Impact of the Three Gorges Dam on sediment deposition and erosion in the middle Yangtze River: a case study of the Shashi Reach

Wei Zhang, Jing Yuan, Jianqiao Han, Chengtao Huang and Ming Li

ABSTRACT

Channel morphology in an alluvial river usually varies due to the altered flow and sediment regime from upstream damming. This paper reports an evaluation of the dynamical changes of sedimentation and erosion in the middle and lower reaches of the Yangtze River after operation of the Three Gorges Dam (TGD). Here, we present the results from a case study of the Shashi Reach in the middle Yangtze River, which is the first sandy-bed and meandering reach downstream of TGD. Databases were constructed using a digital elevation model of channel topography based on the 1:10,000 topographic maps from the 1980s to 2012 and hydrological records from 1956 to 2013. Results indicate that the erosion in the Shashi Reach was mainly confined to the deeper channel and that it has increased since the construction of the TGD. No significant changes were observed above the bank-full level, resulting in the decrease of the width-to-depth ratio. These changes may be principally caused by variations of the seasonal distribution of flow and sediment due to the operation of the dam. In addition, results show that the cross-sectional shape change of the channel is related to the relative erodibility of the channel bed and bank material.

Key words | flow and sediment conditions, fluvial sedimentation, Three Gorges Dam project, Yangtze River

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INTRODUCTION

Large rivers comprise highly complex and dynamic geomorphological systems that can have immense cultural, socioeconomic, and political significance. Natural events such as floods and cutoffs, as well as human activities including dam construction, sediment dredging, and bank revetment, have the potential to alter the supply of water and sediment toward and/or within rivers. Changes in these inputs can affect the morphology of the channel. This phenomenon can influence various environmental and social aspects. For example, it can challenge the management of navigation and of flood hazards. Therefore, an improved understanding of channel responses to changes in these inputs is an important component of responsible water development and land management for large alluvial rivers. The adjustment of large watercourses such as the Nile, Indus, Yellow, and Mississippi rivers has long been a focus of debate (Braga & Gervasoni 1989; Schumm & Winkley 1994; Brandt 2000; Fuller *et al.* 2003; Kesel 2003; Abdelbary 2004; Wang *et al.* 2007).

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These studies established the complex relationship between flow and sediment conditions, as well as the evolution of the downstream channels. Variations of the basic hydrology introduces many degrees of freedom concerning the potential channel adjustments, including changes in the slope, geometry, and planform of the channel and alterations of the texture (Lisle *et al.* 1993) and organization of the bed (Gaeuman *et al.* 2005). The construction of a dam is likely to have different effects from one region to another, making it difficult to predict the channel response.

The largest dam in the world is the Three Gorges Dam (TGD) on the Yangtze River in China. Following its construction, the response of the middle reach of the river has received considerable attention. The channel degradation and adjustment downstream of the TGD were predicted by many different methods over the last 20 years (Wang & Han 1997; China Institute of Water Resources and Hydropower Research (CIWHR) 2002; Yangtze River Scientific Research Institute (YRSRI) 2002; Xu & Milliman 2009; Dai *et al.* 2011a; Yang *et al.* 2011). However, recent research on the impact of the TGD has focused mainly on the changes in the material fluxes in the middle and lower reaches of the river and on the water exchanges between the river and several large lakes (Yu *et al.* 2009; Xu *et al.* 2010; Hu *et al.* 2011; Guo *et al.* 2012; Sun *et al.* 2012; Yang *et al.* 2014; Lai *et al.* 2016; Yang *et al.* 2015). Relatively little attention has been paid to the processes of sedimentation and channel adjustment. Although a global study on the channel adjustments of large fluvial rivers has previously provided a starting point for research into channel adjustments downstream of the TGD, detailed predictions and explanations need to take into account the local and regional geological settings, geomorphic history and controls, hydrological regime, reservoir operation, and other local variables (Friedman *et al.* 1998). Investigating the channel response of such a large fluvial system to the storage of water and sediment by the TGD would provide valuable information for this area of research. This study focuses on a 70-km segment in the middle reach of the Yangtze River (the Shashi Reach), downstream of the TGD, with the following objectives: (1) to quantify the erosion/deposition of the channel, including changes in the thalweg and cross section and (2) to examine the variations in water and sediment fluxes and their impact on the fluvial morphology of the Shashi Reach.

MATERIAL AND METHODS

Study area

The middle reaches of the Yangtze River stretch from Yichang to the confluence with Lake Poyang, covering a length of 950 km and a total drainage area of about 68×10^4 km^2. Dongting Lake, its local tributaries, and the Hanjiang River join the trunk river in this reach from the southern and northern sides, respectively.

