

Mechanisms of suspended sediment restoration and bed level compensation in downstream reaches of the Three Gorges Projects (TGP)

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Abstract: River basin reservoir construction affects water and sediment transport processes in downstream reaches. The downstream impact of the Three Gorges Projects (TGP) has started to become apparent: (1) reduction in flood duration and discharge, and significant reduction in sediment load. Although there was some restoration in downstream sediment load, the total amount did not exceed the pre-impoundment annual average; (2) in 2003–2014, the $d > 0.125$ mm (coarse sand) load was restored to some degree, and to a maximum at Jianli Station, which was mainly at the pre-impoundment average. After restoration, erosion and deposition characteristics of the sediment was identical to that before impoundment. The degree of restoration during 2008–2014 was less than during 2003–2007; (3) after TGP impoundment, there was some restoration in $d < 0.125$ mm (fine sand) sediment load, however, it was lower than the pre-impoundment average; (4) due to riverbed compensation, the $d > 0.125$ mm sediment load recovered to a certain degree after impoundment, however, the total did not exceed 4400×10^4 t/y. This was mainly limited by flood duration and the average flow rate, and was less affected by upstream main stream, tributaries, or lakes. Restoration of $d < 0.125$ mm suspended sediment was largely controlled by upstream main stream, tributaries, and lakes, as well as by riverbed compensation. Due to bed armoring, riverbed fine suspended sediment compensation capability was weakened; (5) during 2003–2007 and 2008–2014, Yichang to Zhicheng and upper Jingjiang experienced coarse and fine erosion,

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lower Jingjiang experienced coarse deposition and fine erosion, Hankou to Datong had coarse deposition and fine erosion, and Chenglingji and Hankou was characterized by coarse deposition and fine sand erosion in 2003–2007, and coarse and fine erosion in 2008–2014. This difference was controlled by flood duration and number at Luoshan Station.

Keywords: sediment restoration; riverbed compensation; TGP; middle and lower reaches of the Yangtze River

1 Introduction

Reservoirs and associated dams can have a tremendous effect on river runoff, changing the natural hydrological cycle and sediment transport processes in downstream reaches, especially with the powerful regulatory capacity of cascade reservoirs (Benn and Erskine., 1994). Reservoir operating rules differ on various rivers, as do the arrangement of tributaries and lakes, riverbed erosion, river adjustment, and other conditions. Moreover, there are differences in water discharge amounts in the same river throughout a year. There is some sediment load restoration along reaches downstream of the reservoir after its construction; however, the amount never exceeds the annual average before reservoir construction. Williams, *et al.* analyzed 21 reservoirs in the United States, with respect to sediment sources from erosion. They found that the proportion of sediments from the riverbed increases with proximity to the dam, while the proportion of sediments from the river bank and beach increases as distance from the dam increases (Williams and Wolman, 1984). After construction of the Danjiangkou Reservoir, during 1970–1979 and 1980–1985, different components of the sediment load were restored in reaches downstream of the dam. Due to a high water volume during 1980–1985, the level of restoration was higher than during 1970–1979, however, the total sediment load was still lower than the average before reservoir impoundment (HB, CWRC, 2002). After construction of the Sanmenxia reservoir on the Yellow River, sediments with grain size $d < 0.05$ mm were restored. Restoration of sediments with grain size $0.05 \text{ mm} < d < 0.1 \text{ mm}$ decreased after a certain distance downstream, and sediments with grain size $d > 0.1 \text{ mm}$ showed an increasing trend after Huayuankou, which was possibly due to the convergence of tributaries, choice of time period of study, and other factors (Chen *et al.*, 2002). In summary, coarse and fine sands were restored to a certain degree in reaches downstream of the dam after reservoir construction. At certain stations, coarse sands were restored to a level similar to that before reservoir construction, and downstream sediment transport identical to that before reservoir construction. The degree of restoration of coarse and fine sand in reaches downstream of a dam is determined by total discharge and runoff processes, riverbed composition, tributaries and lakes, and other factors. Riverbed sediment compensation capability is dependent on riverbed composition, hydrodynamic power, erosion layer thickness, and other factors.

Since the impoundment of the Three Gorges Projects (TGP) in June 2003, a large data collection has accumulated and formed the basis of many research projects by Chinese scholars. In terms of total sediment load, there has been a decreasing trend in the middle and lower reaches of the Yangtze River (Dai *et al.*, 2008, 2009). The reduction in sediment load gradually decreases toward the lower reaches, to the Hekou area (Yang *et al.*, 2014a, 2015a). Based on data before TGP impoundment, it was predicted that riverbed erosion would occur, and that during the restoration process sediment load in the different grain size fractions would not exceed average values before TGP construction (Li *et al.*, 2003). This prediction

