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RESEARCH ARTICLE

Dramatic sediment load changes and sedimentation characteristics upstream of the Three Gorges Dam due to the large reservoirs construction

Jie LIU[1,2], Wenwu ZHANG[1,3], Ying SHEN[1,3], Xin WANG (✉)[1,4]

1 National Inland Waterway Regulation Engineering Research Center, Chongqing Jiaotong University, Chongqing 400074, China
2 State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
3 School of River & Ocean Engineering, Chongqing Jiaotong University, Chongqing 400074, China
4 Tianjin Research Institute for Water Transport Engineering, Tianjin 300456, China

Abstract After the construction of cascade reservoirs in the upper reaches of the Three Gorges Reservoir (TGR), the sediment load outflow of the upper Yangtze River Basin (YRB) has been significantly altered, decreasing from 491.8 Mt/yr (1956–2002) to 36.1 Mt/yr (2003–2017) at Yichang station. This has widely affected river hydrology, suspended sediment grain size distribution, and channel morphology. This study analyzed hydrological variations in water discharge and sediment load of the upper YRB over the past 62 years (1956–2017) by employing a double mass curve. The variations in the source areas of sediment yielding for the upper YRB were quantified, and field measurement data of the cross-channel profile were collected to investigate the sedimentation process in the TGR from 2003 to 2017. More than 90% of the sediment load reduction in the upper YRB may be explained by human activities. The Jinshajiang River was no longer the largest sediment source area for the Zhutuo station (accounting for 5.23%) in the 2013–2017 time span, and the sediment rating rates for the inflow and outflow of the TGR shifted to negatively correlated. A longitudinal fining trend was revealed in the suspended sediment size. Still, the mean median grain size of suspended sediment in the TGR had an increasing trend in the 2013–2017 period. This result may be closely related to sediment regulation in reservoirs and incoming sediment load reduction. Sedimentation in the TGR decreased sharply from 299.8 Mt/yr in 2003–2012 to 47.2 Mt/yr in 2013–2017, but the sedimentation rate of the TGR remained at > 80% annually. Moreover, some cross sections in the fluctuating backwater zone experienced scouring.

Keywords cascade reservoirs, sediment load, sedimentation characteristics, suspended sediment grain size, Three Gorges Reservoir

1 Introduction

The sediment transport by rivers from land to oceans is a critical avenue in recycling global substances (Dai et al., 2018; Yang et al., 2018; Guo et al., 2020). Over the past 100 years, water and sediment fluxes in large rivers worldwide have been subject to significant changes owing to climate change and increasing human activities, such as soil conservation, water diversion and abstraction, dam construction, and river sand-mining (Guo et al., 2018; Sirisena et al., 2021). Among these, dams are designed to control river floods and store water for irrigation, generating hydropower, and navigation. However, dams caurse significant decreases in river sediment fluxes (Bhattacharyya and Singh, 2019). According to the statistics of the International Commission on Large Dams (ICOLD), as of 2017, globally, there were approximately 58519 large dams, resulting in a more than 60% reduction in the sediment load of rivers from 1985 to 2010 (Wang et al., 2011; Liu et al., 2022b).

The Yangtze River (YR) is strongly influenced by dam construction. There are over 50000 dams of various sizes in its basin, with more than 200 km^3 of total storage capacity and accounting for about 22% of the annual water discharge of the basin (900 km^3/yr) (Yang et al., 2014; Li et al., 2016; Yan et al., 2021). Among these dams, the Three Gorges Dam (TGD), located in Yichang (Fig. 1(a)), has a total storage capacity of 39.3 km^3, making it the largest hydropower project worldwide. Additionally, the TGD has a flood regulation capacity of

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E-mail: yefuxinxin@126.com

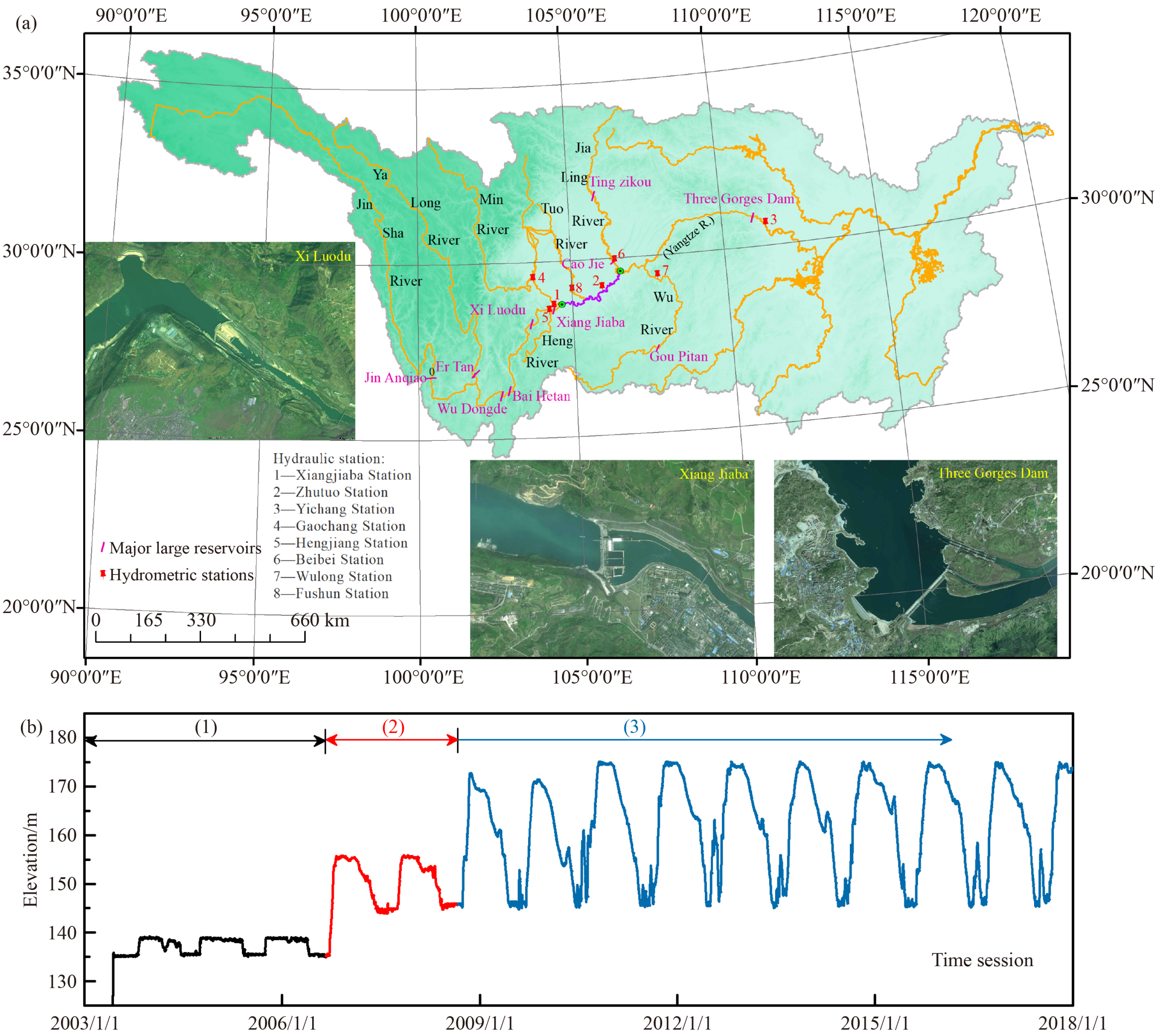

Fig. 1 Map of the study area. (a) Yangtze River Basin (YRB) with main hydrometric stations and dams of the upper YRB. (b) The variation in water level in front of the TGD, based on Wusong elevation, (1) cofferdam stage: 135–139 m; (2) initial impoundment stage: 144–156 m; (3) pilot impoundment and the normal operation stage: 145–175 m.