The Shashi Reach lies within the middle reaches of the Yangtze River, about 194 km from the TGD (Figure 1). This 70 km-long meandering channel is the first sandy-bed reach downstream of the TGD. It stretches from Yangjialao to Gongan County (Figure 1(b)), with a confined channel boundary and low sinuosity in planform. At Taipingkou in the Shashi Reach (138 km from Yichang), there is one diversion, formed by historical avulsions, which links the Yangtze River with the Dongting Lake. This usually diverts the discharge from the main stream during the flood season but it is commonly dry in the low-flow season. The flow and sediment discharge of the Shashi Reach are characterized by the observations from the Shashi gauging station. From 1955 to 2002, the mean annual runoff and sediment load were $3{,}942 \times 10^8$ m^3 and 4.27×10^8 t, respectively, before the impoundment by the TGD. After the impoundment, the mean annual runoff and sediment load were $3{,}690 \times 10^8$ m^3 and 0.67×10^8 t, respectively, from 2003 to 2013.

Human activity in the Shashi Reach includes the ongoing construction of levees, bank revetments, and waterway-regulation engineering. The Shashi Reach is considered as one of the most dangerous reaches on the Yangtze River during flood seasons. Since the 19th century (or possibly even earlier), modifications made to the form of bank protections have disrupted the pathways of the sediment and water into the adjacent floodplains and lakes. This led to the elevation of the channel bed due to a continuous deposition and to the subsequent increase of the flood stage. Furthermore, the flood hazard has increased because of

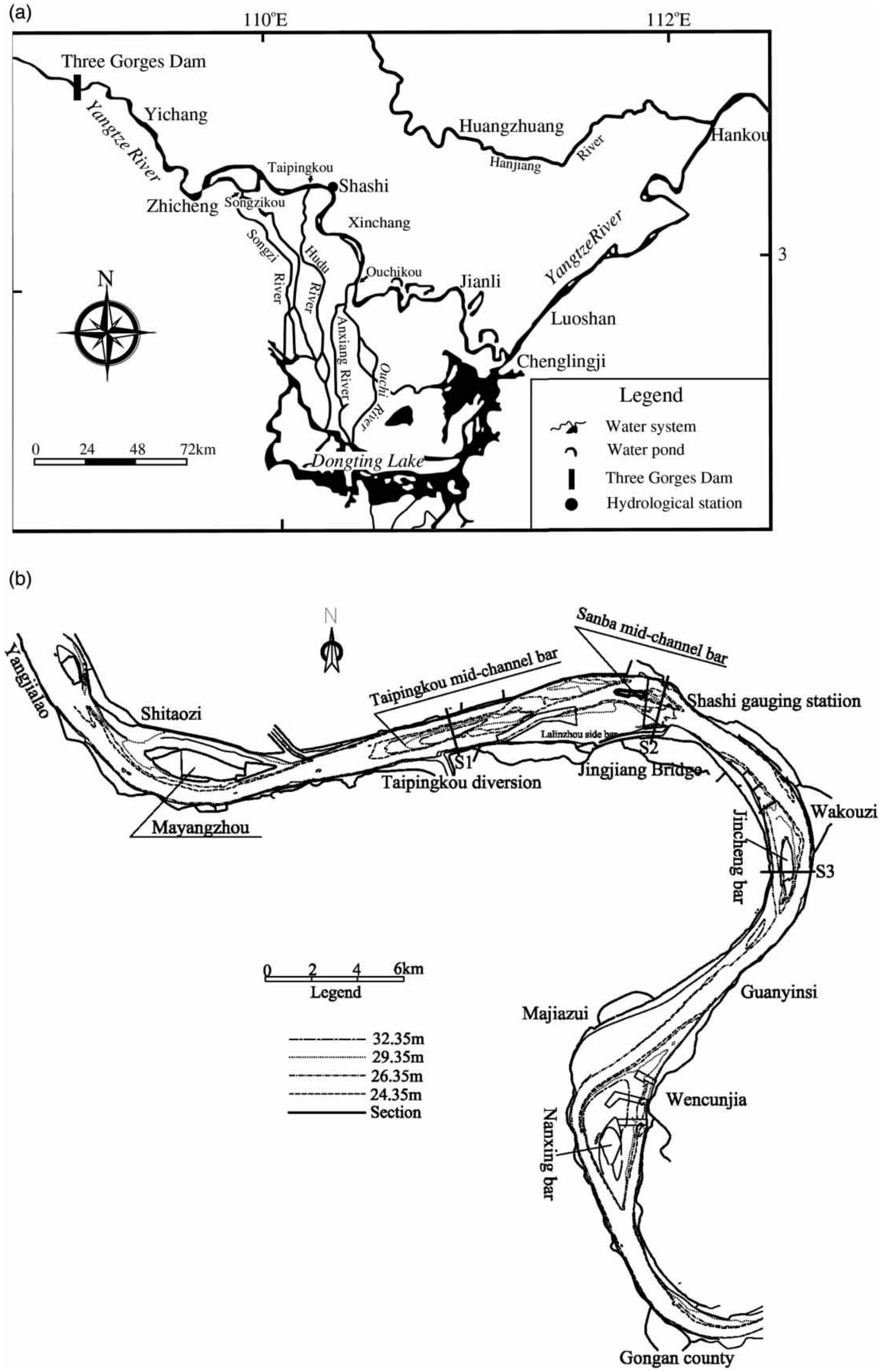

Figure 1 | (a) Map of the middle Yangtze basin showing the locations of the Three Gorges Dam (TGD) and the gauging station. (b) Enlarged map of the Shashi Reach showing the planform of the reach and the locations of the three cross sections (captions 32.35, 29.35, 26.35 and 24.35 m give the elevation of contour).

the susceptibility of the bank conditions and the fragile foundations of the levees along the banks. The Shashi Reach is currently protected by 120 km of levees, including the great Jingjiang levee and the major Yangtze levees funded by the national government. After the 1998 flood, the levee bodies were reinforced to 8–12 m in width and another 47 m in height (based on the Wusong Datum level) (Yu *et al.* 2009).