was verified by data collected after the TGP impoundment during 2003–2011 (Chen *et al.*, 2010; Guo *et al.*, 2014). Data from 2003–2007 showed that long distance erosion in downstream reaches was mainly due to a lack of riverbed compensation, especially for fine sand in the riverbed (Chen *et al.*, 2010). During 2003–2011, sediment of grain size $d < 0.125$ mm was slowly restored along the middle reaches of the Yangtze River, however, the total amount was much less than the average before impoundment, which promoted long distance erosion. The load of grain size fractions $d > 0.125$ mm was restored relatively quickly, within 200 km downstream of the dam, which indicated that erosion mainly occurred in Jinjiang after the TGP impoundment (Guo *et al.*, 2014). In terms of riverbed composition, there was a coarsening trend in the middle and lower reaches of the Yangtze River, which was most pronounced in reaches within 200 km of the dam (Luo *et al.*, 2013). With the increased water level of the TGP, there is enhanced ability to regulate downstream flow. Changes in flow distribution during flood and dry seasons (Li *et al.*, 2011), and in flow quantity and duration (Ban *et al.*, 2014), could alter the sediment transportation capability of downstream water bodies. However, the impact of such flow changes on transport of different sediment size fractions sizes has not been adequately investigated in existing studies. Since impoundment, downstream riverbed composition has undergone constant adjustment. Riverbed compensation to suspended sediments has been limited by interchange of coarse and fine sands, and by flow. Meanwhile, lakes and tributaries in the middle and lower reaches of the Yangtze River also affect the amount of sediment transport in the main stream. In view of the above issues, for the period 1987–2014, in this study we investigate process and patterns of change in river runoff, sediment load, and suspended sediment composition at hydrologic stations along the main stream, tributaries, and lakes of the middle and lower reaches of the Yangtze River, and identify mechanisms of suspended sediment restoration and bed sand compensation.

2 Survey area and data sources

2.1 Survey area

The downstream reach of the TGP between Yichang and Datong is 1183 km in length, and riverbed composition can be classified as sand/gravel or sand. The reach between Yichang and Zhicheng (61 km) is mainly composed of sand/gravel; the reach from Zhicheng to Dabujie (56.4 km) is the transition region; and the section from Dabujie to Datong (1065.6 km) is sand bedded (Figure 1). The main stream reaches studied include Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Datong, and other hydrologic stations. Also included in the study, are tributaries of Dongting Lake, the Songzikou River, Taipingkou River, and Ouchikou River, which are often called the Dongting Lake Three Outlets. The hydrologic stations at the confluences of Dongting Lake, Hanjiang, and Poyang Lake are Chenglingji Station, Huangzhuang Station, and Hukou Station, respectively.

2.2 Data sources and time periods

A range of data was obtained for the time period 1987–2014, including hydrological sediment and suspended sediment grading data from the main stream, tributaries, and lakes downstream of the TGP, riverbed grain size and composition for the reach between Yichang

and Datong, and total annual erosion and deposition for the reach between Yichang and Datong (Table 1). The study time period can split into two phases: the pre-impoundment period (1987– 2002) and post-impoundment period (2003–2014). During 2003–2007 cofferdam impoundment and initial impoundment took place, with a water level of 135–156 m. The impoundment water level reached 172.8 m in 2008 and was maintained at 175 m after 2009. The time period during 2008–2014 was termed the pilot impoundment period. Each time period was characterized by different degrees of flow regulation and sediment interception, which could help explain the impact on suspended sediment restoration and sand bed compensation downstream of the dam. The load of different sediment sizes was determined based on the amount of sediment with grain size greater than, less than, or between certain ranges on the sediment grading curve. A particle size of $d = 0.125\text{ mm}$ was the criteria used to classify suspended sediment and sand bed in the middle and lower reaches of the Yangtze River.

