

# Changes of Water stage in the middle Yangtze River influenced by human activities in the past 70 years

Jianqiao HAN<sup>1,2\*</sup>, Yao WANG<sup>2,3\*</sup>, Zhaohua SUN (✉)<sup>1</sup>

<sup>1</sup> State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

<sup>2</sup> Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China

<sup>3</sup> College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 213022, China

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**Abstract** Water stages play a critical role on flood control, water supply, navigation, and ecology in rivers. Investigation of water stages provides better understanding of riverbed evolution processes and river management. Based on the hydrological observation in past 70 years, the changes of low-flow and flood stages were investigated by a combination of Mann-Kendall test, moving *t*-test, and wavelet analysis. 1) In accordance with the location, the middle Yangtze River was divided into upper reach, middle reach, and lower reach. Water stages in the upper reach show a decreasing trend, while that in the middle reach present an increasing trend, and the lower reach are mainly dominated by natural evolution. 2) The mutation year of water stages in the upper reach was around 1985, indicating that the Gezhouba Dam facilitated the reduction of water stages. The trend mutation in the middle reach was in 1969, which was consistent with the implementation of Jingjiang Cutoff. 3) Human activities aggravated the change of water stages, leading the primary period of water stage time series to exceed 20 years. 4) In the upper reach, the reductions of water stages were attributed to the riverbed erosion induced by human activities. While in the middle reach, the recent falling effects of riverbed erosion can hardly offset the rising effects of the channel resistance on water stages. 5) In the future, the increasing trend in the middle reach may be arrested due to the riverbed erosion induced by the Three Gorges Dam. Long-term observation of the flood stage must be conducted in the middle Yangtze River.

**Keywords** flood stage, low-flow stage, human activity, Yangtze River

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E-mail: Lnszh@126.com

\*Contributed equally to this work.

## 1 Introduction

River water stage, a comprehensive characterization of river morphology and resistance, has considerable influences on river flood control, water supply, navigation, riverbed morphology, and ecological protection (Haber-sack et al., 2016; Zhu et al., 2017; Han et al., 2018). The water stage is affected by water, sediment conditions, and riverbed boundaries (Qu et al., 2012). Under natural conditions, the incoming flow and sediment processes interact with the riverbed morphology in a relatively balanced state (Han et al., 2017; Han et al., 2018). However, this equilibrium state could be disturbed by human activities, resulting in water stage changes. For instance, reservoirs change sediment processes, which accelerate riverbed erosion and then affect water stages (Yang et al., 2017). Waterway regulation engineering, wharf, and other river projects could increase the resistance of flow (Ye et al., 2013).

Various changes of water stages are attributed to different types of human activities, and the same type of activity could induce different changes in different reaches (Zhou et al., 2017). For instance, the low-flow stage in the lower reach of the Han River decreased after the operation of the Danjiangkou Dam. Conversely, the flood stage did not change, and even increased, in the near-dam reach (Chen et al., 2007). In addition, the artificial cutoffs conducted on the Mississippi River from the 1920s to the 1930s led to a decline in the upstream stage and a rise in the downstream stage (Criss and Luo, 2017). Adjustment principles of the water stages not only depend on the input flow and sediment process but also relate to the original river channel pattern, riverbed morphology, and other environmental conditions (Tealdi et al., 2011). Therefore, the research on water stages should be conducted in combination with the characteristics of specific rivers.

The middle Yangtze River is the golden waterway connecting eastern and western China; however, this area

suffers severe flood disasters (Fan et al., 2016; Zhang et al., 2018). Meanwhile, water stages in the Yangtze River have remarkable effects on the evolution of Dongting and Poyang Lakes. During the past 70 years, the middle Yangtze River has been influenced by intense human activities, especially hydraulic engineering. The three largest engineering projects were the Jingjiang Cutoff from 1968 to 1972, the Gezhouba Dam constructed in 1981, and the Three Gorges Dam operated in 2003. Moreover, numerous waterway engineering and revetments have been conducted in recent years. Many studies have been performed on water stage evolution in the middle Yangtze River (Han et al., 2017). Three cutoffs projects in the Jingjiang River increased the upstream water surface gradient, resulting in the upward trend of flow velocity and then reducing the upstream flood stage (Xia et al., 2016; Lin et al., 2017; Deng et al., 2019). After the impoundment of the Gezhouba Dam, low-flow stage showed a decreasing trend, while flood stage exhibited no significant change in the upstream of Chenglingji (Huang et al., 2019). The Three Gorges Dam caused the scouring state of the riverbed from Yichang to Hankou (Chen et al., 2010; Yuan et al., 2012), and the low-flow stage of Yichang–Chenglingji reach decreased (Fang et al., 2012; Lai et al., 2014; Wang et al., 2017). Some studies proposed that future flood stage will further decrease (Wang et al., 2013; Mei et al., 2018). However, other investigations showed that the variation of flood stage caused by the Three Gorges Dam is insignificant (Lai et al., 2014).

Previous studies have explored the effects of large-scale engineering on water stages by comparing these stages before and after engineering operations. However, the water and sediment conditions will fluctuate between years due to the influence of climate change (Markovich et al., 2016; Cheng et al., 2019). Furthermore, the water stage changes under periodic hydrological processes; for example, the increase of water stage at the same discharge in a wet year and fall back in a dry year (Westerberg et al., 2011). Therefore, further studies are needed to investigate the change and its causes in water stages influenced by multiple human activities for a long time series. In this study, 70-year water level observations in five hydrological stations are collected to investigate the temporal and spatial changes in water stages along the middle Yangtze River. In addition, the change mechanisms of water stages in response to human activities are discussed through the riverbed evolution. The results of this study are valuable for understanding the effects of human activities on long-term water stages and could also support the management strategies in rivers influenced by intense human activities.

## 2 Study area

The middle Yangtze River extends from Yichang to Hukou with a total length of approximately 955 km. The water and

sediment in this reach mainly originate from the upstream of Yichang. The sediment transport in the middle Yangtze River was significantly reduced due to the impact of human activities during these years. The runoff (575.1 billion m<sup>3</sup>) and sediment transport (754 million m<sup>3</sup>) were the largest in 1954, while the runoff (347.5 billion m<sup>3</sup>) and sediment transport (210.0 million m<sup>3</sup>) in 1994 were the smallest (Li et al., 2011). Along the river, the size of sand gravel particles in the riverbed is nonuniform, and the upstream and downstream channel reaches of Yangjiano are characterized by gravel and sandy riverbeds, respectively (Fig. 1)

The Jingjiang Reach (Zhicheng–Chenglingji) is the critical region for flood prevention in the middle Yangtze River. The Zhicheng to Ouchikou Reach comprises anabranching channel patterns, and the lower reach of Ouchikou belongs to a typical meandering river type. The south bank has three tributaries diverting the flow and sediment from the mainstream to Dongting Lake through Songzikou, Taipingkou, and Ouchikou, and the outflow of Dongting Lake and Jingjiang River converges near Chenglingji (Wang et al., 2014; Zhang et al., 2018).