The TGD is the world's largest hydroelectric power plant and the most important water control project on the Yangtze River. Its construction began in 1992 and water impoundment began in June 2003. The TGD was designed with a flood control capacity of 22.15×10^9 m^3 and its total storage capacity can reach 39.3×10^9 m^3. This storage volume is relatively small, e.g., it is only 9.2% of the long-term mean annual flow at Yichang. Although the TGD was not designed to change the total flow volume released into the river downstream of the dam, the storage strategy does induce changes in the distribution of the seasonal flow. Furthermore, the dam stores most of the sediment that arrives from the upstream catchment. Thus, these changes affect the dynamics and morphology of the Yangtze channel downstream of the dam.

Data collection and methods

Data obtained from the Shashi gauging station on the Shashi Reach of the Yangtze River (Figure 1(a)) were used to construct a database of flow and sediment load. This station is operated by the Changjiang Water Resources Commission (CWRC). Flow, suspended sediment concentration (SSC), suspended sediment discharge (SSD), and suspended sediment and bed-material grain sizes were measured daily following the standard procedures of the Chinese Ministry of Water Resources, published by the CWRC (1956–2013). Based on the time series of daily SSC, SSD, and water discharge from the Shashi gauging station, the annual water quantity, annual sediment load, and monthly distributions of flow discharge and sediment load for different periods were plotted and analyzed (Figure 2). In addition, the water discharge and sediment discharge, which can be used to test the consistency of the water–sediment relationship at a specific river cross section, were plotted to analyze the variations in the water–sediment relationship in the pre- and post-TGD periods (Figure 3).

Historical maps and aerial photographs are useful tools in the analysis of channel changes (Castiglioni & Pellegrini 1981; Bravard & Bethemont 1989; Hooke & Redmond 1989; Castaldini & Piacente 1995). In the case of the Shashi Reach, a historical analysis is particularly pertinent because of the availability of high-quality large-scale topographic maps covering a long period. We used topographic 1:10,000 maps from the 1980s to 2012 to construct digital elevation models (DEMs). In order to investigate the channel planform, quantitative analyses of the channel area, width, and thalweg, as well as patterns of erosion and deposition were made based on the information derived from the topographic maps. Subsequently, three cross sections (shown in Figure 1) were extracted from each DEM to analyze the pre- and post-TGD changes of channel geometry along the studied reach.

All the original raw data and published data used in this study were obtained from the CWRC (http://www.cjh.com.cn) and the Changjiang Waterway Bureau. Before these data were released to the public, they underwent rigorous verification and uncertainty analysis following government protocols published by the China Ministry of Hydraulics and Ministry of Transport (Dai & Liu 2013). The quality control imposed by the surveying agencies ensures the reliability of the data used in this study.

RESULTS

Changes in the hydrological conditions

The runoff and sediment load of the Shashi Reach predominantly come from the upper reaches. Based on data from the Shashi gauging station and on previous research (Chen *et al.* 2001), it was established that the fluxes of discharge and sediment load in the Yangtze River vary seasonally, primarily reflecting the effect of monsoonal precipitation. Along the upper basin of the Yangtze River, precipitation occurs mostly from May to September, the period during which the rainfall amount accounts for 79.1% of the annual total. Thus, the maximum discharge and associated flooding always occur