22.1 km^3, making it the most significant scheme for water regulation in the YR. However, the construction of the TGD has dramatically disrupted river connectivity and has widely affected the river hydrology and channel morphology (Xiao et al., 2016; Tang et al., 2018; Yan et al., 2021). Numerous research efforts have been made to confirm the influence of large upper dams on the hydrological patterns and channel morphology in the middle and lower reaches of the YR. The TGD has been identified as the leading cause of the sharp reduction in sediment load to the lower YR and even to the East China Sea (Xu and Milliman, 2009; Dai and Liu, 2013, Yang et al., 2014; Dai et al., 2016; Li et al., 2016; Guo et al., 2018).

Recently, growing research attention has been focused on altering water discharge and sediment load patterns in the upper YRB. A quantitative analysis of the contribution of natural and anthropogenic factors to sediment load and water discharge has been conducted. It was observed that there was no significant change in water discharge since 1987, while sediment load on the upper YRB had reduced drastically, and more than 85% of the reduction was induced by dam construction (Zhao et al., 2017; Ren et al., 2020; Yan et al., 2021). The sediment fluxes of the upper YRB are mainly attributed to these tributaries, such as the Jinshajiang, Minjiang, Tuojiang, Jialingjiang, and Wujiang Rivers, where dam constructions have increased in the last few decades (Chu et al., 2019; Zhang et al., 2019; Zhou et al., 2020). However, results of the varying contribution of the sediment load from these tributaries to the upper YRB remains to be reported.

On the other hand, the fluvial hydrodynamics in the backwater zone of the TGR, such as the discharge magnitude and sediment-carrying capacity, has been changed by the operation and regulation of upstream cascade reservoirs (Xu and Milliman, 2009; Tang et al., 2016; Kellner and Hubbart, 2018; Liu et al., 2022b). As a result, the suspended sediment particle-size distribution and fluvial suspended sediment delivery regime have been altered (Tang et al., 2018), demonstrating different sedimentation characteristics along the backwater zone of the TGR (Tang et al., 2021). It was revealed in a recent study that the TGR trapped most of the suspended sediment after its impoundment in 2003. The sedimentation rate of the TGR in the 2003–2015 period was 76%, and 92% of silt was trapped in the river section of Fuling-TGD (Fig. 1) (Liu et al., 2022a). However, how sediment redistribution and sedimentation characteristics are regulated by flow regulation remains unclear. Thus, quantitative research in which particle size regimes and sedimentation characteristics are characterized is required to advance the understanding of mechanical processes and management outcomes of extensive reservoir regulation.

This study attempts to provide more systematic findings on sediment problems in the upper YRB, focusing on several aspects: 1) analyzing hydrological variation in water discharge and sediment load of the upper YRB over the past 62 years (1956–2017), determining the variations in the source areas for the upper YRB, 2) clarifying the effect of sediment load reduction on the suspended sediment grain size distribution, and 3) clarifying the effect of sediment load reduction on the sedimentation profile in the TGR.

2 Data sets and methods

2.1 Study area

The YR originates in the Tanggula Mountains on the Qinghai–Tibet Plateau is the longest river in Asia with a total length of over 6300 km and a total drainage area of 1.8 million km^2 (Huang et al., 2019). The upper reaches of the YR are 4504 km long, with a watershed area of nearly 1.08 × 10^6 km^2, and the average gradient from headwater to Yichang (elevation varies from 5100 m to below 500 m) is approximately 1.1‰ (Yang et al., 2007). The main stem of the upper YR is joined by four main large tributaries, such as the Jinshajiang, Minjiang, Jialingjiang, and Wujiang Rivers (Fig. 1). A significant number of large reservoirs (with storage capacity larger than 0.1 km^3) has been built in these sub-basins (Yan et al., 2022).

The basin of the four major tributaries of the Yangtze River, namely the Jinshajiang, Minjiang, Jialingjiang, and Wujiang Rivers, had a total of 41 reservoirs with a combined storage capacity of 79.06 km^3 by the end of 2016. Minjiang River basin had the lowest capacity, with six reservoirs storing 7.37 km^3 of water.The Jialingjiang River basin had 13 reservoirs with a capacity of 13.04 km^3, while the Wujiang River basin had 11 reservoirs with a capacity of 19.77 km^3. The total reservoir storage capacity is twice the size of the TGR. Before the construction of these mega cascade reservoirs, the Jinshajiang River supplied more than half of the sediment load for the upper YR (Wei et al., 2014).

The TGR is a mountainous channel-type reservoir connected by wide valleys and gorges channels. The backwater terminal of the TGR extends to Chongqing, including a perennial backwater area, from Fuling to the dam site (475.5 km in length). It also includes a fluctuating backwater area from Jiangjin to Fuling (198 km in length), which varies in line with changes in the operational water level in front of the dam. The actual water level process in front of the TGD from 2003 to 2017 is shown in Fig. 1(b). The TGD lies at the outlet of the upper YR, approximately 38 km upstream of the Yichang hydrological station. Thus, it is used to evaluate the outflow data from the TGR in this study.

2.2 Data sets

This study used annual water discharge and sediment load data for the hydrological analysis of the TGR inflow and outflow from 1956 to 2017 at Zhutuo, Beibei, Wulong, and Yichang stations. The data were collected from the Bulletin of Yangtze River sediment and downloaded from the Changjiang Water Resources Commission (CWRC). The water and sediment source areas at Zhutuo station changed with the mega cascade reservoir construction in the middle-lower Jinshajiang River basin. It was necessary to quantitatively assess the variations in the water and sand contributions of the main rivers to the Zhutuo station. Therefore, the annual water discharge and sediment load data at the Xiangjiaba, Gaochang, Fushun, and Hengjiang stations from 1956 to 2017 were also collected from the Bulletin of the Yangtze River sediment. The Xiangjiaba, Gaochang, Fushun, and Hengjiang stations represented the control stations of the Jinshajiang River, Minjiang River, Tuojiang River, and Heng River (HR) basins, respectively.

The annual topographic data of typical river sections of the TGR from 2003 to 2017 were obtained from the Yangtze River Waterway Institute of Planning and Design to analyze the suspended sediment particle-size distribution and sedimentation characteristics of the TGR during different impoundment periods. In addition, the annual sediment particle distribution data at these stations (1987–2017) were also collected for sedimentation characteristics assessments.