Large-scale water conservancy projects built in the middle Yangtze River are presented as follows: First, the Jingjiang Cutoff included cutoffs at the Zhongzhouzi, Shangchewan, and Shatanzi reaches completed in 1972. This project reduced the length of the reach by 78 km and increased the river gradient (Xia et al., 2016; Lin et al., 2017). Second, the Gezhouba Dam was the first large-scale hydropower station on the Yangtze River with a total storage capacity of  $1.58 \times 10^9$  m<sup>3</sup>. Third, the Three Gorges Dam, which was located 40 km upstream from Yichang, was opened in 2003. In addition, numerous revetments, waterway regulation engineering, and other projects have been implemented in the middle Yangtze River to support the development of the Yangtze River Economic Belt.

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## 3 Materials and methods

### 3.1 Data sources

Daily water stage and discharge of the Yichang (1950–2011), Zhicheng (1955–2012), Shashi (1955–2012), Luoshan (1955–2011), and Hankou (1956–2011) stations were collected from the Changjiang Water Resources Commission (CWRC).

Annual erosion and deposition data in the middle Yangtze River channel were collected from the CWRC. The profiles of the typical cross-section were collected in February 2002, 2008, 2012, and 2014 from the CWRC. The typical cross-section is denoted as A in Fig. 1.

### 3.2 Methods

The middle Yangtze River was divided into three parts by

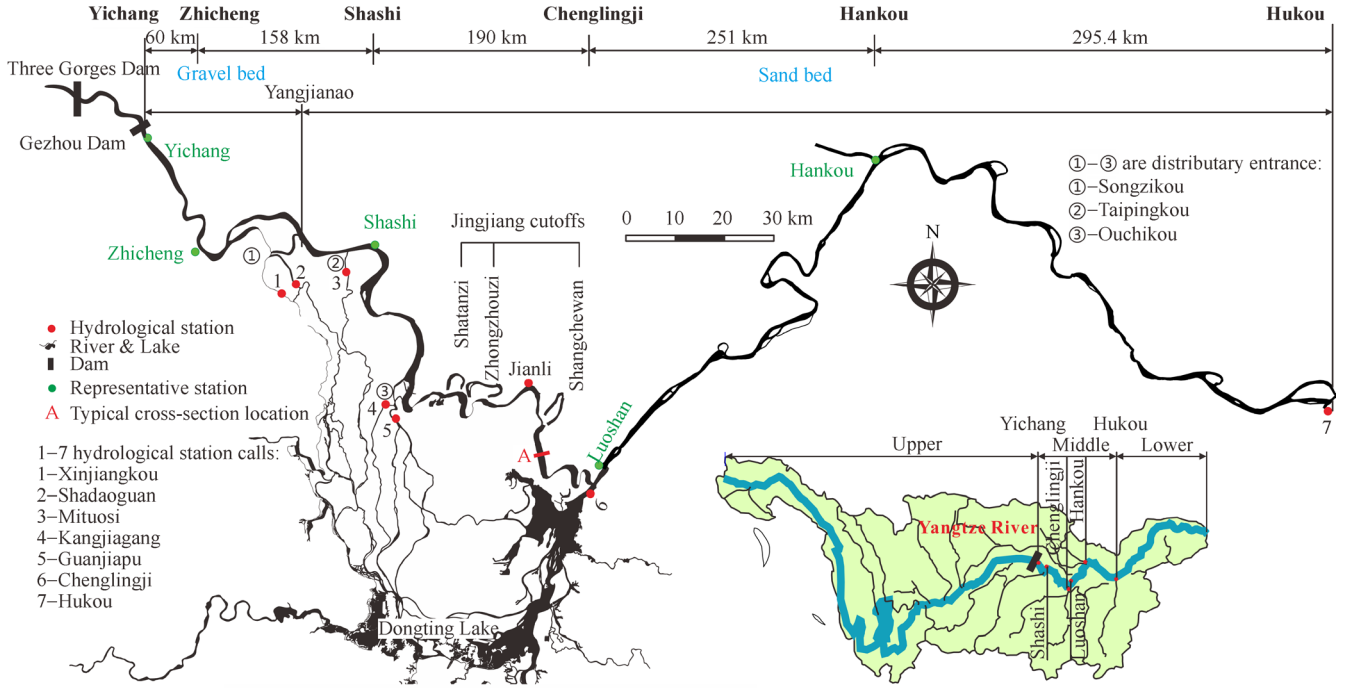


Fig. 1 Sketch of the middle Yangtze River.

Chenglingji and Hankou. The Yichang, Zhicheng, and Shashi stations represented the upper reach, Luoshan station represented the middle reach, and Hankou station represented the lower reach.

Trend and periodicity of the water stage series were investigated through the following three steps. First, a long time series of water stage residual was established to eliminate the change randomness. Then, the linear regression equation and Mann-Kendall (MK) analysis method were combined to analyze the trend and abrupt point of water stage changes. The moving *t*-test was employed to assess whether the abrupt point was receivable. Meanwhile, it can also be used to estimate the trend of water stage changes. Finally, the dominant periods of water stage changes were determined by the wavelet analysis.

3.2.1 Time series of water stage residual under the specific discharge

Due to the influence of flood fluctuation, the water stage-discharge presented a rope loop curve relationship. Therefore, the data of each hydrological year were unified to the same standard, which enhanced the comparability between different periods (Fig 2).

1) The average values of three consecutive days were calculated from the hydrological annual water level and discharge data to eliminate the disturbance induced by flood fluctuations and measurement errors.

2) The obtained water stage and flow data were fitted by

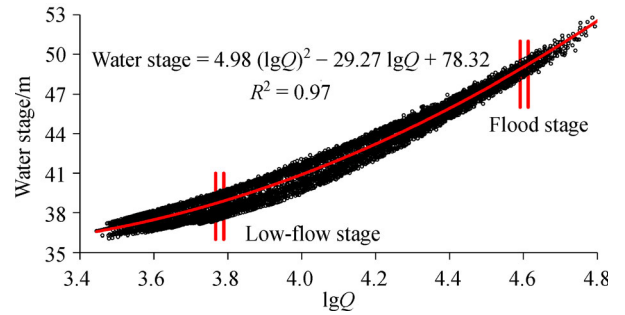


Fig. 2 The schematic diagram of calculating stage-flow regression residuals

the least square method, which unified the water stage or discharge in different periods to a similar standard. The water level residual value (Pacheco and Fallico, 2015) is calculated as follows:

$$e_j = y_j - \hat{y}_j, \quad (1)$$

$$\bar{e}_n = \sum_{j=1}^M e_j / M, \quad (n = 1, 2, \dots, M), \quad (2)$$

where  $e_j, y_j, \hat{y}_j$  are the residuals of the water stage, the measured value of the water stage, and the predicted values of the regression curve, respectively.  $\bar{e}_n$  is the average of the residuals within a specific *n* year. *M* is the number of measured points in the *n* year. *N* is the length of time series.