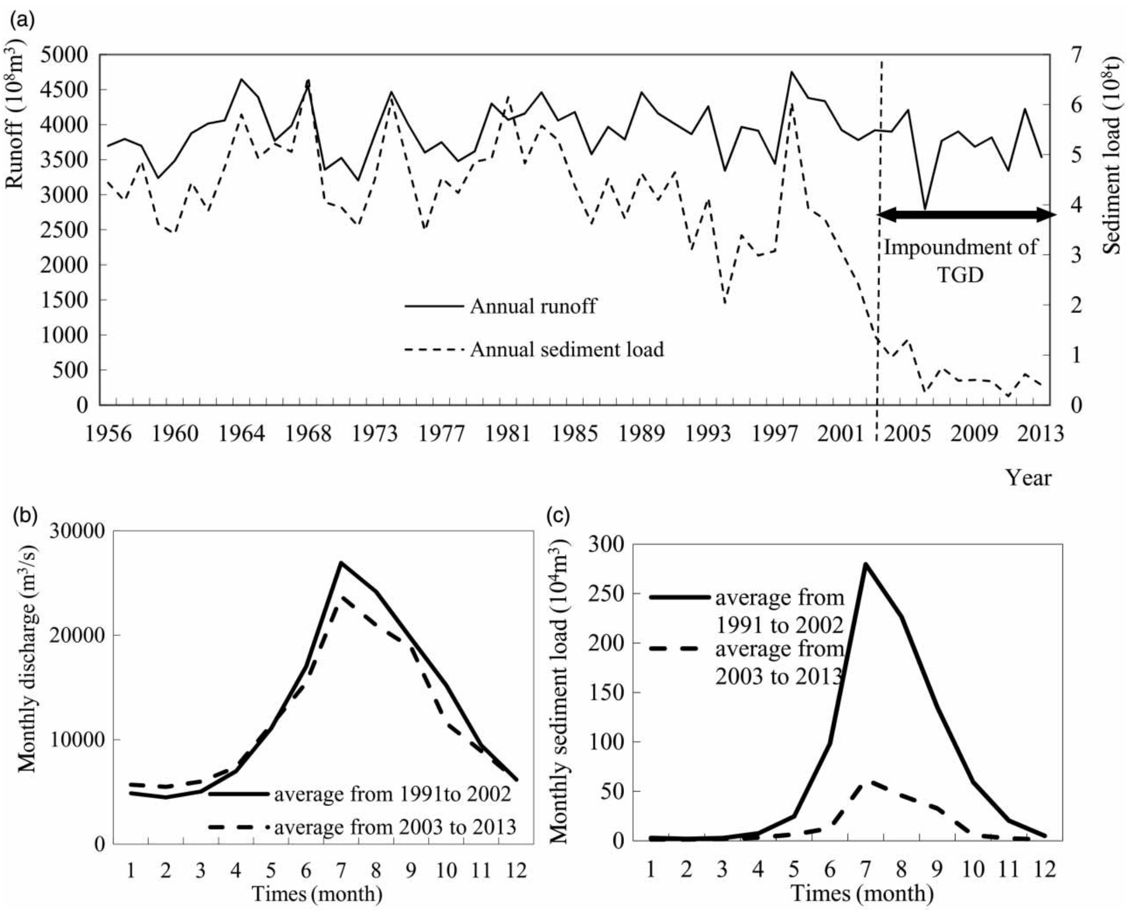

Figure 2 | Time series of annual runoff and sediment load at the Shashi Station (a), and average monthly water discharge and sediment load at the Shashi Station for the pre- and post-TGD period, (b) monthly discharge, and (c) monthly sediment load.

between May and September. During the wet season of May to October, the sediment load measured at the Shashi Reach comprises 88%–95% of the annual total.

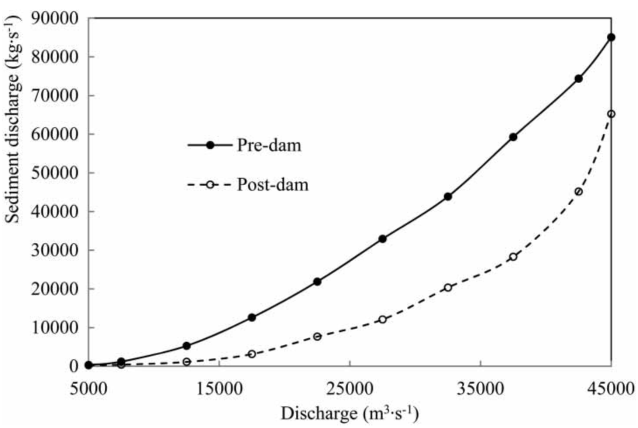

Figure 3 | Relationships between the flow discharge and the sediment discharge at Shashi gauging station for the pre- and post-TGD periods.

Floods play an important role in sediment transportation in the middle reaches of the Yangtze River. For example, in large flood years such as 1998, the sediment loads were far in excess of the mean annual value (Figure 2).

The TGD began impounding water in June 2003. Similar to other dams on this large alluvial river, the management of flood control, electric power generation, and navigation by the TGD caused a change in the hydrological regime of the river. Figure 2 and Table 1 show that dam regulation has little impact on the annual runoff. For example, compared with the average annual runoff during the pre-TGD period, the change in the post-TGD average annual runoff is no larger than 7%, except for the runoff during 2006 (an exceptionally dry year); however, the flow process is significantly altered. The main characteristics of the change in flow consist of a decrease in the flood peaks and an increase

Table 1 | Comparison of pre- and post-TGD annual runoff and sediment load at the Shashi gauging station

	Pre-TGD average (1956–2002)	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Post-TGD average (2003–2013)
Annual runoff ($\times 10^8$ m^3)	3,943	3,920	3,901	4,210	2,795	3,770	3,902	3,686	3,819	3,345	4,224	3,538	3,737
Annual sediment load ($\times 10^8$ t)	4.34	1.38	0.956	1.32	0.245	0.751	0.492	0.506	0.48	0.181	0.617	0.402	0.666

in the magnitude and duration of low-flow periods (Figure 2). As shown in Figure 3, the flow amplitude (ratio of maximum discharge to minimum discharge) changes from 10.9 to 7.3 between the pre-TGD and post-TGD periods. In comparison with the pre-TGD period, the frequency of the discharges of 6,000–19,000 m^3·s^{-1} increased by 7.1% in the post-TGD period. In the same period, the frequency of observed river flows >19,000 m^3·s^{-1} decreased significantly, especially for flood discharges, while the relative frequency of discharges >35,000 m^3·s^{-1} was only 2.2%.

