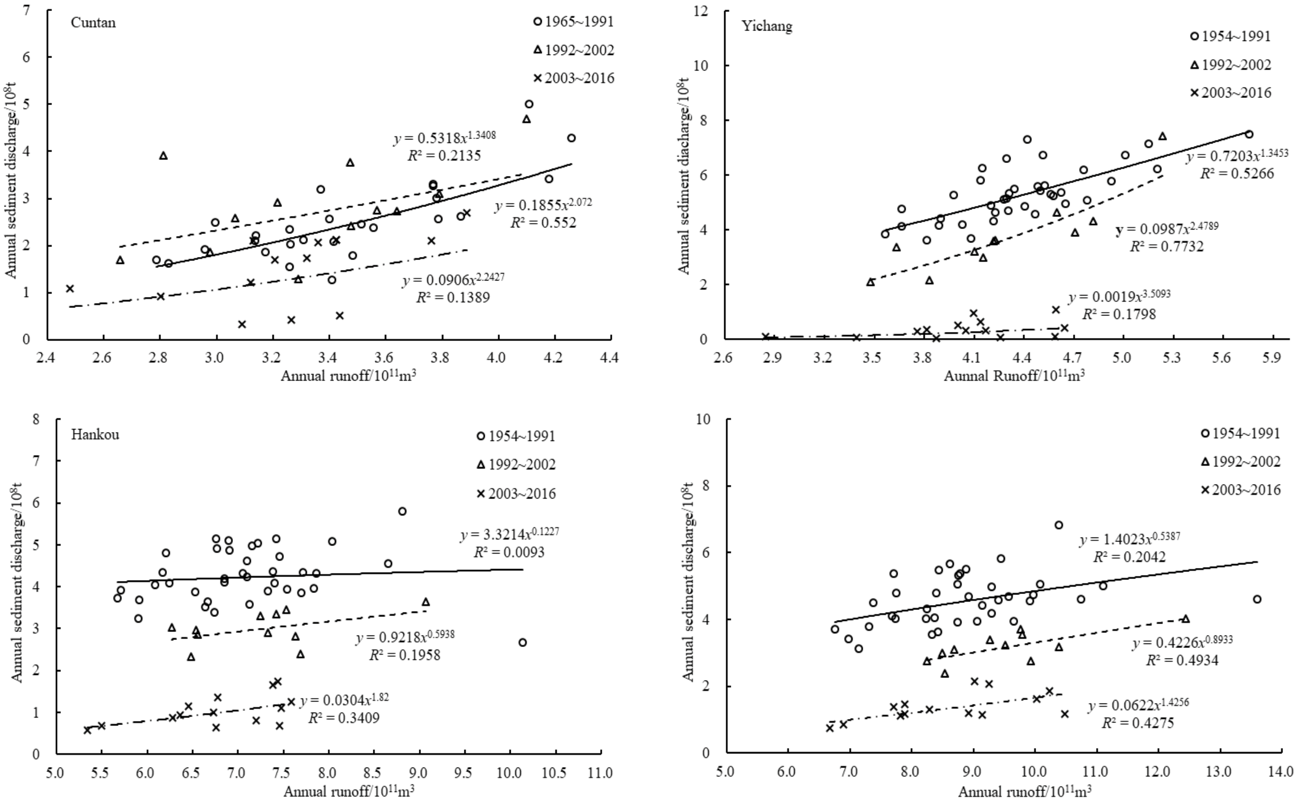


Fig. 8. Relationship between the annual runoff and sediment discharge at the four hydrological stations in the Yangtze River.

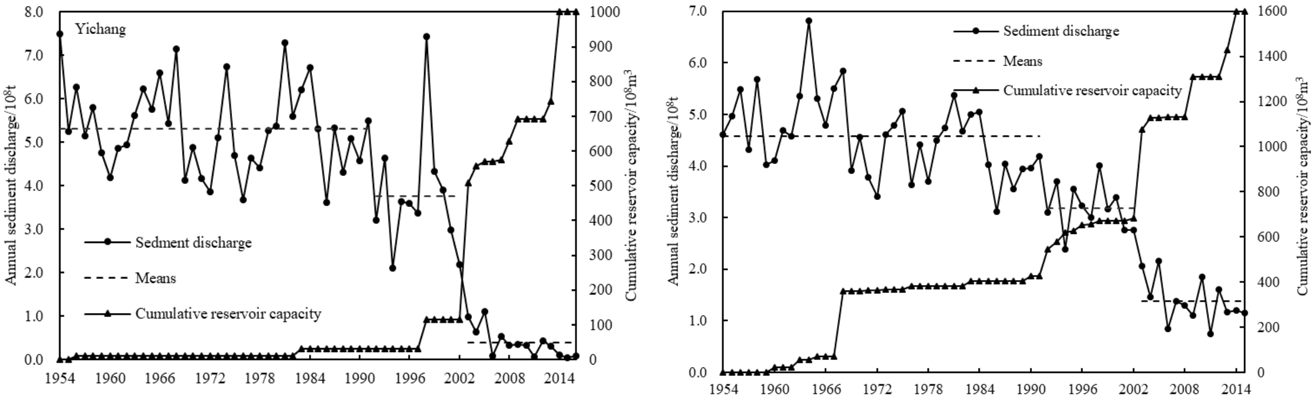


Fig. 9. Variations in sediment load and cumulative reservoir capacity at the Yichang and Datong Stations.