3) Taking the specific discharge as the baseline and enlarging the  $\pm 5\%$  flow interval as the discharge range, the

time series of water stage variation at each hydrological station was obtained from the average of water stage residual.

The specific discharge should not only reflect the characteristics of flood or low flow but also maintain a continuous time series. The specific low-flow discharges in Yichang, Zhicheng, Shashi, Luoshan, and Hankou were taken as 6000, 6000, 6000, 7500, and 12000 m<sup>3</sup>/s, respectively, which were equal to half of the average flow discharge of each station. The specific flood discharges were 40000, 40000, 35000, 40000, and 40000 m<sup>3</sup>/s, exceeding the bank-full discharge (Han et al., 2017).

Data series normality was assessed with the Kolmogorov–Smirnov test (Sang et al., 2014). The method compared the pre-assumed distribution function with the function of hydrological time series based on observations and then analyzed the fitting degree of the two functions. At the specified significance level, if the observed value was larger than or equal to the critical tabulated value of the Kolmogorov–Smirnov statistic, then the hypothesis of normal distribution was rejected (Mora-López and Mora, 2015).

### 3.2.2 Linear regression equation

Simple linear regression, specifically the parametric *t*-test at the 95% confidence level, was used to test the statistical significance of the correlation between the trend of water stage and time series. The probability (*p*) value which lower than 0.05 was considered statistically significant (Zhang et al., 2017). The parametric *t*-test comprised two steps: fitting a simple linear regression equation with time *t* and water stage residuals as the independent and dependent variables, respectively, following by testing of the statistical significance of the regression equation slope.

### 3.3 MK method

The MK method is a non-parametric statistical method used to predict the long-term trend of the water stage time series. The statistic *S* is defined by the MK method (Peña-Arancibia et al., 2012; Li et al., 2018):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k), \quad (3)$$

where  $x_j$  and  $x_k$  are the water stage values of corresponding years.

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & x_j - x_k > 0 \\ 0 & x_j - x_k = 0, \\ -1 & x_j - x_k < 0 \end{cases} \quad (4)$$

$$UF = \begin{cases} \frac{S + 1}{\sqrt{VAR(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S - 1}{\sqrt{VAR(S)}} & S < 0 \end{cases}, \quad (5)$$

$$VAR(S) = \frac{n(n-1)(2n+5)}{18}. \quad (6)$$

A positive (negative) value of *S* indicates an upward (downward) trend (Li et al., 2018). Among the MK trend figure, if  $|UF| > 1.96$ , the water stage showed a significant change trend ( $p < 0.05$ ). The *UB* curve was the parameter of reverse order calculation. If an intersection existed between *UF* and *UB* curves, then the intersection point was between the critical lines, indicating the start of mutation (Ye et al., 2013). Otherwise, the moving *t*-test was selected to test whether the mutation point was receivable.

### 3.4 Moving *t*-test

The moving *t*-test is used to examine the difference between the averages of two random samples. In this article, five years before and after the certain year were selected as the sample distribution function to do the moving *t*-test on the continuous hydrological date. The *T*-function statistics are constructed as follows (Zhang et al., 2013):

$$T = \frac{\bar{x}_1 - \bar{x}_2}{\frac{4S_1^2 + 4S_2^2}{8} \left(\frac{2}{5}\right)^{\frac{1}{2}}}, \quad (7)$$

where  $\bar{x}_i, S_i^2$ , represent the mean value and variance, respectively. Among the moving *t*-test figure, if  $t > 0$  ( $t < 0$ ), then the water stage was proven to demonstrate a downward (upward) trend with time. The water stage significantly fluctuated ( $p < 0.05$ ) when  $|T| > 4$ . If the mutation point obtained by the MK analysis significantly fluctuated in the moving *t*-test, then the year was identified as a mutation year.

### 3.5 Wavelet analysis

The wavelet analysis method is a multi-resolution signal analysis and processing method (Doucoure et al., 2016). This method could perform multiscale analysis of signal time. The definition of time series transformation of wavelet function (Labat, 2008; Shan et al., 2017) is as follows:

$$W_t(a,b) = |a|^{-\frac{1}{2}} \Delta t \sum_{k=1}^N f(k\Delta t) \bar{\varphi}\left(\frac{k\Delta t - b}{a}\right), \quad (8)$$

where  $a$  is the scale factor reflecting the period length of the wavelet,  $b$  is the time factor reflecting the translation in time,  $t$  is time, and  $W_t(a,b)$  is the wavelet transform coefficient.

The wavelet variance was obtained by integrating the squares of the wavelet coefficients with different scale factors, and the main period of the sequence can be determined. The calculation formula is as follows (Labat, 2008; Shan et al., 2017):

$$VAR(a) = \int_{-\infty}^{\infty} |W_t(a,b)|^2 db, \quad (9)$$

where  $VAR(a)$  is wavelet variance. By establishing the relationship between the wavelet variance diagram and the time scale, the corresponding wavelet variance at different time scales could be identified correspondingly. Meanwhile, the main period of wavelet analysis was identified in accordance with wave peaks in the wavelet variance diagram.

## 4 Results

### 4.1 Upper reach

Figure 3 shows the trend and mutation of the water stage residual in Yichang station. The simple linear regression presents a significant downward trend for the low-flow stage series ( $p < 0.05$ ). The MK test of low-flow stage increases from 1950 to 1966 and decreases after 1966 (this decreasing trend is significant at  $> 95\%$  confidence level after 1973). Among these years, the  $UF$  and  $UB$  curves intersect in 1983 as verified that  $F > F_\alpha$  ( $\alpha = 0.05$ ) using the moving  $t$ -test, indicating that the low-flow stage mutates in 1983. A peak value of wavelet variance at different time scales is observed in Yichang station, and the dominant period is 12 a (Fig. 4).