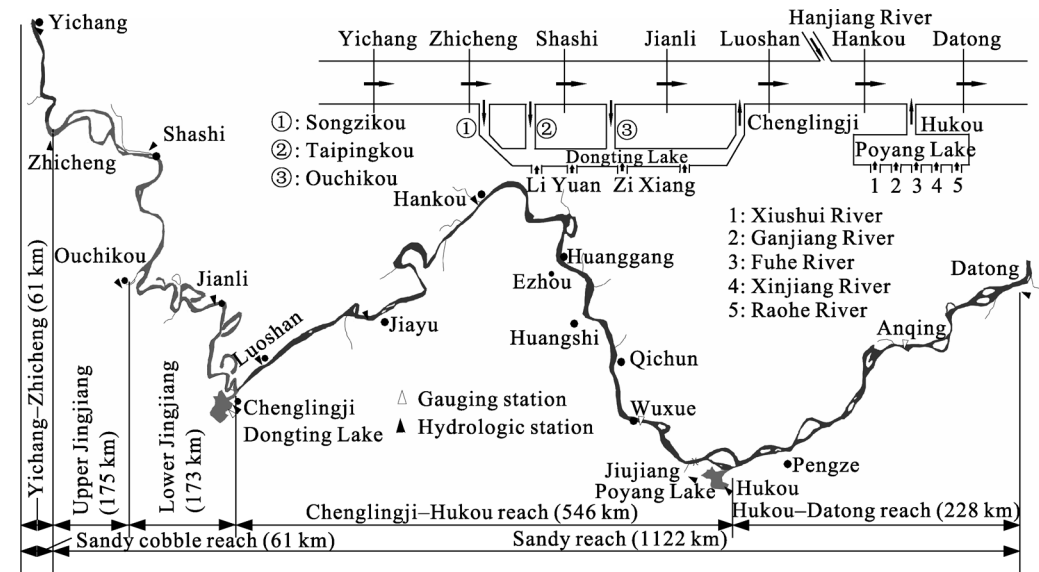


Figure 1 Location of the survey areas in downstream reaches of the Three Gorges Projects (TGP)

Table 1 Source of hydrological and sediment data for middle and lower reaches of the Yangtze River

Number	Hydrologic station	Data	Period	Data source
1	Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Datong	Water discharge, sediment load, flow, suspended sediment and sand bed grading	1987–2014	Yangtze River Middle and Lower Reach Region Hydrological Yearbook
2	Songzikou, Tiapingkou, Ouchikou (Dongting Lake Three Outlets), Chenglingji, Hukou	Water discharge, sediment load, flow, suspended sediment grading	1987–2014	Yangtze River Middle and Lower Reach Region Hydrological Yearbook; Changjiang Waterway Planning Design and Research Institute
3	River reach between Yichang and Datong	Typical river and section sand bed grading	2002–2014	

2.3 Hydrological and sedimentological characteristics

Figure 2 shows changes in water flux and sediment load at hydrologic stations of Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, and Datong during 1987–2014. The maximum water flux at each hydrologic station occurred in 1998 and the minimum in 2006. The average water flux during 2003–2014 was lower than that during 1987–2002, with a reduction of 5%–10%. The flow split at the Three Outlets showed a decreasing trend; the inflow from Chenglingji at Luoshan Hydrologic Station reduced, the inflow from Hanjiang at Hankou Hydrologic Station first decreased and then increased, and the ratio of inflow from Poyang Lake at Datong Hydrologic Station first decreased and then increased. The overall sediment load at each station showed a decreasing trend, with a 58%–90% reduction in 2003–2014 as compared to 1987–2002. Yichang Station had the largest reduction, and the sediment load reduction decreased downstream. Sediment flux at Dongting Lake Three Outlets decreased, a large portion of the sediment flux at Luoshan Station was from Chenglingji Station, the sediment flux from Hanjiang at Hankou Station first increased and then decreased, the sediment flux from Poyang Lake at Datong Station also increased first and then decreased.

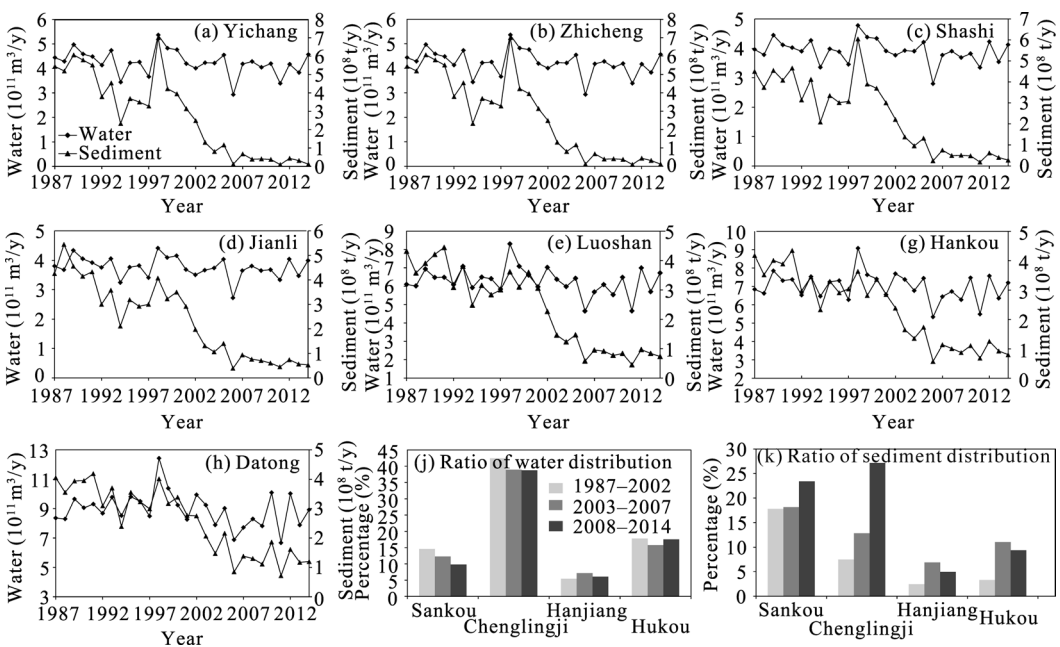


Figure 2 Variation in water and sediment flux in the middle and lower reaches of the Yangtze River