In addition to water discharge, sediment transport was affected. Observational data have shown that the combined sediment trap efficiency of the TGD and the Gezhouba Dam was about 80% from 2003 to 2013, i.e., only a small proportion of the upstream load was carried into the downstream reaches. Based on the data from the Shashi gauging station, the average annual sediment load decreased by 80% after TGD impoundment (Table 1), and both the sediment load and the monthly sediment discharges were reduced, as shown in Figure 2. The decrease observed in the sediment load was largest in the flood season from May to October.

Changes in the runoff volume and the sediment load in the post-TGD period altered the relationship between the discharge and sediment (Figure 3), as reflected by the suspended sediment transport rate. At the Shashi gauging station, the sediment load decreased more dramatically in the post-TGD period than the discharge, leading to the decrease of the suspended sediment transport rate. As shown in Figure 3, most suspended sediment transport rates measured in the post-TGD period were <43,000 kg·s^{-1}, even for discharges >40,000 m^3·s^{-1}, while in the pre-TGD period, SSC typically reached about 43,000 kg·s^{-1} at discharge rates ~30,000 m^3·s^{-1}. In addition to reduced load and concentration, a decrease in the grain size of the released suspended sediments was observed. The annual sediment load at d > 0.125 mm decreased by 38%.

Channel adjustment amounts of erosion and deposition

As shown in Figure 1, numerous bars exist in the Shashi Reach, which can appear during the low-flow season but may remain submerged during floods. According to the heights of these bars, the channel can be divided into the low-flow channel, which is below the water level corresponding to a flow of 5,050 m^3·s^{-1}, and the bank-full channel, which is below the level of the active floodplain with a corresponding flow of 27,000 m^3·s^{-1} at the Shashi gauging station (the water level is 38.4 m based on China's Huanghai datum). To demonstrate the initial impact of the TGD on fluvial sedimentation in the Shashi Reach, the sediment budget was estimated based on relief maps of the river channel for the periods before (1981–2002) and after (2003–2010) the construction of the TGD, and the deposition/erosion in the Shashi Reach during these periods was calculated and analyzed.

In the pre-TGD period, the sediment budget shows that the Shashi Reach was subjected to significant erosion (Table 2). The sediment eroded from the reach amounted to 0.7×10^8 m^3 from 1981 to 2002. Erosion mainly occurred in the low-flow channel and reached 0.77×10^8

Table 2 | Quantification of the erosion and the deposition in the river channel ($\times 10^8$ m^3)

	1980–2002	2003–2006	2006–2008	2008–2013
Bank-full flow channel	−0.70	−0.48	−0.14	−0.64
Low flow channel	−0.77	−0.45	−0.13	−0.57

Negative values indicate erosion.

m^3, while in the bars, accretion took place, reaching $0.07 \times 10^8\ m^3$ (the value is the amount of bank-full flow channel minus low-flow channel). After the TGD began to operate, the mean SSD decreased noticeably. The average annual sediment load decreased by 80% post-TGD. This change generally matched the changes in erosion/accretion on the riverbed in the reach. The erosion that occurred pre-TGD continued. Table 2 shows that during the initial stage (*c.* 2003–2006), transitional stage (*c.* 2006–2008), and normal stage of the TGD project, the eroded sediment in the flood channel of the reach reached 0.48×10^8, 0.14×10^8, and $0.64 \times 10^8\ m^3$, respectively. Erosion still occurred predominantly in the low-flow channel. Over all three stages of the TGD project, the ratio of the amount of erosion in the low-flow channel to the amount in the bank-full channel was about 90%.

For further comparison, erosion/accretion values were converted to provide the amount of erosion/accretion per unit length per year. These values show that post-TGD erosion was greater than pre-TGD erosion. In the pre-TGD period, the eroded sediment in the reach only reached $6.67 \times 10^4\ m^3 \cdot km^{-1} \cdot yr^{-1}$, whereas in the three stages of the TGD project, the sediment erosion levels were 21×10^4, 12.6×10^4, and $20.8 \times 10^4\ m^3 \cdot km^{-1} \cdot yr^{-1}$, respectively.

Cross-sectional changes

Changes observed in the three selected cross sections (S1–S3) show that the riverbanks were basically stable, but with an enlargement of the cross-sectional areas between the different periods (Figure 4(b)). Significant down-cutting appeared in the troughs. For example, the down-cutting of the right-hand trough at S3 was about 10 m. For all three cross sections, accretion occurred on the mid-channel shoals (e.g., the accretion on the mid-channel shoal was about 3 m at S3). These changes show that erosion still occurred predominantly in the low-flow channel, whereas the area above the bank-full level saw almost no change.