Simple linear regression analysis shows a decreasing

trend of flood stage. The MK test displays a downward trend except 1952–1955, and this downward trend is significantly found after 1989 ( $p < 0.05$ ). Moreover, 1981 is determined to be the mutation year through the combined application of MK and moving  $t$ -tests ( $p < 0.05$ ). Among the three peaks of wavelet variance, the time scale of 23 a corresponds to the maximum peak value. The first, second, and third periods of flood levels are 23 a, 14 a, and 6 a, respectively (Fig. 4).

Low-flow and flood stages in Yichang station exhibit downward trends in the past 70 years ( $p < 0.05$ ). The low-flow stage with a main period of 12 a mutates during 1983, while the flood stage with a dominant period of 23 a has a mutation year of 1981.

Figure 5 shows a significant downward trend in the low-flow stage series in Zhicheng station, and the downward trend becomes significant after 1973 ( $p < 0.05$ ). The  $UF$  and  $UB$  curves intersect in 1986 as verified by moving  $t$ -test, indicating the low-flow stage mutates this year. A peak value of 20 a is found in the wavelet variance (Fig. 4).

Linear regression analysis presents a decreasing trend of flood stage. The MK test exhibits increasing and decreasing trends during 1965–1975 and after 1975, respectively (this decreasing trend is significant at  $> 95\%$  confidence level after 1994). Although the curves of  $UF$  and  $UB$  intersect in 1981, the mutation year remains unverified by the moving  $t$ -test. The time scale of 21 a, 14 a, and 6 a corresponds to the dominant, second, and third periods of flood stage changes (Fig. 4).

The low-flow stage in Zhicheng station with the dominant period of 20 a mutates in 1986 and shows a significant downward trend after 1973. The flood stage with the main period of 21 a demonstrates a significant downward trend from 1994 and does not reveal a mutation year.

The result of simple linear regression for the low-flow stage in Shashi station shows a downward trend. The MK test indicates that this trend becomes significant after 1971

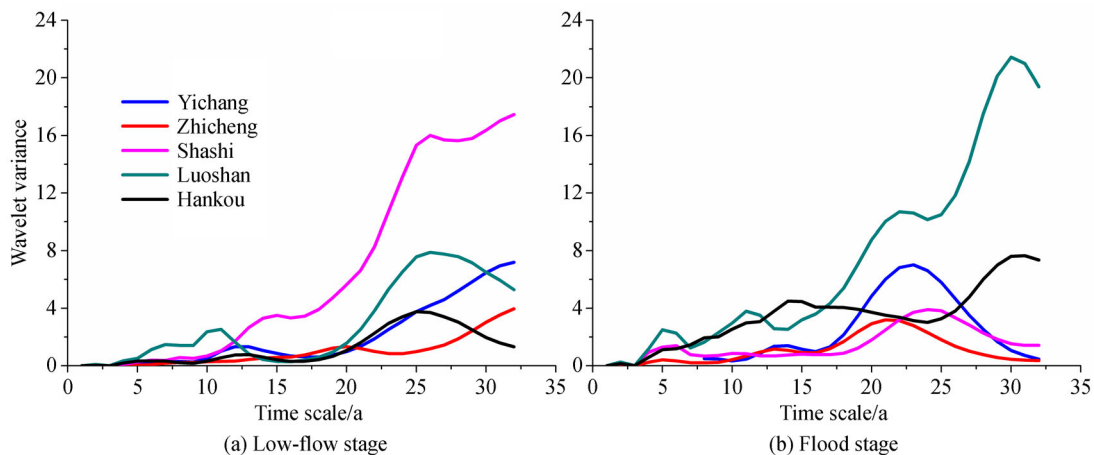


Fig. 3 Changes in low-flow and flood stages at Yichang station.

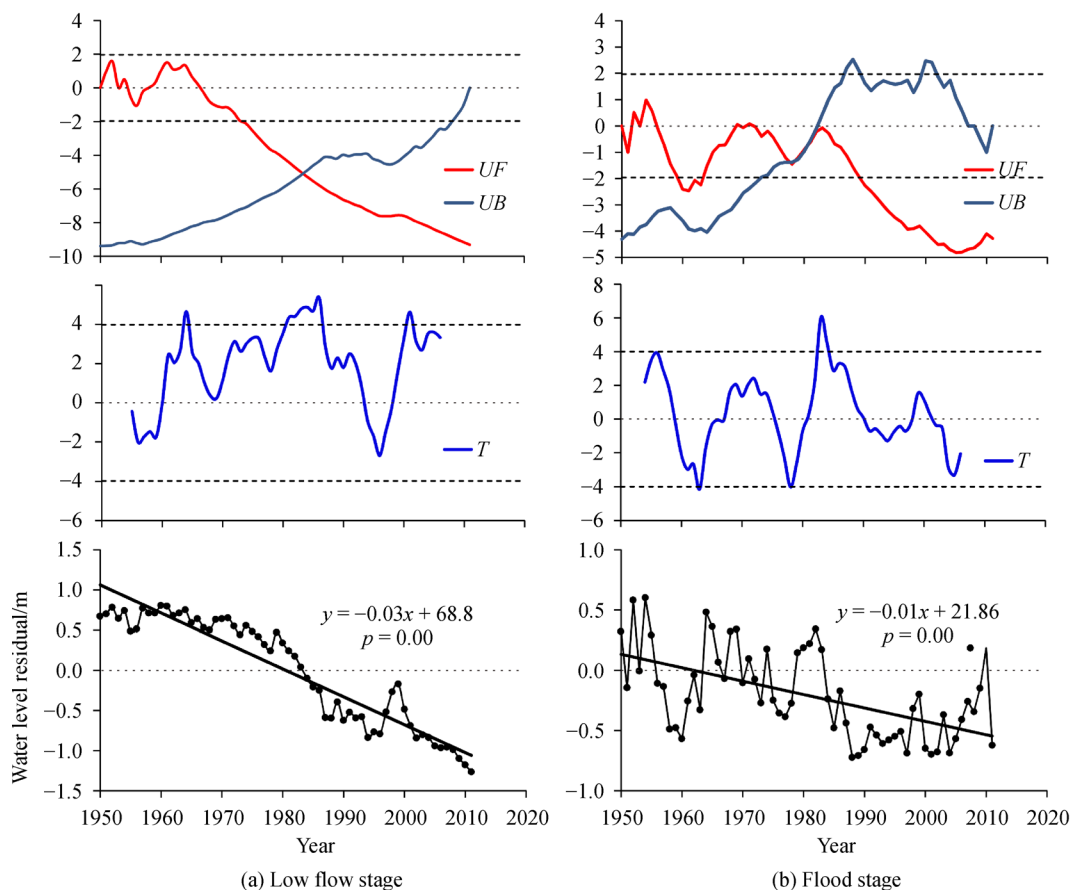


Fig. 4 Wavelet variance charts for the five stations in the middle Yangtze River.

at a 95% confidence level (Fig. 6). The low-flow stage mutates in 1985 when the intersection appears in the UF and UB curves. Two main periods of wavelet variance graph (Fig. 4) at different time scales reveal the dominant and second periods of 26 a and 15 a.