2.3 Analysis methods

Methods, such as the Manner-Kendall (M-K) test, the Pettitt test, cumulative anomaly, and the double mass curve, have been proven to detect abrupt change points in hydro-meteorological time series (Zhai and Tao, 2017). Among them, the double mass curve has been extensively employed to detect the variations in hydrological regimes caused by human interference (Wang et al., 2016; Guo et al., 2020; Zhou et al., 2020; Yan et al., 2022). The damming in the upper YR is to generate electricity (as opposed to other dams in the region that are used for irrigation) meaning the water discharge is mainly determined by climate change (precipitation) while the dams have little impact. Therefore, we employed the double curve method (cumulative annual water discharge vs. cumulative annual sediment load) to detect abrupt change points and quantify the extent to which human activities and climate change contribute to sediment load variation. Assuming that water discharge change is attributed to climate change and human activities in the three periods (e.g., 1, 2, 3), the following principle is applied (Yan et al., 2021):

$$\Delta S_1 = \beta_1 \Delta R_2, \tag{1}$$

$$\Delta S_2 = \beta_2 \Delta R_2, \tag{2}$$

$$\Delta S_{\mathrm{NW}} = \Delta S_2 - \Delta S_1, \tag{3}$$

$$\Delta S_{\mathrm{W}} = \beta_1 (\Delta R_{\mathrm{m}} - \Delta R_2), \tag{4}$$

$$C_{\mathrm{p}} = \frac{\Delta S_{\mathrm{W}}}{\Delta S_{\mathrm{W}} + \Delta S_{\mathrm{NW}}} \times 100\%, \tag{5}$$

$$C_{\mathrm{h}} = \frac{\Delta S_{\mathrm{NW}}}{\Delta S_{\mathrm{W}} + \Delta S_{\mathrm{NW}}} \times 100\%, \tag{6}$$

where β_1, β_2, and β_3 are the slopes of the three linear fitted curves for the corresponding periods. ΔS_1 represents the expected sediment load under the constant water-sediment relation in period two, while ΔS_2 is the actual sediment load in period two. ΔR_2 represents the accumulated water discharge in period two. ΔS_{NW} is the sediment load change triggered by factors apart from water discharge, while ΔS_{W} is the change in sediment load due to water discharge due to climate change. Based on the mean annual water discharge over the entire period, ΔR_{m} presents the predicted total amount of water discharge in period two. This is based on the average annual water discharge for the whole period and may differ from the actual water discharge. Contributions of climate change and human activities to the change in sediment load are represented by C_{p} and C_{h}, respectively.

3 Results

3.1 Annual variation in water discharge and sediment load

The water discharge and sediment load in a natural river mainly depend on climate and tectonic changes without human intervention. The larger the annual water discharge, the higher the annual sediment load (Steffen et al., 2003). YR has a relatively high-water discharge (fifth globally) and a high sediment load (fourth globally) (Yang et al., 2015; Zhao et al., 2017). The mountainous terrain and significant relief variations in the upper YRB provide suitable conditions for hydropower generation. As of 2017, there were 14624 dams in the upper YRB with a storage capacity of > 10000 m^3 (Guo et al., 2020). As the outlet control station of the upper YRB, the sediment load at Yichang had an apparent change after 2003 when the TGR impoundment commenced, and a substantial amount of sediment was intercepted in its backwater zone. As a result, the sediment load at Yichang was significantly reduced, from 491.8 Mt/yr between 1956 and 2002 to 36.1 Mt/yr in the 2003 to 2017 period. The reduction rate of the mean annual sediment load was approximately 92.7% (Fig. 2(d)). Water discharge in the upper YRB showed a slightly decreasing trend over the period 1956–2017 (Fig. 2): the flux at Yichang decreased by 7.2% from 431.5 km^3/yr (1956–2002, pre-TGR) to 400.3 km^3/yr (2003–2017, pro-TGR), and the sum of the annual flux at Zhutuo, Beibei, and Wulong, contributed 88.7% and 89.5% of the water to Yichang station annually in the pre- and post-TGR periods, respectively, with the variation being < 1% (Fig. 2).

Following the TGR, over a dozen mega dams have been built in the upper YR basin in recent years, including the Xiangjiaba, Xiluodu, Baihetan, and Wudongde reservoirs in the Jinshajiang River (with a total capacity of 44.3 km^3), Caojie and Tingzikou reservoirs in the Jialingjiang River (with a total capacity of 6.34 km^3), and the Goupitan reservoirs in the Wujiang River (with a total capacity of 6.45 km^3) (Fig. 1 and 2). The absolute magnitude of the sediment load and the relative contribution of the three stations changed significantly over the same period (Fig. 2). Before 2003, the sediment load that inflowed to the Three Gorges (451.2 Mt/yr, 1956–2002) was smaller than that at Yichang station (491.8 Mt/yr, 1956–2002). Compared with 1956–2002, the sediment loads at Zhutuo, Beibei, and Wulong stations during 2003–2017 fell steeply, decreasing 60.1%, 77.6%, and 81.7% to 124.4, 25.6, and 4.7 Mt/yr, respectively. However, the contribution of Zhutuo station to the total sediment load flowing in the TGR increased from 69.1% to 80.5%. In comparison, the total sediment load flowing in the Beibei and Wulong stations decreased from 25.3% and 5.6% to 16.5% and 3%, respectively.

3.2 Variation in suspended sediment grain size and composition along the upper Yangtze River Basin

The upper YR is a mountainous river with a relatively steep bed, high flow velocity, and suspended sediment is