Water flux and sediment load in downstream reaches of TGP are subject to the influences of rainfall, urban water consumption, TGP, other dams, soil and water conservation, and other factors (Yang *et al.*, 2015b). After due to TGP impoundment, during 2003–2005, 2006–2007, and 2008–2012, sediment flux at Yichang Station reduced by 63%, 84%, and 87%, respectively, compared to before impoundment. The reduction at Hankou Station was 43%, 58%, and 59%, respectively, and at Datong it was 35%, 45%, and 49% (Yang *et al.*, 2014b). Compared to the 1993 to 2002 period, the contribution of rainfall, urban water consumption, the TGP, other dams, and soil and water conservation to water flux reduction was

61%, 2%, 3%, 5% and 9%, respectively, during 2003–2012. Their contribution to sediment flux reduction was 14%, 1%, 65%, 10%, and 10%, respectively, during 2003–2012 (Yang *et al.*, 2015b). In extremely dry years like 2006, downstream water reduction was more pronounced due to reduced rainfall, as was the decrease in sediment flux. As a result, 2006 was the year with the lowest water and sediment flux since TGP impoundment (Dai *et al.*, 2011). In summary, rainfall contributed the most to water reduction, and retention of sediment by TGP contributed most to the reduced sediment load.

3 Restoration of suspended sediment in the downstream reaches of the TGP

3.1 Median suspended sediment size

Variations in median sediment size at hydrologic stations along the main stream, tributaries, and downstream of the TGP are shown in Figure 3. The main trends are:

- Yichang Station: increase first and then decrease
- Zhicheng Station: slight decrease
- Shashi, Jianli and Luoshan stations: increase first and then decrease
- Hankou Station: increasing
- Datong Station: slight increase
- Dongting Lake Three Outlets: increase first and later decrease
- Chenglingji Station: increasing
- Huangzhuang Station: increase first and later decrease; change much greater than at Luoshan and Hankou stations.

Water flow and sediment transport from Hanjiang accounts for a small proportion of those at Hankou Station. Meanwhile, between Huangzhuang Station and the estuary suspended sediment composition was under constant adjustment, with coarse sand deposition and fine sand erosion (Han, 2003). However, the total sediment load from Hanjiang was relatively small, so it only had a small effect on suspended sediment sizes in the main stream. Median suspended sediment diameter at Hukou Station was less than 0.006 mm, and the proportion of suspended sediment with grain size $d > 0.125$ mm was only 1.23%. The small grain size of suspended sediments from Poyang Lake indicates that they did not contribute to bed formation processes; the sediments would be transported downstream to Datong Station within the water, causing the median suspended sediment diameter to be slightly smaller at Datong Station than that at Hankou Station.

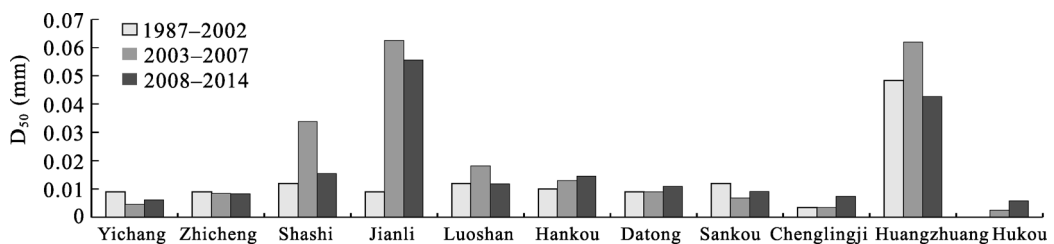


Figure 3 Variations in median suspended sediment size in downstream reaches of the TGP (1987–2014)

3.2 Restoration of suspended sediment composition

Figure 4a shows that during 2003–2014, the annual average sediment load for $d > 0.125$ mm was lower than during 1987–2002. During 2003–2007, sediment load significantly decreased at Yichang Station, changed little at Jianli Station, and was higher than that before impoundment at Luoshan Station and Hankou Station in some cases. This indicates that the $d > 0.125$ mm sediment load was completely restored between Jianli Station and Hankou Station. For the same period, there was a decrease at Datong Station. During 2008–2014, $d > 0.125$ mm sediment load showed a decreasing trend between Yichang Station and Hankou Station, and slightly increased at Datong Station. We then analyzed the relationship between water flux and $d > 0.125$ mm suspended sediment load during 2008–2014 and 2003–2007. We found that water flux during 2003–2007 was lower than that during 2008–2014, however, $d > 0.125$ mm suspended sediment load showed the opposite pattern (except for Datong Station). This suggests that the total amount of water was not the major factor affecting sediment load variations.