Simple linear regression analysis for the flood water stage indicates an insignificantly decreasing trend in the Shashi station ( $p > 0.05$ ). The MK test displays the downward trend of the flood stage, except for 1957, 1965, and 1967, and this trend becomes significant after 1973 ( $p < 0.05$ ). Since 1988, the downward trend of flood stages has gradually weakened. Among these years, the intersection of UF and UB curves in 1959 and 1963 has not passed the moving  $t$ -test, and no mutation year is found in Shashi station. Among the two peaks of wavelet variance graph (Fig. 4) at different time scales, 24a and 6a correspond to the dominant and the second periods, respectively.

The change of the low water stage shows a significant downward trend, while the downward trend of the flood stage is insignificant in Shashi station. The low-flow stage with the main period of 26 a mutates in 1985, and the flood stage with the dominant period of 24 a reveals a significant downward trend from 1973 without a mutation year.

#### 4.2 Middle reach

A significantly upward trend in the low-flow stage series ( $p < 0.05$ ) is found in the Luoshan station (Fig. 7). MK test shows decreasing and increasing trends from 1956 to 1959 and after 1959, respectively (this increasing trend is significant at  $> 95\%$  confidence level after 1964). Among these years, the intersection of the UF and UB curves in 1969 is verified that  $F > F_{\alpha}$  ( $\alpha = 0.05$ ) through the moving  $t$ -test. Two main periods of wavelet variance graph are found at different time scales, dominant and second periods are 25 a and 11 a (Fig. 4).

Simple linear regression analysis displays an increasing trend of annual flood stage ( $p < 0.05$ ). An upward trend is found in the flood stage series, except 1955–1974, and this upward trend becomes significant after 1989 at a 95% confidence level. The intersection of the UF and UB curves in 1987 is not verified by the moving  $t$ -test, indicating the absence of a mutation year at Luoshan station. The dominant, second, and third periods of the flood stage changes are 30 a, 22 a, and 11 a, respectively (Fig. 4).

The change of the stages in Luoshan station shows an upward trend ( $p < 0.05$ ). The low-flow stage with the dominant period of 25 a mutates at 1969 and exhibits a

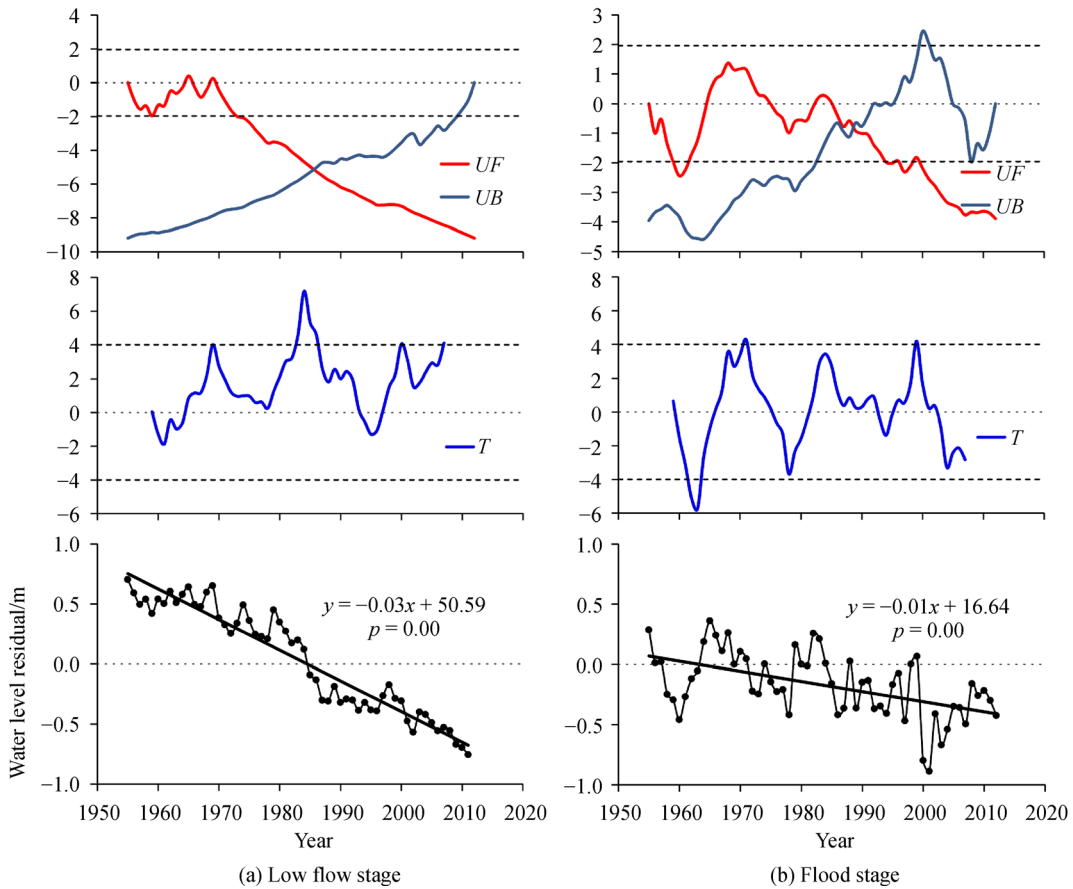


Fig. 5 Changes in low-flow and flood stages at Zhicheng station.

significant downward trend after 1964. The flood stage with the dominant period of 30 a presents a significant upward trend from 1989 without a mutation year.

#### 4.3 Lower reach

The low-flow stage fluctuates within a certain range in the Hankou station (Fig. 8). A decreasing trend is found during 1955–1965 and 1976–1981, and a significant increasing trend is demonstrated during 1996–2006 at > 95% confidence level (Fig. 8). Intersections of *UF* and *UB* curves remain unverified in the moving *t*-test, indicating the absence of mutation year in the low-flow stage. The dominant, second, and third periods are 25 a, 13 a, and 6 a, respectively (Fig. 4).

Linear regression analysis shows an increasing trend in the flood water stage. An upward MK trend of flood stage is found, except during 1955–1974, and this upward trend becomes significant after 1993 at a 95% confidence level (Fig. 8). The combination of MK and moving *t*-test indicates the absence of mutation year in Hankou station. The dominant and the second periods are 31 a and 14 a, respectively (Fig. 4).