The width-to-depth ratio ($B^{1/2}/h$) provides further information on the changes in the river's cross-sectional shape, as shown in Figure 4. This ratio shows a decreasing trend for all cross sections from 2002 to 2012. The value decreased by a larger amount where the initial width-to-depth ratio was greater. For example, in the Sanba bar segment, the width-to-depth ratio was about 5.5 and the maximum decrement was about 1. In contrast, in some single segments, the width-to-depth ratio was about 2.4

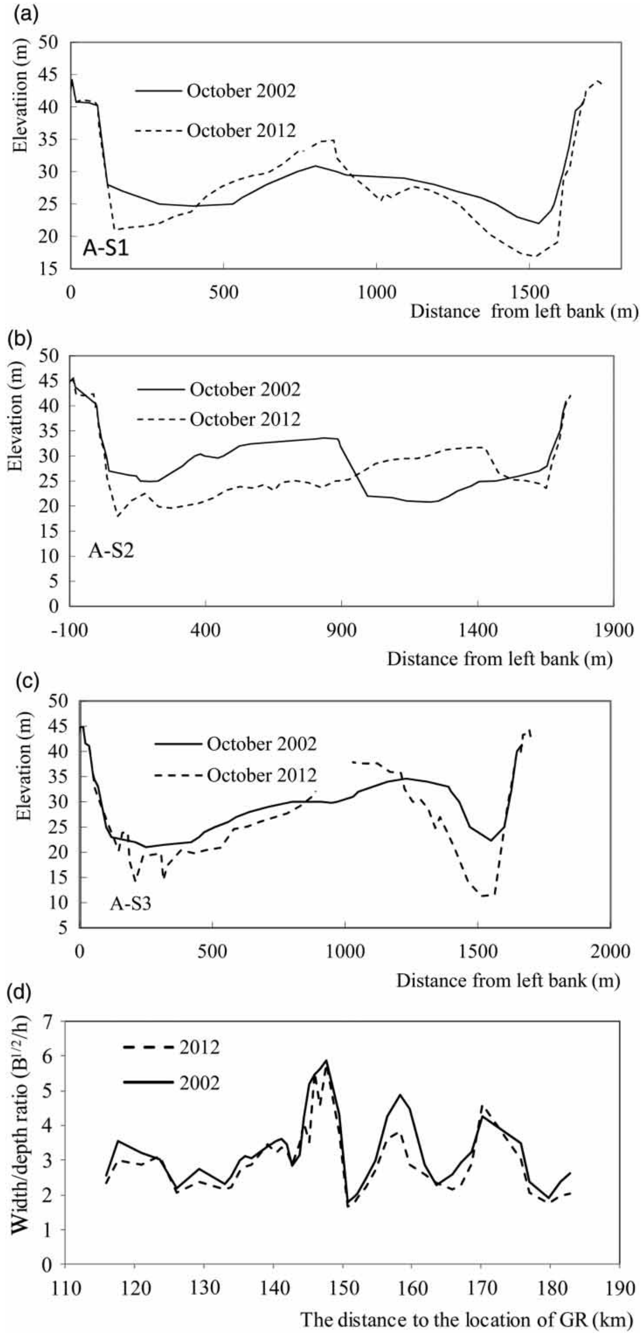

Figure 4 | Spatial and temporal variability for cross sections in the Shashi Reach. (a)–(c) Changes in typical cross sections (S1, S2, and S3) from 2002 to 2012 derived from DEMs. Cross sections are shown from the left bank to the right bank, facing downstream. The location of each cross section is indicated in Figure 1. (d) Changes in the width-to-depth ratio for different cross sections along the reach; B and h are the bank-full width and bank-full water depth, respectively.

and the maximum decrement was only 0.5. These results indicate that the overall change in the cross-sectional shape was from wide and shallow to narrow and deep, and that erosion was stronger where the initial width-to-depth ratio was relatively large.

Along-river thalweg depth changes

Depth changes along the thalweg in the Shashi Reach (Figure 5) show a gradual deepening. After the initial impoundment of the TGD in 2003, the thalweg depths at the Chenjiawan and Shashi gauging stations lowered significantly, and the down-cutting was 8 and 7 m, respectively. The maximum depth reached 6 m and the average down-cutting was 2 m.

To demonstrate further the cross-sectional shape deformation, the relationship between cross-sectional shape and erosion/accretion in the thalweg was estimated for the post-TGD period (2002–2012) (Figure 6). The width-to-depth ratio ($B^{1/2}/h$) shows the cross-sectional shape, and the difference in the thalweg depths from 2008 to 2012 presents the erosion/accretion in the thalweg. These results confirm that erosion increases with the width-to-depth ratio, indicating that erosion was strongest where the cross-sectional shape was wide and shallow. For example, in anabranch segments, such as the Sanba bar segments, the mean width-to-depth ratio was about 5.5 and the down-cutting in the thalweg was about 3.76 m. In contrast, in the single segments, the mean width-to-depth ratio was about 2.5 and the down-cutting in the thalweg was only 1.41 m.