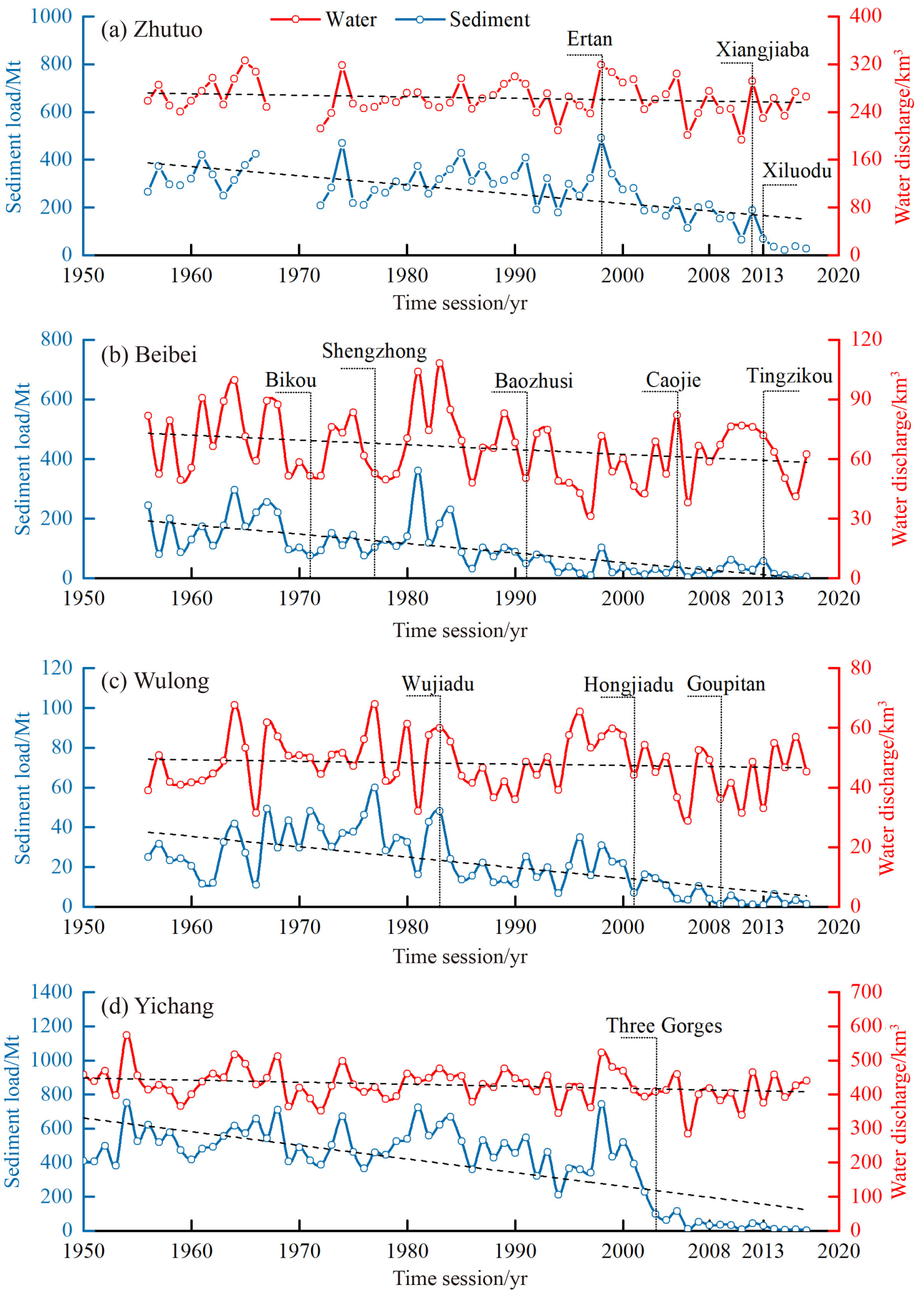

Fig. 2 Temporal variations of annual water and sediment discharge at four hydrological control stations in 1956–2017. The water and sediment discharge dates at Zhutuo from 1967 to 1971 were not measured. Bold vertical lines label the operation time of large reservoirs in tributaries and the main stem of the upper YR in recent years.

generally considered the wash load. The reservoirs constructed in the upstream drainage area trap coarser sediment, resulting in a sharp reduction in sediment load released from the dam and a decline in sediment grain size. Before the TGR, no reservoirs were constructed on the main stem of the upper YR. The mean median grain size (d_{50}) varied from 0.012 mm at Zhutuo to 0.011 mm at Cuntan and Wanzhou and 0.009 mm at Yichang in 1987–2002, displaying a slightly longitudinal fining trend. The grain size for $d > 0.125$ mm decreased from 11% at Zhutuo to 9.0% at Yichang (Fig. 3). After the closure of the TGD, the fluvial hydrodynamics of the TGR, such as the sediment-carrying capacity, were changed by seasonal water level fluctuations (Xiao et al., 2015). As a result, the mean median grain size (d_{50}) at Wanzhou station (located in the perennial backwater zone, Fig. 3) declined by 45.5% to 0.006 mm in 2003–2012. In contrast, the mean median grain size at Cuntan station (located in the fluctuating backwater zone) only decreased by 9% to 0.010 mm in 2003–2012 (Fig. 3).

Moreover, we observed that the suspended sediments at the Qingxichang and Wanzhou stations were composed

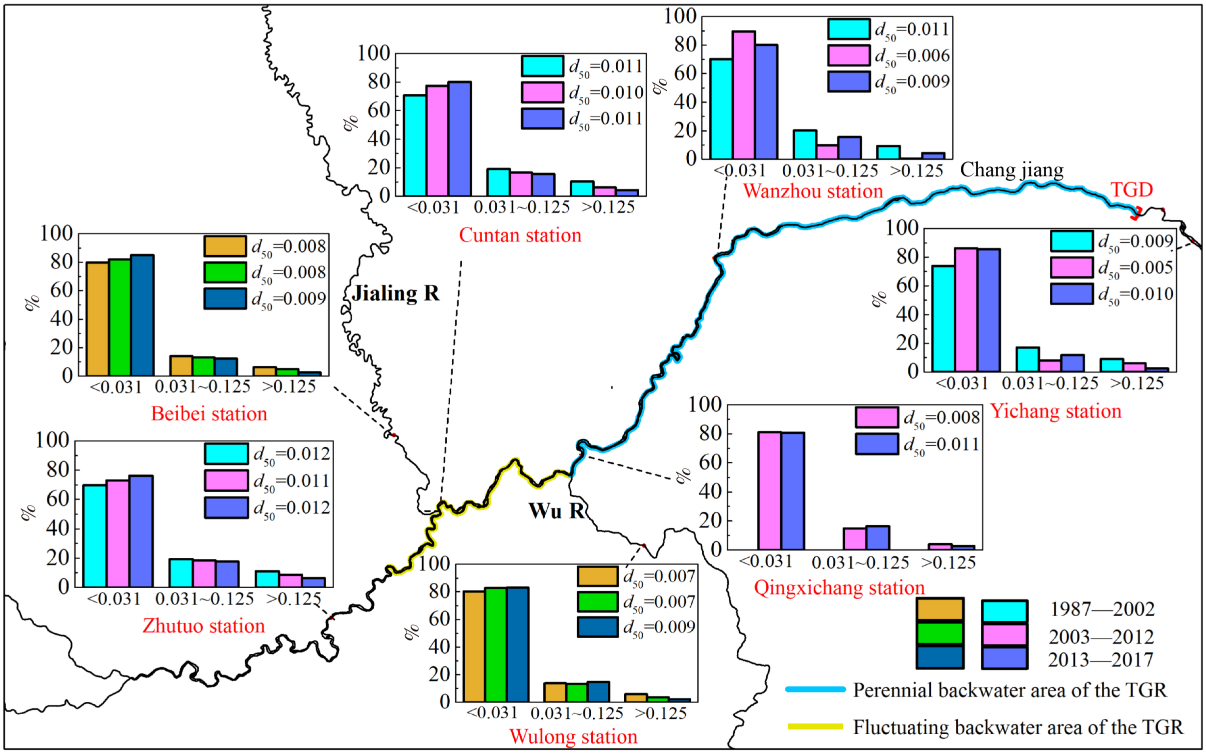

Fig. 3 Variation of the median grain size and grain-size composition of suspended sediment along the upper YR and its tributaries in 1987–2002, 2003–2012, and 2013–2017.

of 81.3% and 89.6% primary particles with $d < 0.031$ mm in 2003–2012, respectively. Cohesive sediment flocculation has been confirmed by *in situ* observation and experimental tests. Sediment flocs have a larger grain size, which can accelerate sedimentation in the TGR (Li and Yang, 2015; Hu, 2018; Liu et al., 2022a), thus, the sedimentation rate of the TGR was 76.3% in 2003–2012, with a high content of primary particles ($d < 0.031$ mm) (Figs. 3 and 8). This result differed significantly from the predictions, indicating that sediments with a grain size $d < 0.01$ mm were considered the wash load in the demonstration stage of the TGR project (Three Gorges Sediment Specialist Group, 1988; Li and Yang, 2015). The mean median grain size (d_{50}) outflow of the TGR became fine, decreasing by 44.4% to 0.005 mm at Yichang station, and the percentage of particles with grain size ($d < 0.031$ mm) gradually increased to 86%.

However, since 2013, the d_{50} of the suspended sediment in the upper YR and its tributaries have had increasing trends (Fig. 3). Particularly, d_{50} at the Qingxichang and Wanzhou stations of the perennial backwater zone and Yichang station of the upper YR outlet increased by 37.5% from 2002 to 2012, 50% from 2012 to 2013, and 50% from 2013 to 2017. This finding corresponds to the changes from 0.008 to 0.011 mm at Qingxichang, 0.006 to 0.009 mm at Wanzhou, and 0.005 to 0.01 mm at Yichang (Fig. 3). These changes in sediment grain size have a fundamental environmental impact, as sediment flocs can carry the nutrients and contaminants to transport in the river continuum. Therefore, future studies are necessary.