The low-flow stage with the dominant period of 25 a in

Hankou station reveals a stable fluctuation trend, and changes in water mutation year are not observed. The flood stage with the dominant period of 31 a presents an upward trend without water level mutation.

## 5 Discussion

### 5.1 Spatial and temporal changes in water stages

The changes of water stages in the five hydrological stations are shown in Table 1. Results indicate that the low-flow stage exhibits a downward trend in the upper reach, while that in the middle reach shows an upward trend ( $p < 0.05$ ). The low-flow stage with an insignificant trend fluctuates during the past 70 years in the lower reach. Moreover, the low-flow stage changes in the upper reach has similar mutation points around 1985, indicating that the construction of the Gezhouba Dam facilitates the decreasing trend of water stages. The fluctuations of water stages in the middle and lower reaches are similar, and the dominant periods of these reaches are approximately 25 a.

In upper reaches, similar downward trends exist in the flood stage of Yichang and Zhicheng stations. The

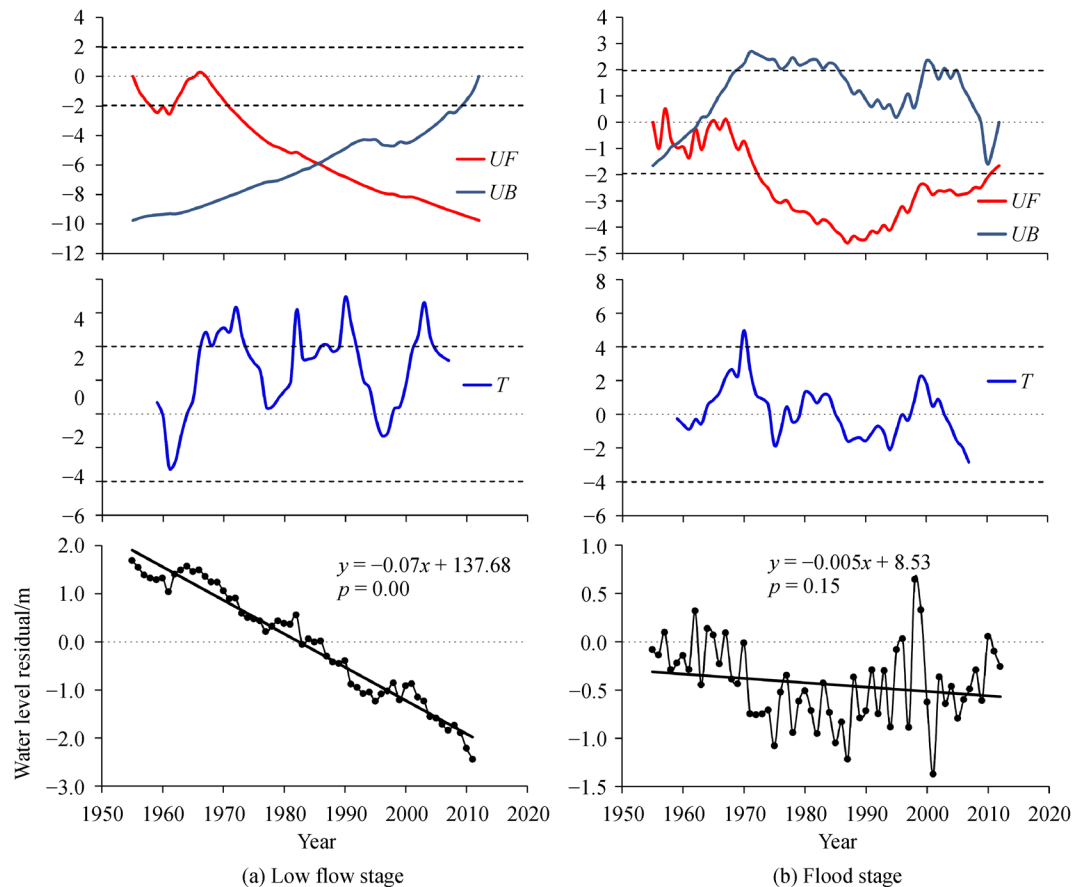


Fig. 6 Changes in low-flow and flood stages at Shashi station.

decreasing trend of flood stage in Shashi station is insignificant. By contrast, the middle and lower reaches demonstrate similar rising trends. The mutation year of the middle reach is around 1969, which is consistent with the implementation of the Jingjiang Cutoff. Table 1 exhibits similar main periods in the upper reach. The dominant periods in the middle and lower reaches are near 30 a.

The characteristics of water stage change in the middle Yangtze River can be declared as “Decreasing in upper reach, increasing in middle and lower reach except for the low-flow stage in the lower reach.” Moreover, the change of the low-flow stage is larger than that of the flood stage.

## 5.2 Causes of water stage changes

The water stage in the middle Yangtze River is directly affected by the flow, sediment, and river channel boundary (Habersack et al., 2016; Han et al., 2018). Intense human activities, including the Jingjiang Cutoff, Gezhouba Dam, Three Gorges Dam, and other projects, have changed the natural evolution process of the riverbed, leading to erosion and deposition in the channels and affecting the water stage (Fig. 9). The changes in riverbed evolution could be divided into four periods based on the

implementation history of the major engineering projects along the middle Yangtze River.

First, the Jingjiang Cutoff project conducted during 1966–1972 shortened the river length and increased the flow gradient ratio, scouring the riverbed in the Jingjiang Reach. The sediment from the Jingjiang Reach deposited into the lower reaches of Chenglingji, causing rising water stages in the middle and lower reaches of the middle Yangtze River. The Jingjiang Cutoff led to the trend mutation of the low-flow stage in the middle reach (Table 1).

Second, the construction of the Gezhouba Dam in 1981 retained a large amount of sediment, resulting in the erosion of the downstream reaches (Huang et al., 2018). However, the channel erosion mainly occurred in the upper reach, which was near the dam. Simultaneously, the middle and lower reaches remained in the state of siltation. These riverbed adjustments led to the decreasing and increasing of water stages in the upper and middle reaches, respectively. The Gezhouba Dam also aggravated the mutation trend of water stages in upper reach (Table 1).