DISCUSSION

Fluvial channels are able to make self-adjustments (Leopold et al. 1964; Knighton 1984; Richards 1985; Merritt & Wohl 2003; Liu et al. 2016). Based on the case of the Yangtze River, one decade after the TGD began operation, the impact of the dam on the studied reach was assessed. First, given the small storage volume of the TGD in relation to the total annual flow and the lack of any significant diversions from the dam, it is not surprising that the annual flow totals were not significantly affected by the operation of the dam. The runoff record at the Shashi gauging station did not show any apparent change between the pre- and post-TGD periods (Table 1). Furthermore, regarding the changes in sediment transport, the records of sediment transport load showed a slight decrease between 1981 and 2002, i.e., the mean annual sediment transport load of 1981–1990 and 1991–2002 was 4.68×10^8 and 3.55×10^8 t, respectively. However, the sediment load decreased sharply in the reach in 2003 (corresponding to the beginning of the impoundment at the TGD). The mean sediment load of 2003–2013 was only 0.69×10^8 t and the minimum value (which occurred in 2011) was 0.181×10^8 t (see Figure 2). This result stems from the relationship between the sediment carrying capacity of the river, the river flow, the

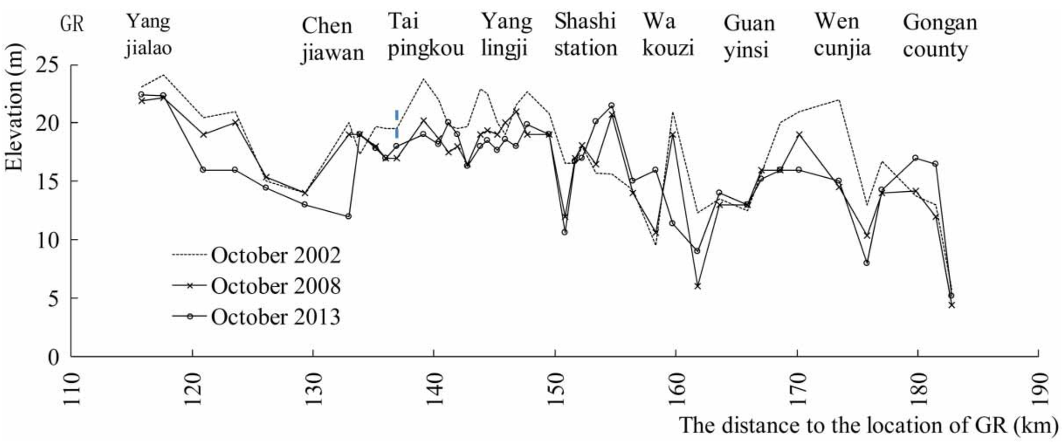

Figure 5 | Depth of the thalweg (in elevation) along the course of the Shashi Reach (for place name locations see Figure 1(b)).

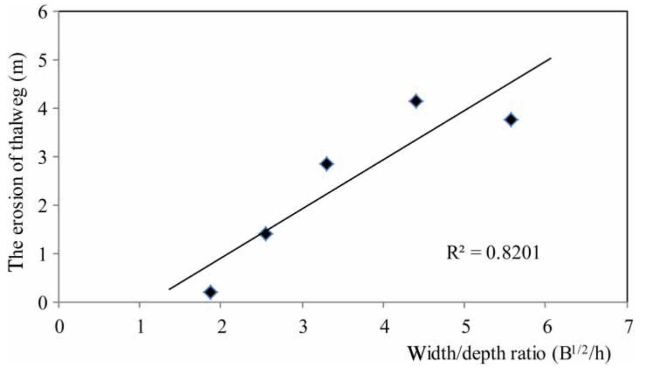

Figure 6 | Relationship between the width-to-depth ratio and the changes in the thalweg depth (2002–2012). B and h are the bank-full width and bank-full water depth respectively.

initial SSC, and the slope of the riverbed (Young *et al.* 2001; Ali *et al.* 2012). The overall river flow in the Shashi Reach remained unchanged but the SSC decreased noticeably. To return the river to its equilibrium state, this change should cause the erosion of the riverbed so that the carrying capacity remains constant. Consequently, the thalweg has deepened and, moreover, the mean medium grain size of the riverbed sediment has increased from 0.19 mm in the pre-TGD period to 0.251 mm in the post-TGD period (Figure 7); these results are consistent with those of Luo *et al.* (2012). The coarsening trend suggests that the erosion maintained an increasing trend.

Although the annual flow totals were not significantly affected by the operation of the dam, recent research reveals that the TGD can explain 6% of the total decrease of the water discharge (Yang *et al.* 2015). However, the TGD was the most important cause of changes in water and sediment discharges, because significant changes were brought to the

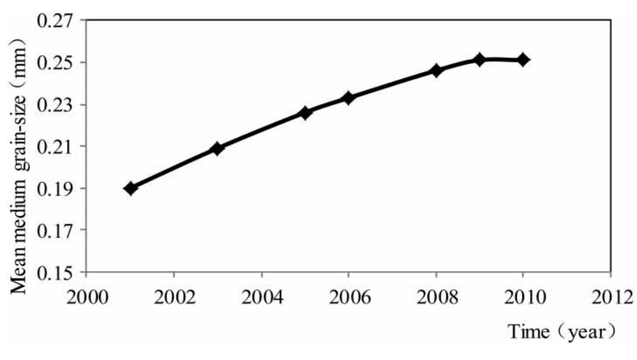

Figure 7 | Average grain size of the bed material load in the Shashi Reach.

distribution of the flow over the years, and in the apportionment of the flow between the high and low flows. This reflects the operation of the dam and more particularly the functions related to providing flood storage and generating hydroelectric power.