4 Discussion

4.1 Causes of sediment load reduction and the contribution of human activities

The double mass curve analysis results are shown in Fig. 4. Obvious and abrupt change points at the four hydrological stations mean that human activities, mainly dam constructions, have contributed to the reduction in sediment load in the upper YR basin (Fig. 5).

The first boom of dam construction in the upper YR basin was in the 1960s–1980s, when approximately 11000 small and 150 medium-sized reservoirs were built, with a total reservoir capacity of > 7 km^3 (Li et al., 2011). During this period, although sediment flux reduction mainly occurred in the Jialingjiang River basin, about 4489 small and 50 medium-sized reservoirs were built in the mid-1970s. Still, the first abrupt change in sediment load at the Beibei station occurred in 1985 (Fig. 4(b)). This means the abrupt change was mainly caused by the construction of large-scale reservoirs, such as the Bikou, Luban, and Shengzhong reservoirs (with a total storage capacity of 2.15 km^3) (Fig. 2(b)) (Zhou et al., 2020), which were predicted to cause a 12 Mt drop in the sediment flux at Beibei station by 1989 (Xu et al., 2008).

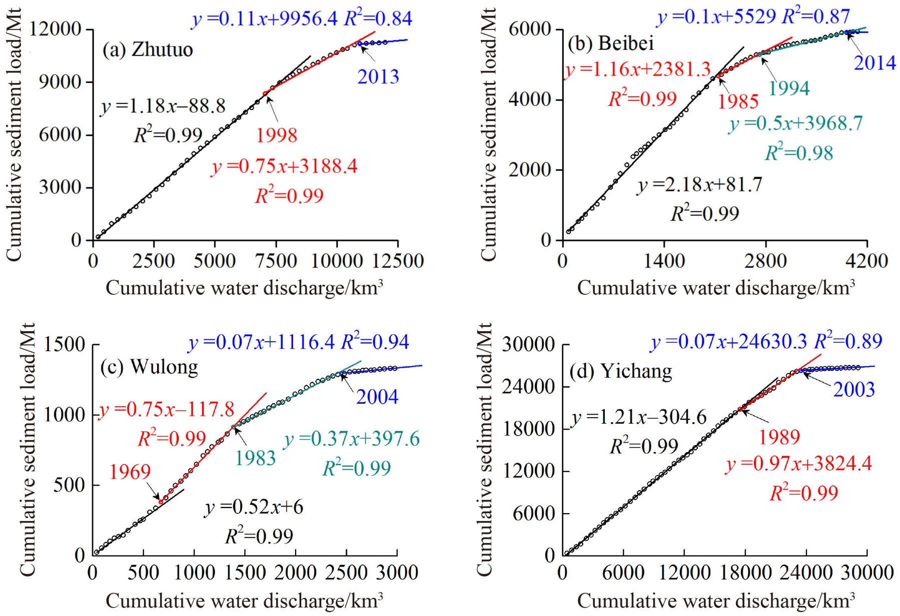

Fig. 4 Double mass curves of the annual sediment load and water discharge at four key hydrological stations in the upper YRB.

Furthermore, the Water and Soil Conservation Project (WSCP) has been conducted since the mid-1980s and may have contributed to the sediment fluxes in the Jialingjiang River basin (Hayashi et al., 2015; Zhou et al., 2020). By 2000, about 33169 km^2 of land had been governed, causing 16–19 Mt/yr sediment reduction at Beibei station (Xu et al., 2008). As a result, the contribution of human activities decreased from 102.2% in 1985–1993 to 87.1% in 1994–2013 (Fig. 5(b)). The change point of 2014 at Beibei station may be primarily attributed to the impoundment of the Tingzikou Reservoir (with a total capacity of 4.12 km^3) since 2013 (Figs. 2(b) and 4(b)). Such impoundment may have resulted in a sharp decline of the double mass curve gradient, from roughly 0.5 in 1994–2013 to 0.1 in the fourth stage, in the 2014–2017 period.

A catchment basin area of 694725 km^2 is covered by the Zhutuo Station, which mainly monitors the incoming water and sediment discharges from the Jinshajiang, Minjiang, Tuojiang, and Hengjiang Rivers. Due to the impoundment of the mega reservoirs in the lower Jinshajiang River basin (Fig. 1 and Fig. 2(a)), the abrupt points for sediment load at Zhutuo station occurred in 1998 and 2013. Before 2013, the Jinshajiang River was

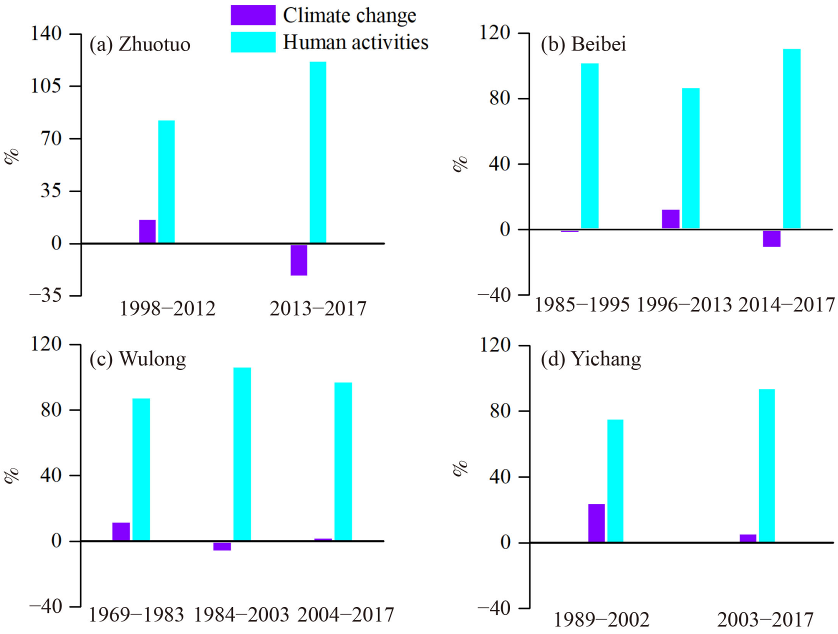

Fig. 5 Contributions of climate change and human activities to sediment load in the upper YRB.

the largest sediment source for the upper YR basin, supplying an average of 240.45 Mt of sediment to the upper YR annually in 1956–1997 (Table 1). However, with the beginning of operations of the Ertan reservoir in the Yalong River (total storage capacity of 5.8 km^3), 90% of the annual sediment was trapped by the Yalong River. This was equivalent to about 20% of the annual sediment load at Xiangjiaba station (Figs. 1 and 2) (Lu et al., 2010; Li et al., 2018).

After the impoundment of the Xiangjiaba and Xiluodu reservoirs in the lower Jinshajiang River (the total storage capacity of 24.24 km^3) (Figs. 1 and 2), Jinshajiang River is no longer the largest sediment source area for Zhutuo station. The proportion of sediment load from the Xiangjiaba station declined sharply from 89.71% to 5.23%. As a result, the sediment load at Zhutuo decreased by 71.2% from 216.89 Mt/yr in 1998–2012 to 37.86 Mt/yr in 2013–2017 (Table 1). The sediment flux source area of Zhutuo station also changed noticeably. The sediment flux contribution of the Min, Tuo, and Heng Rivers to the Zhutuo station increased from 13.89%, 4.8%, and 3.86% in 1998–2012 to 33.02%, 22.16%, and 18.65% in 2013–2017, respectively (Fig. 6). However, despite some minor fluctuations, the water flux of these four rivers and the corresponding contribution for the Zhuotuo station were very stable in the three subperiods (Fig. 5 and Table 1).