From 1975 to 1996, the total siltation of the reach from Yichang to Hukou was 179 million  $m^3$ , with average annual siltation of 9 million  $m^3$ . The upstream from

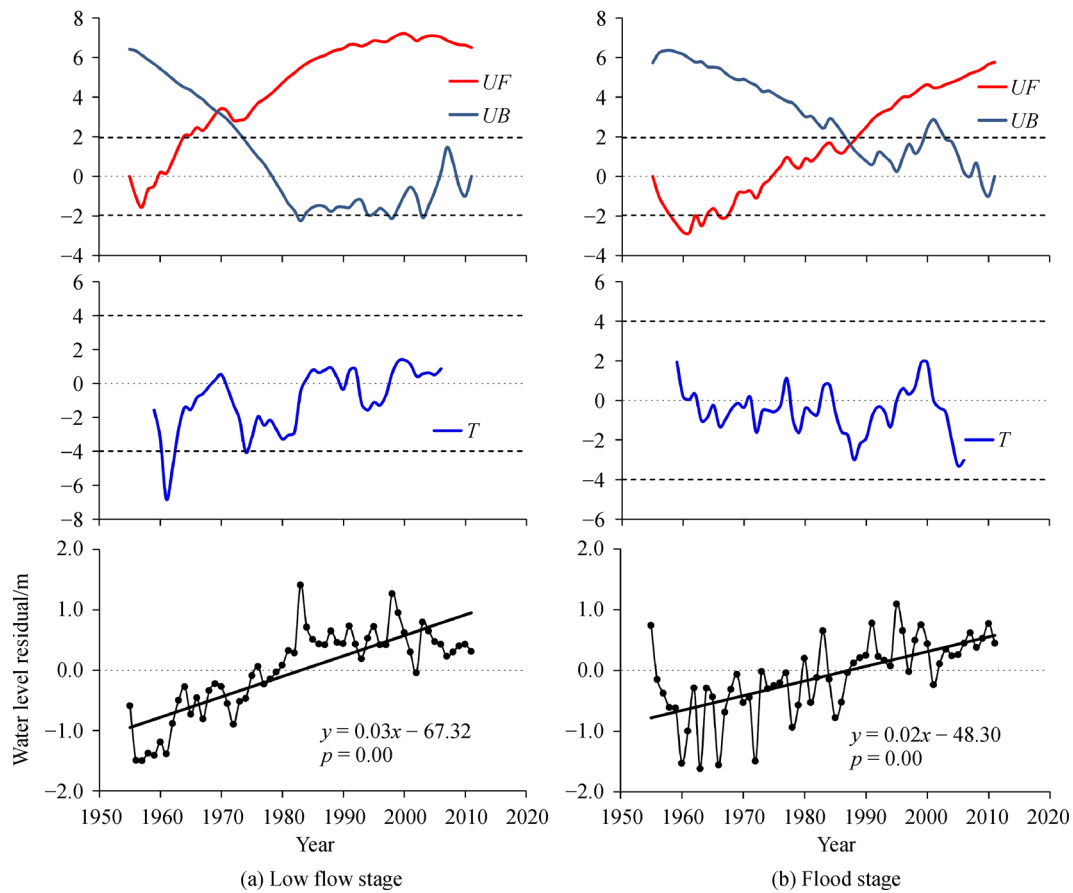


Fig. 7 Changes in the low-flow and flood stages at Luoshan station.

Table 1 Characteristics of water stage changes in the middle Yangtze River

Station	Trend (low-flow/flood)	Mutation year (low-flow/flood)	Dominant period (low-flow/flood)
Yichang	Decrease <sup>a)</sup> / Decrease <sup>a)</sup>	1983/1981	12/23
Zhicheng	Decrease <sup>a)</sup> / Decrease <sup>a)</sup>	1986/ -	20/21
Shashi	Decrease <sup>a)</sup> / Decrease <sup>a)</sup>	1985/ -	26/24
Luoshan	Increase <sup>a)</sup> / Increase <sup>a)</sup>	1969/ -	25/30
Hankou	Fluctuation/ Increase <sup>a)</sup>	- / -	25/31

Note: a) Indicates that the trend is significant at 95% confidence level.

Yichang to Chenglingji Reach scoured 338 million m<sup>3</sup>, and the downstream from Chenglingji to Hukou Reach deposited 517 million m<sup>3</sup>. The riverbed evolution could be characterized as “upstream scour and downstream siltation.”

Third, the continuous flood years of Dongting and Poyang Lakes from 1996 to 1998 had also affected the water stage in the middle Yangtze River. The middle Yangtze River was silted up with an amount of 199 million m<sup>3</sup>, except for the lower reach. From 1998 to 2002, the entire river reaches scoured with an erosion amount of 547 million m<sup>3</sup> under the continuous dry water condition.

Fourth, after the impoundment of the Three Gorges Dam, the middle Yangtze River remained in a state of scouring along the entire channel. From 2002 to 2013, the total scour volume from Yichang to Hukou was 1189.7 million m<sup>3</sup>. The length of upper reach accounted for 42.7% of Yichang–Hukou, while the amount of scouring accounted for 70.7%. This finding indicated that the scour intensity in the upper reach was larger than that in the middle and lower reaches. Meanwhile, the resistance of the downstream reach of the dam increased under the influence of different factors, such as the desertification of the river bed (Li et al., 2011), the vegetation of the flood plain