The flow appearance frequency at the Shashi gauging station was analyzed. Results show that higher flows have become less common, while the occurrence of lower flows has increased. The relative frequency of flows larger than the bank-full discharge (27,000 $m^3 \cdot s^{-1}$) has decreased from 9.6% in the pre-TGD period to 4.2% in the post-TGD period, and the relative frequency of flows >35,000 $m^3 \cdot s^{-1}$ was only 2.2%. The relative frequency of flows of 6,000–19,000 $m^3 \cdot s^{-1}$ increased to 7.1%. These changes in flows have various effects on the channel. The lower flows, which only use the deeper part of the old channel, can only cause deposition/erosion in the low-flow channel, whereas high flows near the bank-full stage can efficiently control the main channel. During the post-TGD period, the frequency of occurrence of high flow decreased and that of low flow increased significantly. This could explain why the erosion in the post-TGD period occurred mainly in the low-flow channel, and why the area above the bank-full level saw almost no change during this period.

According to Brandt's classification of geomorphological effects downstream of dams (Brandt 2000), when the water discharge (especially the peak water discharge) decreases and the transported load is less than the flow's carrying capacity, cross-sectional changes downstream of dams are different. Channel capacity may be reduced and some degradation may occur; however, the cross-sectional shape of the channel would ultimately be determined by the relative erodibility of the channel bed and bank material. In the Shashi Reach, the bank material is characterized by a double-layered structure, i.e., an upper cohesive soil (silt and clay) and a lower non-cohesive soil, where the thickness of the upper layer is greater than that of the lower layer. The channel bed material is sand and silty sand. In addition, traditional bank revetment construction on the reach used boulders and lumber to strengthen the delicate riverbank. Thus, additional stress could be added to the riverbed, making it more vulnerable than the riverbank. This may explain, in part, why the width-to-depth ratio of each of the cross sections showed a decreasing trend.

As mentioned in other studies, the riverbed in the middle and lower reaches shifted from accretionary before the TGD to erosional afterwards (Xu *et al.* 2011; Dai & Liu 2013; Yang *et al.* 2015). Currently, most erosion occurs a few hundred kilometers immediately downstream of the TGD (Luo *et al.* 2012; Dai & Liu 2013), although it is stronger in the sandy-bed reaches downstream of the TGD. Because there is still a large quantity of erodible deposits in the mid-lower Yangtze River and because the zone of maximum erosion is expected to move downstream toward the Yangtze estuary (Luo *et al.* 2012; Yang *et al.* 2015), phenomena occurring in the Shashi reach will occur in other reaches of the Yangtze River. In fact, observations such as the predominant occurrence of erosion in the low-flow channel and the decrease of width-to-depth ratio in other reaches (Xu *et al.* 2011; Xia *et al.* 2016), show that the change extent was smaller than the variations in the Shashi Reach.

CONCLUSIONS

This study considered the example of the Shashi Reach in the central section of the Yangtze River. We compiled a database of flow and sediment data, and historical maps of the Shashi Reach, covering the periods before and after the construction of the TGD, in order to identify changes in the channel in the post-TGD period. We found that significant changes have occurred in the Shashi Reach. The dominant modes of channel adjustment were that erosion predominantly occurred in the low-flow channel and that the area above the bank-full level saw almost no changes in the post-TGD period. These results are related to changes in the flow and sediment regimes. Although changes in water and sediment discharges between the pre-TGD and post-TGD periods were attributed to not only the TGD but also other natural and anthropogenic factors (Yang *et al.* 2015), the channel changes observed in the Shashi Reach cannot be attributed to the TGD alone. Nonetheless, the TGD remains the most important cause of these changes (Yang *et al.* 2015). The operating strategy for the dam includes the provision of storage of part of the high flows in summer to maintain hydroelectric power generation during winter (the low-flow season), and while the total flow was not affected significantly by the operation of the dam, this strategy was reflected in changes of the distribution of seasonal flow below the dam. In the post-TGD period, the frequency of occurrence of high flow decreased and that of low flow showed a clear increase, and these trends correlated with noticeable decreases in the SSC and SSD, which have caused channel adjustment.

We found that the width-to-depth ratio in all the sample cross sections showed a decreasing trend related to the lower water discharge and a transported load that was less than the carrying capacity of the flow, although this ratio was ultimately determined by the relative erodibility of the channel bed and bank material. As the bank material is composed mainly of silt and clay, the bank revetment has made the riverbed more susceptible to erosion.

The implications of the analyses above are that the erosion predominantly occurred in the low-flow channel and that the decrement of the width-to-depth ratio will be maintained for longer periods because of the operating strategy of the dam, which will occur not only in the study area, but also in other reaches in the mid–lower Yangtze River. Eventually, a new channel equilibrium will develop dependent on a combination of bed scour and bank erosion that is likely to occur over many decades. A deeper understanding of the changes in the study area requires further monitoring and analysis to determine the extent and consequences of the TGD impact.

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