As observed in Fig. 4(c), there was a marked separation between water discharge and sediment load at Wulong station in 1984 (Fig. 4(c)). This was highly interrelated with the operation of the Wujiangdu Reservoir (with a total capacity of 2.4 km^3) in the Wujiang River basin in 1983 (Fig. 2(c)). This resulted in a significant reduction in sediment load at Wulong station. Similarly, the sediment load reduction at the Wulong station since 2004 was the result of the operation of the Hongjiadu reservoir (with a total capacity of 4.95 km^3). This resulted in the double mass curve gradient decreasing from about 0.37 in 1984−2003 to 0.07 in the fourth stage, in the 2004–2017 period (Fig. 4(c)). It is noteworthy that there was an abrupt change of sediment flux increase in 1968–1983, mainly because the vegetation was destroyed to cultivate grain to reduce the food shortage due to explosive population growth (Zhao et al., 2017).

Due to the construction of the mega reservoirs and the WSCP in the sub-basins of the upper YR (Fig. 2 and Table 1), the sediment load at Yichang has experienced a drastic decrease in recent decades (Fig. 2), especially since the TGD became operational in 2003. Consequently, there were two abrupt change points at the Yichang station (1989 and 2003) (Fig. 4). The gradient of the double mass curve declined from 0.97 in 1989–2002 to 0.07 in 2003–2017, and the contribution of human activities increased from 75.6% (in 1989−2002) to 94.1% (in 2003–2017).

Notably, there was a sharp sediment load decline around 2013 at the Xiangjiaba, Beibei, and Yichang stations. Still, the gradient of the double mass curve did not show a noticeable change at the Yichang station (Fig. 4(d)). Thus, the sediment rating curves for the inflow and outflow of the TGR in different periods were inspected to determine the impacts of the sediment load reduction (Fig. 7). Generally, the higher the water discharge, the larger the sediment flux. However, sediment rating rates have been decreasing for both the inflow and outflow of the TGR due to human activities. Notably, such activities intensified after the operation of the TGR, resulting in a small sediment load at Yichang station under the same river discharge (Fig. 7). This suggests that the temporal changes in water discharge and sediment load do not correspond to each other. This shifting trend was even more pronounced in the 2013–2017 period, with the sediment rating curves shifting to a negative correlation (Fig. 7). The mean annual water discharge inflow and outflow of the Three Gorges in the 2013–2017 period was only 3.32% and 15.3% lower than that in 1956–2012. In contrast, the mean annual sediment load in the same period declined by 85.58% and 97.3%, respectively.

4.2 Cause of the suspended sediment grain size variation

The information on the suspended sediment grain size distribution is strongly interrelated to sediment transport and adherent nutrients and contaminants, particularly for primary particles ($d < 0.031$ mm). This exhibits a strong cohesion potential (Mehta, 1994; Yang et al., 2018).

Dam construction and soil conservation have

Table 1 Mean annual sediment load and water discharge at five hydrologic stations in 1956–1997, 1998–2012, and 2013–2017. The corresponding rivers for the control hydrological stations are indicated in parentheses

Rivers	Sediment load/(Mt·yr^{-1})			Water discharge/km^3		
	1956−1997	1998−2012	2013−2017	1956−1997	1998−2012	2013−2017
Xiangjiaba (Jinshajiang River)	250.45	194.57	1.98	143.22	151.37	131.92
Gaochang (Minjiang River)	50.39	30.12	12.5	86.43	79.84	77.7
Fushun (Tuojiang River)	12.47	10.53	8.39	10.61	19.7	12.08
Hengjiang (Hengjiang River)	14.24	8.38	7.06	8.34	6.71	8.54
Zhutuo	311.25	216.89	37.86	264.81	265.17	254.24

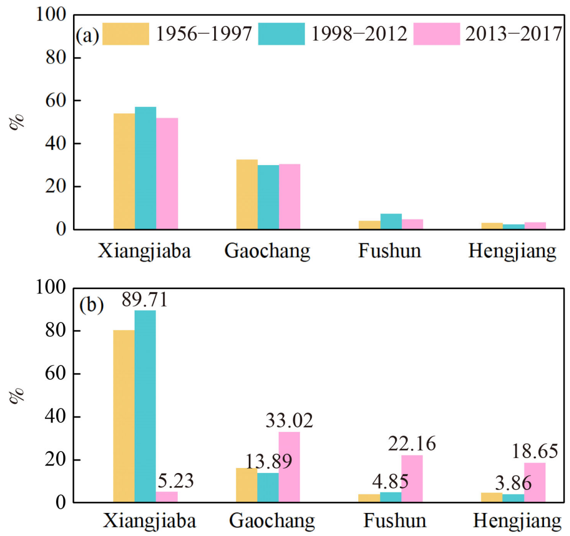

Fig. 6 The proportion of water and sediment source areas for Zhutuo stations in 1956–1997, 1998–2012, and 2013–2017. (a) Water discharge; (b) sediment load.

significantly reduced the sediment load of the upper YRB and have redistributed the grain size of suspended sediments (Guo et al., 2020). After the closure of the TGD, the cascade reservoirs cluster with the TGR as the core has been formed (Fig. 1(b)). Compared to 1987–2002, sediment load at main hydrological stations in the mainstream and tributaries of the upper YR experienced significant fall trends in 2003–2012 (Fig. 2). Due to the sediment-carrying capacity was reduced in reservoirs, the coarser sediment settles first and the finer sediment is released from the dam. As a result, the d_{50} of the suspended sediment at Zhutuo and Yichang decreased from 0.012 mm and 0.09 mm to 0.011 mm and 0.05 mm, respectively (Fig. 3).

However, after the impoundment of the Xiangjiaba and Xiluodu Reservoirs in the lower reach of the Jinshajiang River, which is the main sediment source area for Zhutuo station, the majority of sediment was deposited in the reservoir. Thus, the sediment load at Zhutuo reduced dramatically from 167.67 Mt/yr in 2003–2012 to 37.86 Mt/yr in 2013–2017. At the same time, the d_{50} of the suspended sediment increased to 0.012 mm. A similar change was observed at the Beibei station of the Jialingjiang River and Wulong station of the Wujiang River due to the operation of the Tingzikou Reservoir and the Goupitan Reservoir (Figs. 2 and 3). As a result, the coarse-grained sediment inflow to the TGR increased the d_{50} of the suspended sediment at the Yichang station in 2013–2017 (Fig. 3).

Additionally, the Jiulongpo reach (cross-section CY31) experienced scouring in 2013–2017 (Fig. 11). The resuspension of relatively coarse bed sediment may also lead to an increase in the downstream d_{50}. Furthermore, this increasing trend of the suspended grain size may be ascribed to the sediment regulation of the reservoirs, which is used to discharge the high sediment concentration flowing during flood periods and to reduce the sedimentation of the incoming sediment (Kondolf et al., 2014; Ren et al., 2021). Therefore, the d_{50} of suspended sediment is controlled by multiple factors. This process systematically clarifies the causes of the increasing trend in the d_{50}, and their effects.