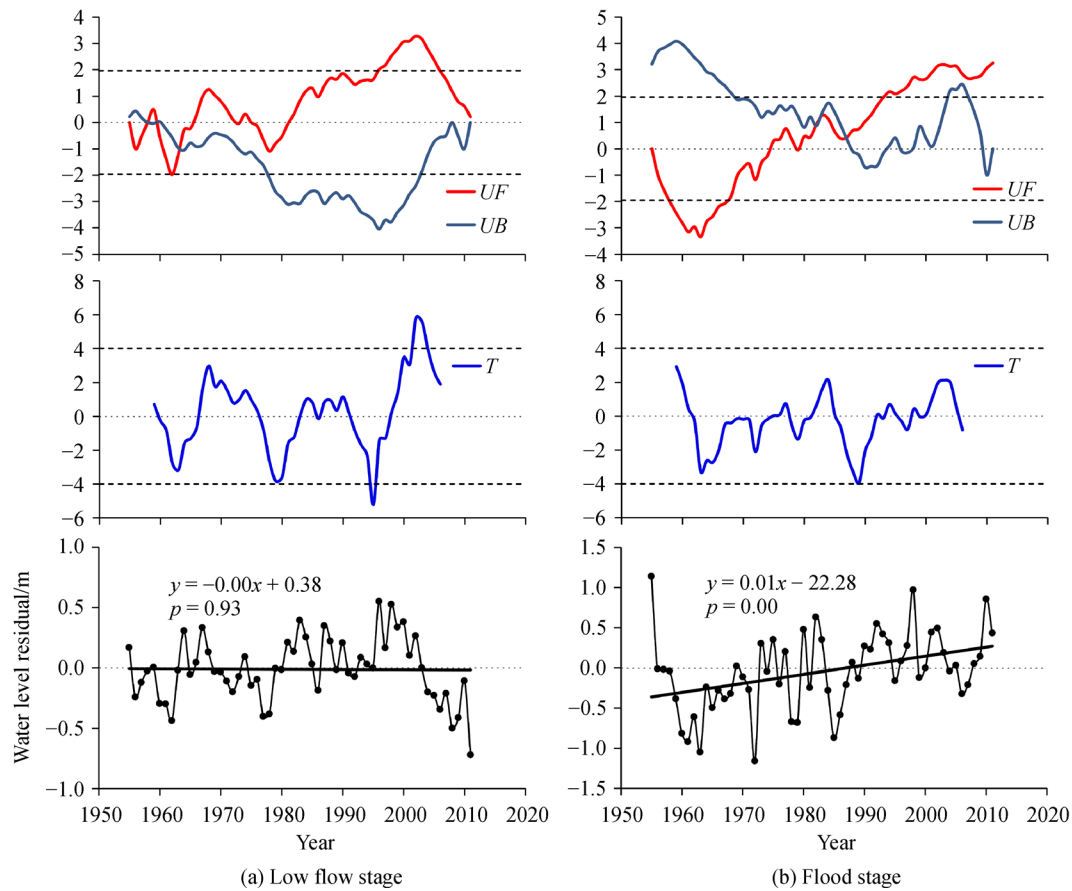


Fig. 8 Changes in the low-flow and flood stages at Hankou station.

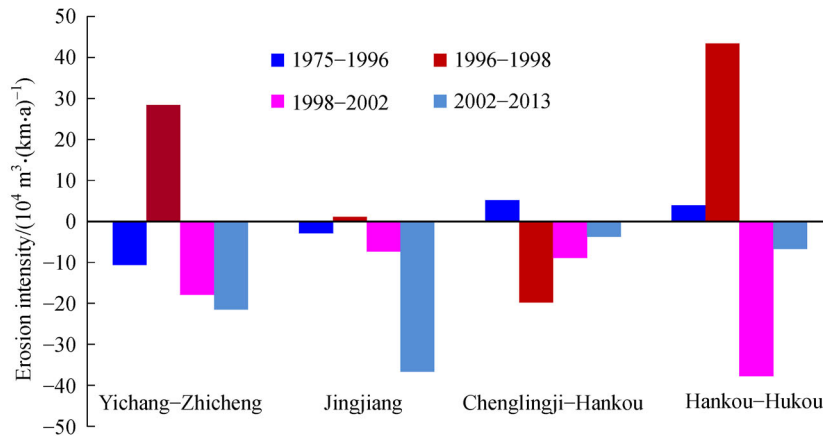


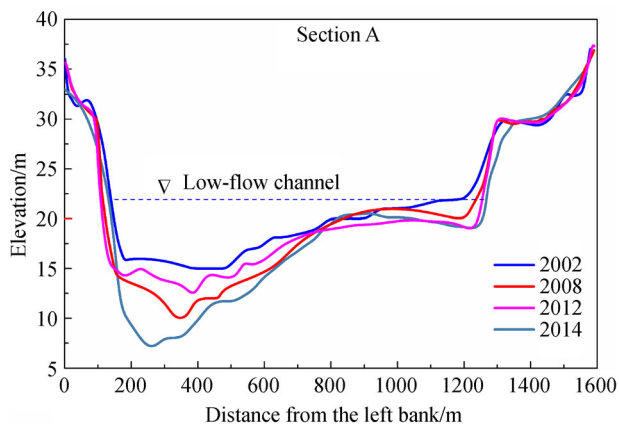
Fig. 9 Erosion intensity of the riverbed in the middle Yangtze River (– erosion; + deposition).

(Chen and Jiang, 2012), and the regulation works of the river bed. The two aforementioned factors indicated that the increasing effects of the resistance can hardly offset the lowering effect of the riverbed deformation in the upper reach, causing the drop of water stages. Meanwhile, the effect of riverbed erosion after 2003 was less than that of riverbed deposition before 2003, leading to the rising trend of water stage in the middle reach in the long timescale.

Owing to the erosion and deposition, water stages in the upper reach revealed a decreasing trend, while those in the middle reach presented an increasing trend in the past decades. The water stage was mainly dominated by the natural evolution in lower reach due to the long distance to the three large engineering structures. Additionally, human activities aggravated the changes in water stages, thereby exceeding 20 years of the primary period of the water stage time series.

### 5.3 Difference of water stage changes between flood and low-flow stages

The completion of large-scale water conservancy projects had caused the scouring of the riverbed in the middle Yangtze River (Li et al., 2011), especially in the low-flow channel. The extension of the cross-section mainly exists at the channels under the low-flow stage (Fig. 10). The proportion of the increase in the cross-section of the low-flow stage overwater caused by the riverbed scouring was larger than that of the flood. In addition, projects, such as the vegetation coverage on the beach and waterway regulation engineering, had increased the resistance of the riverbed above the low-flow stage. This resistance could have weakened the downward trend of the flood stage without affecting the low-flow stage. Therefore, the variation of the low-flow stage was considerably larger than that of the flood stage.



**Fig. 10** Typical cross-sectional profiles after the operation of Three Gorges Reservoir. Location of typical transect is shown as (A) in Fig. 1.

### 5.4 Potential changes in water stages

Since the impoundment of the Three Gorges Reservoir, water stages in the upper reach have shown a significant decreasing trend, while those in the middle and lower reaches presented a limited increasing trend in the past decades. The erosion of the river bed will move downward due to the regulation and storage effect of the Three Gorges Reservoir, causing severe erosion in the middle and lower reaches. Therefore, the downward trend in the upper reach will be maintained, while the upward trend in the middle and lower reaches may be arrested. However, along with the intensification of human activities, the resistance of the riverbed in the middle Yangtze River will further increase. Thus, the flood stage needs additional detailed observation in the future.

## 6 Conclusions

1) In the past 70 years, water stages in the upper reach show a decreasing trend, while those in the middle reach present an increasing trend except for the low-flow stage in the lower reach.

2) Intense human activities have changed the natural evolution process of the riverbed, leading to erosion and deposition in the channels and affecting the water stage. The Jingjiang Cutoff caused riverbed erosion in the upper reach and deposition in the middle and lower reaches. The Gezhouba Dam and Three Gorges Project aggravated the scouring intensity of the middle Yangtze River. Other human activities, such as waterway regulation and levee, also led to an increase in the resistance above the low-flow channel.

3) The variation of the low-flow stage is more significant than that of the flood stage because the scouring is mainly concentrated in the low-water channel.

4) With the intensification of human activities and the operation of the Three Gorges Dam, the downward trend in the upper reaches will be maintained, while the upward trend in the downstream may be arrested. Thus, the stage of the middle Yangtze River needs continuous follow-up observations.

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