Figure 4b shows relatively large $d < 0.125$ mm sediment load during 1987–2002, with first increasing and then decreasing. Differences in sediment load after the establishment of Jianli Station were small. During 2003–2007 and 2008–2014, $d < 0.125$ mm sediment load showed an increasing trend. The sediment load during 2008–2014 was lower than that during 2003–2007. Overall, $d < 0.125$ mm sediment load during 2003–2007 and 2008–2014 was lower than that during 1987–2002, which is consistent with observations worldwide that sediment load downstream of dams is lower than that before impoundment.

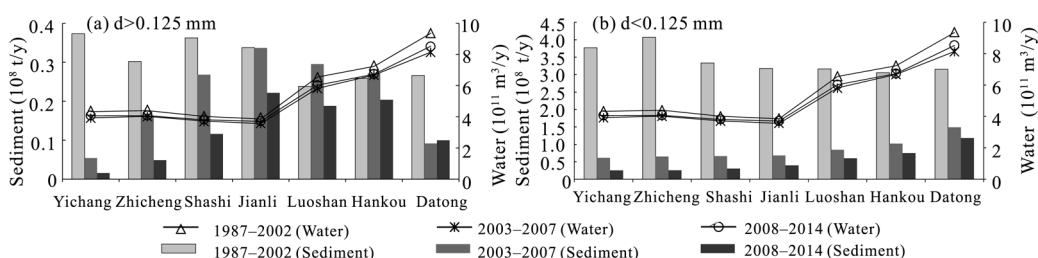


Figure 4 Suspended sediment ($d < 0.125$ mm and $d > 0.125$ mm) transport in downstream reaches of the TGP

3.3 Relationship between the sediment load of different size fractions and flow flux

The relationship between monthly average flow flux and sediment load in 1987–2002, 2003–2007, and 2008–2014 is shown in Figure 5. Sediment load slightly decreased during the dry season, and increased with flow flux, but showed an overall decrease over time. Total water discharge in 2008–2014 was higher than that in 2003–2007. However, both the $d > 0.125$ mm and $d < 0.125$ mm sediment load showed a decreasing trend, which is contradictory. Since flow flux was adjusted in the downstream reaches of the TGP within a year after the impoundment, its impact on sediment load needs to be fully considered.

The relationship of monthly average flow and $d > 0.125$ mm sediment load at each main stream hydrologic station at the downstream of the TGP was fitted using a power function (Figure 6a). The results demonstrate that the $d > 0.125$ mm sediment load in reaches between Zhicheng and Jianli was gradually restored with the increase in discharge, and in

creased downstream. Moreover, the larger the flow flux, the higher the degree of restoration. Reaches between Jianli and Hankou were affected by inflow from Dongting Lake. The $d > 0.125$ mm sediment load at Chenglingji Station was very small, 250,000 t during 2003–2009, which was negligible in terms of total river sediment load. Therefore, with the same monthly average flow flux, $d > 0.125$ mm sediment load at Luoshan Station was lower than that at Jianli Station. The relationship between $d > 0.125$ mm sediment load and flow flux at Hankou Station was identical to that at Luoshan Station. In the section of the Yangtze River between Hankou and Datong, sediment from Poyang Lake was mainly composed of fine sand. During 2009–2014, the total $d > 0.125$ mm suspended sediment load at Hukou Station was 94.46×10^4 t (yearly average 15.74×10^4 t). Its contribution to the total sediment load at Datong Station was insignificant. Due to the inflow of Poyang Lake into the Yangtze River, flow discharge increased at Datong Station and sediment of the $d > 0.125$ mm size group deposited. The combined effect was that the coarse sand sediment load was lower at Datong Station than at Hankou Station. The relationship of monthly average flow flux and the $d < 0.125$ mm sediment load at each main stream hydrologic station downstream of the TGP was fitted using a power function (Figure 6b). The results show that the sediment load of this size group increased in river reaches between Zhicheng and Jianli, suggesting that it was significantly restored under different flow regimes. Also, the $d < 0.125$ mm sediment load

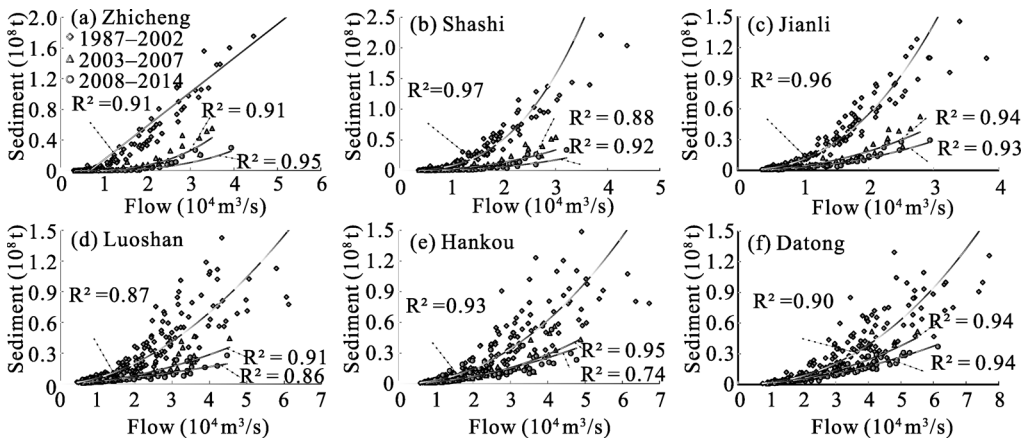


Figure 5 Relationship between monthly sediment load and flow flux in downstream reaches of the TGP