same time, the trend changes in the water and sediment using the Mann-Kendall trend test are all also different, suggesting that the decrease in the annual runoff will have a certain effect on the significant reduction in annual sediment discharge, and human activities will also have an important impact on the reduction of annual sediment discharge. Human activities mainly include factors such as reservoir retention, sand excavation, soil and water conservation, lake regulation and sediment deposition, among which reservoir sediment retention is the main factor affecting the reduction in the annual sediment discharge [17,43]. Therefore, this paper focuses on the impact of reservoir construction on the annual sediment discharge in the Yangtze River.

To evaluate the influence of reservoir impoundment and sediment retention on the annual sediment discharge in the Yangtze River, the relationship between the cascade reservoir construction and the sediment load is analyzed at the Yichang station. Taking the Datong station as the total control station, the relationship between the reservoir construction conditions and the interannual variation in the sediment discharge at the Datong station was analyzed, and the relationship curves between the total reservoir capacity and the annual sediment discharge at the Yichang and Datong station were plotted (Fig. 9).

It can be seen from Fig. 9 that there is a good correspondence between the increase in the total reservoir capacity and the decrease in the annual sediment discharge in the basin. For the Yichang station, some reservoirs have been built in the upper reaches of the Yangtze River since the 1990 s, but the accumulative capacity is small, and most of them are located in the tributaries, thus, the effect on the sediment discharge at the Yichang station is relatively small, and the annual sediment discharge is kept at 5.31 × 10^8 t. After the 1990 s, the sediment discharge began to decrease under the influence of WSCP in the upper reaches of the Yangtze River, as well as the impoundments of hydropower station construction in Ertan and Baozhusi hydropower stations and other reservoirs. By the end of 2002, the annual sediment discharge of the Yichang station was 3.91 × 10^8 t, with a decrease of 26.36%. After the Three Gorges Reservoir was impounded in 2003, the annual sediment transport capacity at the Yichang station decreased significantly. With the large hydropower stations constructed, such as Hongjiadu, Goupitan, Xiangjiaba, Xiluodu, and Tingzikou, the annual sediment transport of the Yichang station was further reduced. The average annual sediment discharge from 2002 to 2016 is only 0.38 × 10^8 t, which is 92.84% lower than that before the 1990 s.

The cumulative storage capacity and annual sediment discharge change at the Datong station are the same as those at the Yichang station. From 1954–1991, some reservoirs were built along the main tributaries of the Yangtze River basin. However, the annual change in the sediment load is small, with a total of 4.58 × 10^8 t. Since the 1990s, the accumulative capacity of the reservoir has been increasing, which also increases the impacts on sediment retention. Before the impoundment of the Three Gorges Reservoir, the total storage capacity of the large reservoirs in the Yangtze River Basin reached 68 billion m^3. The annual sediment discharge at the Datong station is also reduced to 3.19 × 10^8 t, showing a reduction of 30.45%. After the impoundment of the Three Gorges Reservoir, the annual sediment discharge at the Datong hydrological station was reduced to 1.37 × 10^8 t, which is 70.01% less than that before the 1990s. Because the reservoirs are mostly located in the upper reaches of the Yangtze River, the amount of sediment transported into the lower reaches of the Yangtze River has been greatly reduced, resulting in serious erosion along the middle and lower reaches of the Yangtze River and the recovery of the sediment discharge along the course of the middle and lower reaches of the Yangtze River, which is also regulated by the tributaries of the Yangtze River [43]. As a result, the annual change in sediment discharge at the Datong station is less noticeable than that at the Yichang Station.

5. Conclusion

This study analyzed variations in the runoff and sediment loads in the Yangtze River based on updated datasets of four hydrological stations from 1954 to 2016. Changing trends, abrupt change points, and relationships between runoff and sediment were detected from the time series, and the impact of human activities on the runoff and sediment load was evaluated. The runoff and sediment in the Yangtze River exhibit a decreasing trend, among which the annual sediment discharge has a significantly decreasing trend at a 99% confidence level. The annual runoff and sediment variation could be divided into three stages by the double cumulative curve. The runoff and sediment at different stages noticeably change in the flood season. The relationships between the runoff and sediment have also changed along the middle and lower reaches of the Yangtze River in recent decades. Human activities, especially reservoir impoundment, were the major causes of the significant decline in the sediment discharge of the Yangtze River over the past six decades. This study can provide a reference for the effective management of the Yangtze River.

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