4.3 Sedimentation profile along the TGR

Sedimentation threatens sediment balance, water supply sustainability, and dam longevity (Schleiss et al., 2016; Liu et al., 2022b). Due to the sediment load decline and regulation of the mega cascade reservoirs, sedimentation in the TGR underwent remarkable fluctuations in the 2003–2012 period. This is coincident with the variations in sediment load inflow in the TGR (Fig. 8). The mean sediment deposition in the TGR was 154.1 Mt/yr from

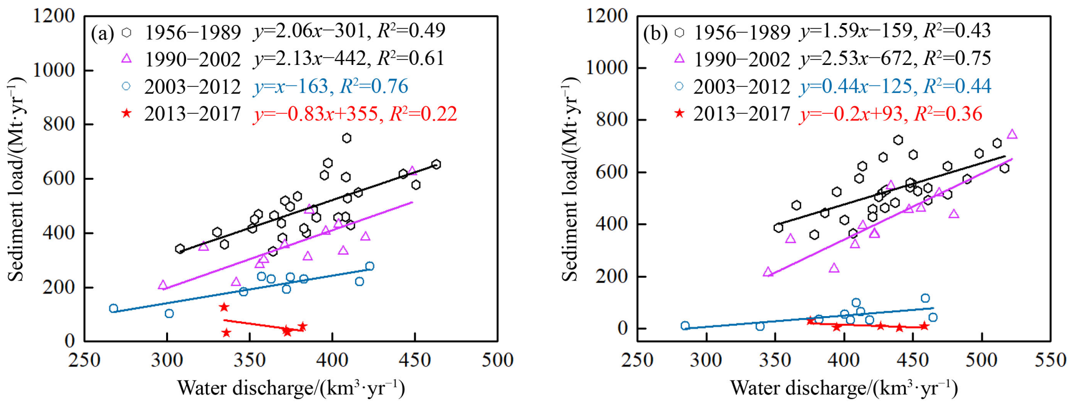

Fig. 7 The rating curves of annual water discharge versus sediment load in 1956–1989, 1990–2002, 2003–2012, and 2013–2017. The annual water and sediment discharge that flows into the TGR is the sum of the values at Zhutuo, Beibei, and Wulong. The dates at Zhutuo from 1967 to 1971 were excluded from the calculation for those years that were not measured. The data for 1998 and 2006 were not calculated for their respective catastrophic floods and extreme droughts. (a) Inflow of three gorges; (b) outflow of three gorges.

2003 to 2017 (Fig. 8), which is much less than the expectation in the demonstration stage (299.8 Mt/yr) (Liu et al., 2022b). Compared with other impoundment stages, the sedimentation rate was relatively low during the Cofferdam stage (2003–2006, water level in front of the TGD: 135–139 m, Fig. 1(b)), at only 69.2%. Following the operation of the Xiangjiaba and Xiluodu Reservoirs in the Jinshajiang River, sedimentation in the TGR decreased sharply to 47.2 Mt/yr in the 2013–2017 period (Fig. 8).

However, the annual sedimentation rate of the TGD did not drop, remaining at > 80% (Fig. 8). This is because sediment input and the sedimentation of the TGR were mainly concentrated in the flood season, and the suspended sediment grain size also increased in the 2013–2017 period. As a result, the sediment-carrying capacity may not be significant enough to discharge all sediment from the TGD (Fig. 8). Given that reservoir construction will continue in the upper YRB, more sediment will be trapped (Liu et al., 2022b). Therefore, it could be predicted that the long-term sedimentation reduction trend in the TGR will continue.

The predicted siltation delta at the entrance of the TGR did not appear. However, the longitudinal profile of the thalweg along the perennial backwater of the TGR has increased to a certain extent. Still, the basic configuration was similar to that of the pre-TGR (Fig. 10). The sediment deposition of the TGR was concentrated in the flood season, with 80.7% and 85.7% occurring from June to October in the 2003–2012 and 2013–2017 periods, respectively (Fig. 9). Sediment deposition in the TGR is asymmetrical, presenting an inconsecutive sheet distribution (Fig. 10) (Li et al., 2015). As a channel-shaped reservoir, a river channel consists of a broad valley, narrow gorges, and a bent channel. With an increase in the water level post-TGR, the wetted area changes little when water enters narrow gorges from the broad valley. Therefore, the reduction in flow velocity in narrow gorges is limited, which is not enough to make sediments settle down and deposit. As a result, scouring occurred in the narrow gorges of the perennial backwater zone (S109) (Fig. 11).

However, the perennial backwater zone of the TGR experienced intensive deposition (Figs. 9 and 10), especially in the reaches with feature bends (e.g., Huanghuacheng Reach (S204)), branches (e.g., Meixi estuary Reach (S113)), and large widths (e.g., near-dam reach (S34)). It has been confirmed that during the flood period, heterogeneous flow could not be discharged from the Xiaolangdi Reservoir (in the Yellow River). The fine sediment was flocculated and deposited in the reservoir after the flood, forming flow mud with a median particle size of 0.006 mm on the riverbed. A mismatch between the numerical calculation results and the measured

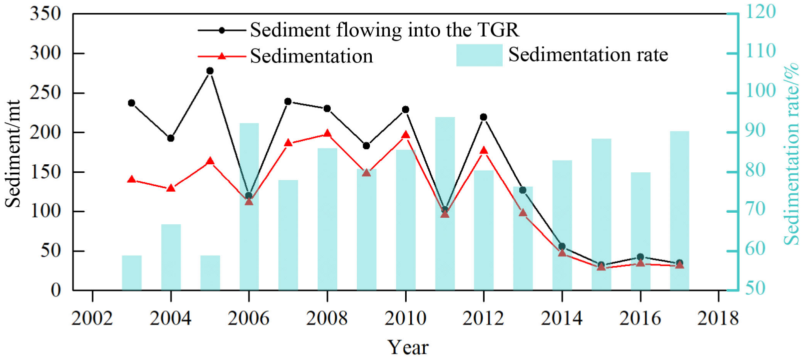

Fig. 8 The annual sediment inflow variation and sedimentation in the TGR.

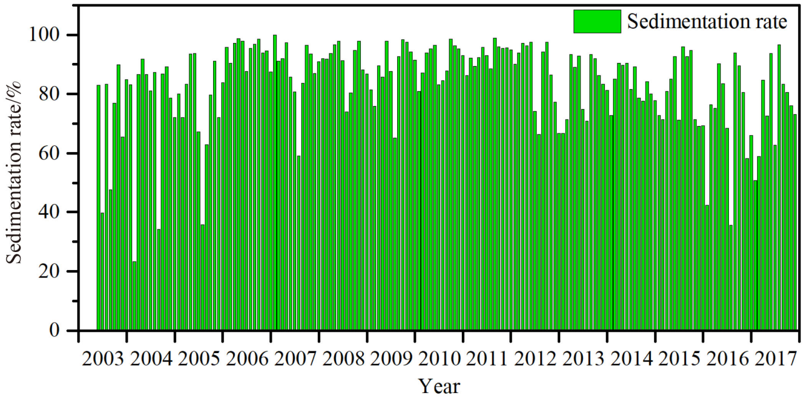

Fig. 9 The monthly sedimentation rate of the TGR.