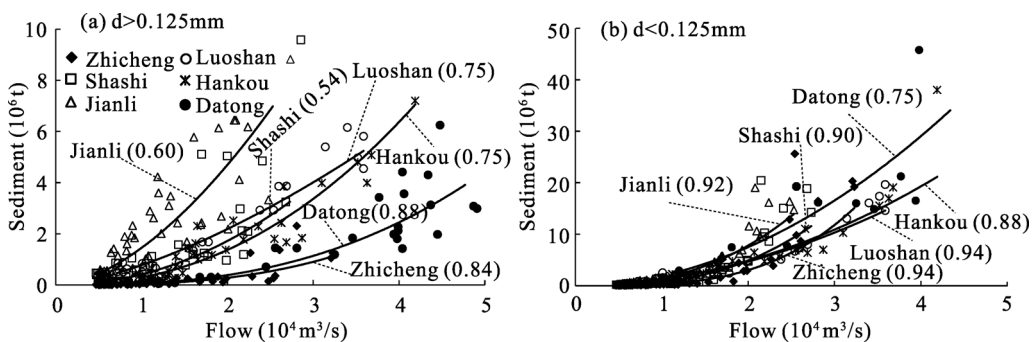


Figure 6 Relationship between sediment load (grain sizes $d > 0.125$ mm and $d < 0.125$ mm) and flow flux in the middle and downstream reaches of the TGP

showed an increasing trend with the increase in flow flux at each station. Considering river reaches between Jianli and Hankou, the $d < 0.125$ mm sediment load at Luoshan Station was significantly lower than that at Jianli Station due to the convergence at Dongting Lake. Because of the inflow from Hanjiang, most of the data points of $d < 0.125$ mm sediment load at Hankou Station lie below those at Luoshan Station. For river reaches between Hankou and Datong, due to the convergence at Poyang Lake, sediment inflow was mainly composed of fine sand with $d < 0.125$ mm. Sediment load at Hukou Station was lower than that at Hankou Station. Due to riverbed compensation and convergence at lakes, the $d < 0.125$ sediment load at Datong Station was higher than that at Hankou Station.

3.4 The influence of flow flux on the restoration of suspended sediment

Since sediment transport in the middle and lower reaches of the Yangtze River mainly occurs in the flood season, and coarse sand transport is concentrated during the high flow period, changes of flow during the year need to be further investigated. Flood discharge varies in different sections of the middle and lower reaches of the Yangtze River. We chose flood discharge thresholds (where Q is discharge) of $Q \geq 2.5 \times 10^4 \text{ m}^3/\text{s}$ for the section between Yichang and Jianli, $Q \geq 3.0 \times 10^4 \text{ m}^3/\text{s}$ at Luoshan Station, $Q \geq 3.5 \times 10^4 \text{ m}^3/\text{s}$ at Hankou Station, and $Q \geq 4.5 \times 10^4 \text{ m}^3/\text{s}$ for Datong Station. During 2008–2014, the average flow above the thresholds downstream of the dam was less than that of 2003–2007, which reduced sediment transport capability during the flood season. Meanwhile, the flood duration at each station (except Luoshan and Datong) showed a decreasing trend. The combined effect was that the $d > 0.125$ mm sediment load during 2008–2014 was lower than 2003–2007 (Figure 7).

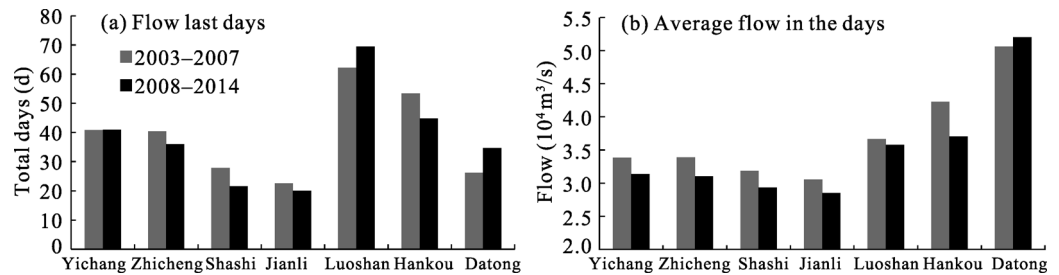


Figure 7 Variations in flood flow and duration at hydrologic stations in downstream reaches of the TGP

The $d < 0.125$ mm sediment in the middle and lower reaches of the Yangtze River mainly comes from upper basin, tributary inflow, and riverbed compensation. Using the sediment load at Yichang Station to represent incoming sediment load, sediment at Zhicheng contributed to the load increase. Downstream of Zhicheng, the proportion of $d < 0.125$ mm sediment to the total sediment at Yichang Station decreased no matter whether there were tributary or lake inputs (Figure 8). During the time periods 2003–2007 and 2008–2014, changes in $d < 0.125$ mm suspended sediment transport were as follows:

- a slight increase from Yichang to Zhicheng, which was consistent with that in 1987–2002, before impoundment
- a trend of restoration from Zhicheng to Jianli, which might have been larger if there were no water diversion at Dongting Lake Three Outlets

- a trend of restoration from Jianli to Datong, which was higher during 2008–2014 than during 2003–2007

The amount of $d < 0.125$ mm sediment at Yichang Station decreased substantially during 2008–2014. Riverbed compensation in the main stream reaches played a positive role in the restoration of sediments. However, the annual average sediment load during 2008–2014 was still lower than 2003–2007.

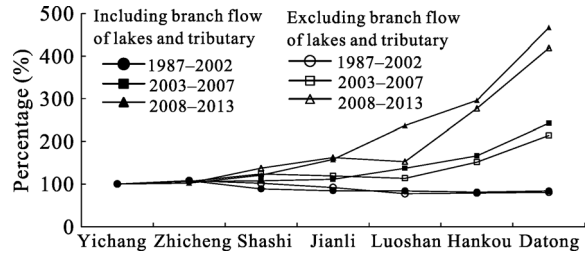


Figure 8 Suspended sediment ($d < 0.125$ mm) compensation from tributaries and lakes in the downstream reaches of the TGP

4 Mechanism of riverbed compensation in downstream reaches

4.1 Change in sediment grain size

Figure 9 shows variations in median grain size. There was a coarsening trend in the years 2003, 2007, and 2010, with the greatest degree of coarsening in reaches between Yichang and Zhicheng. There was a universal coarsening in reaches between Zhicheng and Luoshan, the degree of which decreased downstream. Reaches downstream of Luoshan Station showed an overall coarsening trend, but with alternating coarsening and fining. In general, riverbed armoring is not conducive to the sediment restoration of sizes $d > 0.125$ mm or $d < 0.125$ mm.

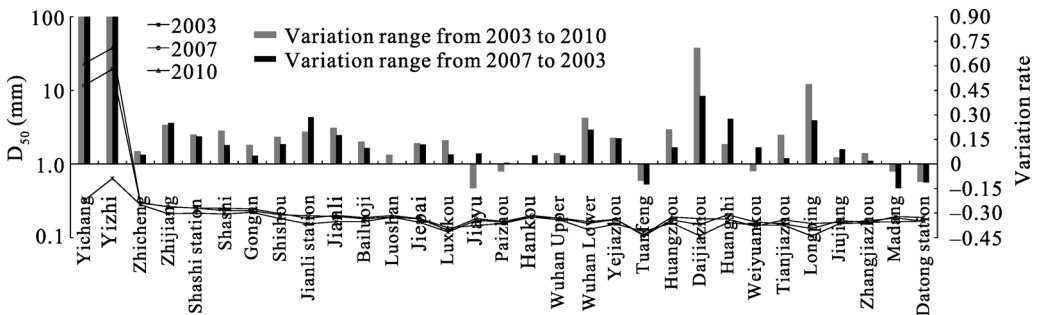


Figure 9 Variations in median size of bed sands in downstream reaches of the TGP

4.2 The riverbed compensation process

Figure 10 shows bed load variations in downstream reaches of the TGP. The $d < 0.125$ mm component near the dam showed a decreasing trend and was close to zero in reaches from Yichang to Zhicheng. This indicates that the compensation for suspended sediment from the $d < 0.125$ mm component in the riverbed decreased, and the riverbed might no longer provide compensation. As a result, the $d < 0.125$ mm sediment load in the same reach showed a decreasing trend, and did not return to the average pre-impoundment level. Although the percentage of the $d < 0.125$ mm component in the riverbed downstream of Zhicheng decreased, the ratio was still above 10% and the riverbed could still compensate for suspended sediment. Therefore, the percentage of the $d < 0.125$ mm component of the riverbed in

downstream reaches decreased after impoundment. If the amount of incoming sediment from upstream reaches continued to keep at a low level, suspended sediment load could still be restored to a certain degree along downstream reaches, but it would be hard to return to the average pre-impoundment level. The percentage of the $d > 0.125$ mm component showed an increasing trend (Figure 10). Compensation by this riverbed component depends on flood flow and duration. As both flood flow and duration in downstream reaches of the TGP showed a decrease, sediment compensation from this component group would be reduced and its total load would further decrease.