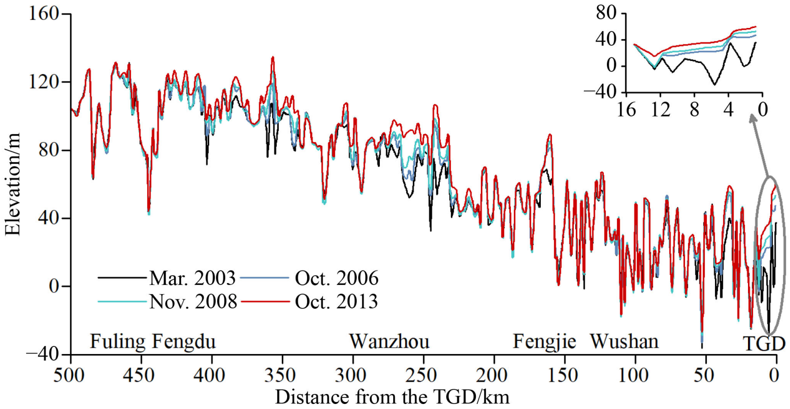

Fig. 10 Change in the longitudinal profile of the backwater zone after the operation of the TGR.

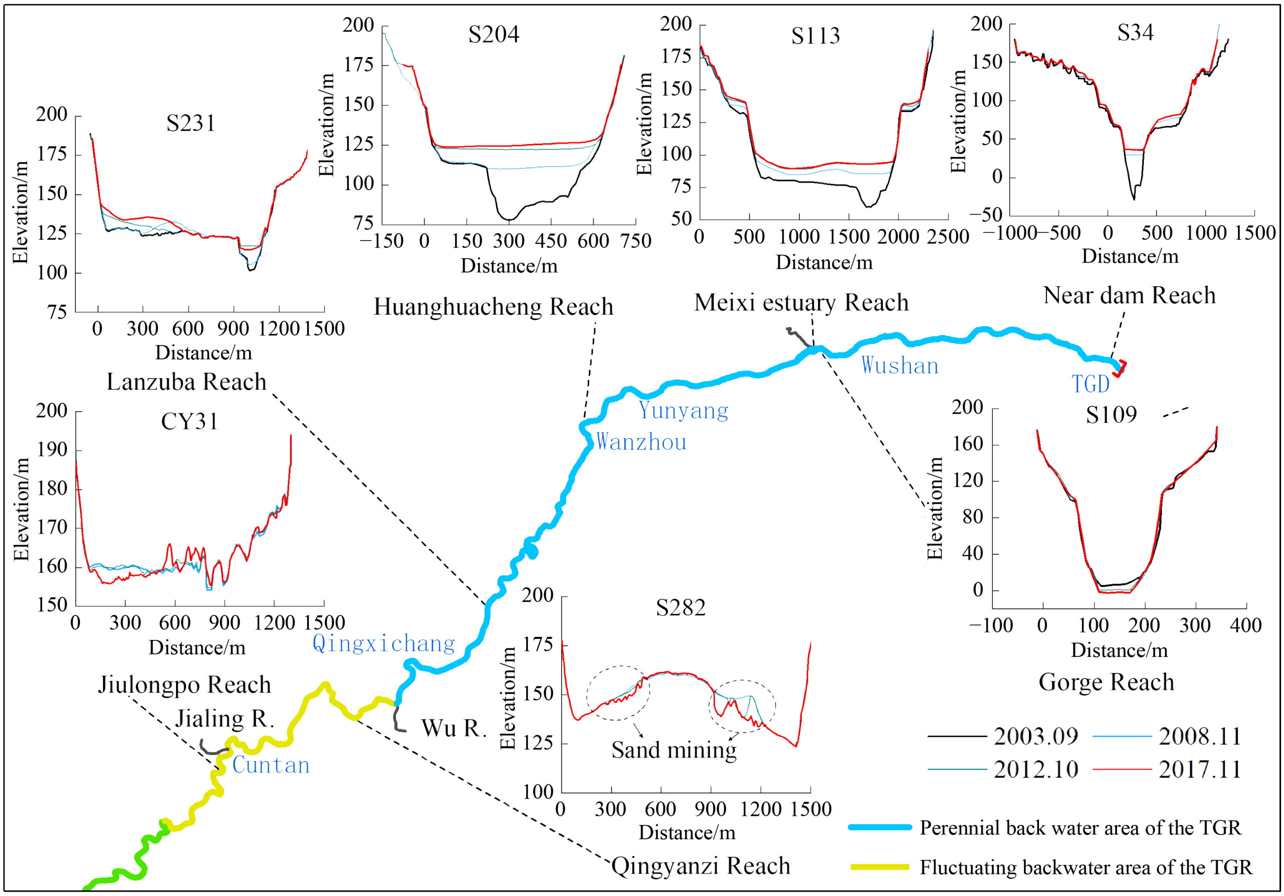

Fig. 11 Cross-channel scouring and sedimentation profiles of typical cross sections in the TGR.

siltation pattern was created by this critical factor (Jia et al., 2020). It has been revealed in recent studies that similar flow mud has been found in the TGR (Li et al., 2020). Therefore, further surveys and studies are needed to systematically analyze fluid mud transport and its impacts on sedimentation.

Due to the operation mode TGR of, "storing clear water and discharging muddy flow", (Bi et al., 2019; Ren et al., 2021) the shapes of some cross-sections maintain comparatively stable in the fluctuating backwater zone. However, due to sediment load reduction (CY31) and sand mining (S282), some cross-sections go through the scouring, and a recent investigation showed that the total volume of sand mining in the river section from Tongluoxia to Dadukou is around 1.81 Mt (Chongqing Water Resources Bureau, 2018; Liu et al., 2022b).

5 Conclusions

We examined the impact of dam construction on water discharge, sediment load, and sediment composition in the upper YRB based on time-series data from 1956 to 2017. The trends and abrupt change points in water and sediment flux were detected by employing a double mass curve. The effects of human activities on sediment load were quantified. Field data of suspended sediment size distribution and cross-channel profiles were collected to investigate the sediment deposition process in the TGR. The following conclusions were drawn.

1) All hydrologic stations in the upper YRB exhibited significantly decreasing sediment load trends. Compared with the pre-TGR, the total sediment load flowing into the TGR decreased by 65.7% post-TGR. Human activities contributed to more than 90% of the sediment load reduction in these sub-basins.

2) The Jinshajiang River is no longer the largest sediment source area for Zhutuo station. The proportion of sediment load from Xiangjiaba station declined sharply from 89.71% in 1998–2012 to 5.23% in 2013–2017. The sediment load for the inflow and outflow of the TGR showed a decreasing trend due to human activities. This shifting trend was even more pronounced in 2013–2017, showing a negative correlation for the first time.

3) The decrease in sediment load caused by mega reservoir construction leads to a directly suspended sediment size distribution in the upper YRB, with a longitudinally fining trend in particle size composition. However, the mean median grain size of suspended sediment in the TGR exhibited increasing trends in the 2013–2017 period, which may be ascribed to decreasing the incoming sediment load and the regulation of the reservoirs. Further research should focus on the reasons for the increased suspended sediment grain size and its effects.

4) Sedimentation in the TGR mainly occurred in the perennial backwater region and decreased sharply from 299.8 Mt/yr in 2003–2012 to 47.2 Mt/yr in 2013–2017. Sedimentation in the reservoir area was significantly slowed. At the same time, the annual sedimentation rate of the TGR did not decrease, remaining at > 80%. Some river sections in the fluctuating backwater zone experienced scouring, possibly due to sediment load reduction and sand mining.

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