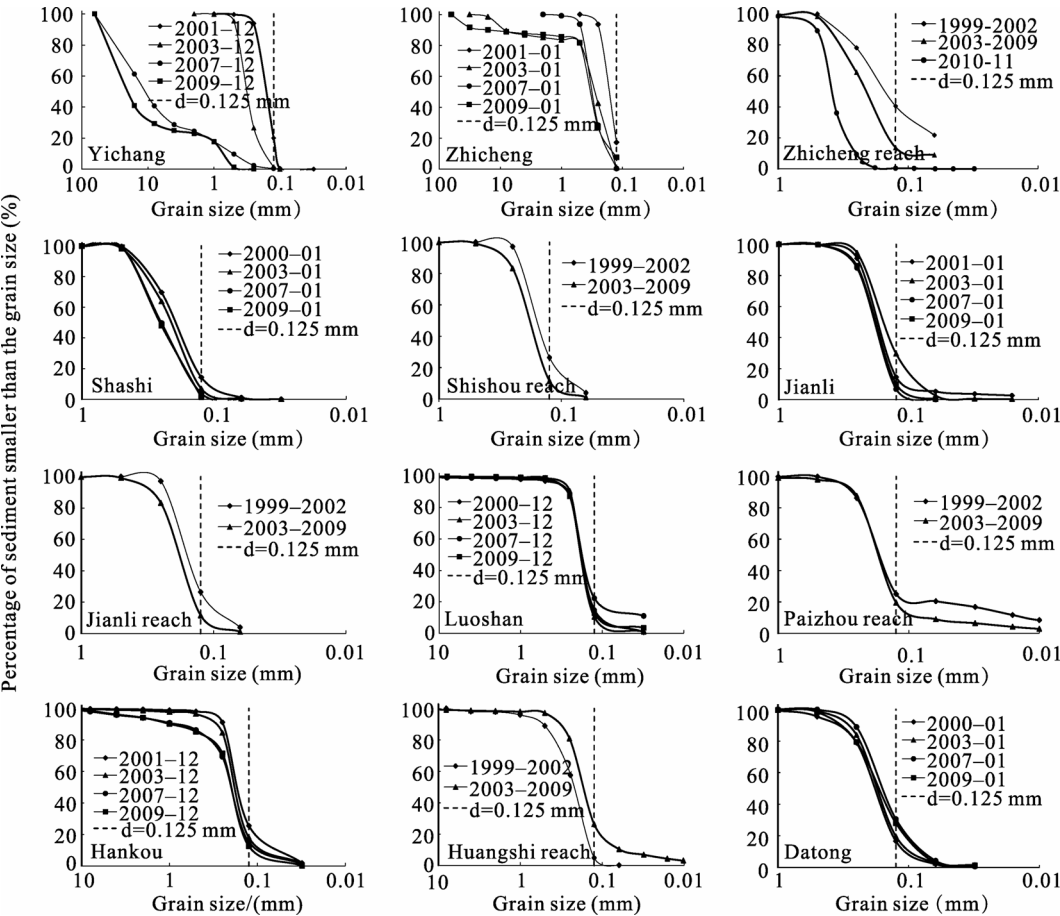


Figure 10 Variations in bed surface load (%) in the downstream reaches of the TGP

Since the water flow was under unsaturated conditions, the riverbed surface would undergo gradual erosion to compensate for suspended sediment. However, the amount and capability of the compensation are limited by the hydrodynamic strength and composition of the bed surface. The amount of compensation is also limited by the thickness of the scourable layer of the riverbed. The reach from Yichang and Zhicheng is of sand/gravel type. It can be seen from Figure 11 that the $d < 0.125$ mm component is close to zero. Data from 2009 show that the $0.125 \text{ mm} < d < 0.5 \text{ mm}$ components of the riverbed were all scoured away. As a result, suspended sediment compensation from the riverbed between Yichang and Zhicheng was very small. Although there was compensation from coarse sand, compensation

from river channels was depleted. Figure 11c shows variations in sediment and sand/gravel top layer in the sand/gravel–sand transition reach between Zhicheng and Changmen (Lujiahe is at the end of the sand/gravel river reach). The scourable layer of the bed surface was thin before impoundment, with a large amount of sand and gravel in deeper layers. With continuous erosion of the reach, compensation from the deep sand/gravel layer decreased. Although the thickness of the riverbed scourable layer in Lujiahe reach became zero after the appearance of deep grooves, the scouring layer of the riverbank was still significant. In the reach between Zhicheng and Lujiahe, both $d > 0.125$ mm and $d < 0.125$ mm suspended sediment were restored. After impoundment, there were frequent riverbank collapses along the Jinjiang reach (Xia *et al.*, 2014), which further demonstrated that the sediment compensation was from riverbank erosion. In the reach between Zhijiang and Jiangkou, the thickness of the main channel sand/gravel cover layer decreased, and scourable layer thickness increased. In recent years, there has been thalweg incision and decrease in the sand layer above the gravel layer. Therefore, there will be a shortage for suspended sediment compensation. The deep incision of the sandy scouring layer of reaches at Shashi was less than 10 m, and the sandy cover layer of the bank and river was still relatively thick. Hence, coarse sand compensation was still abundant in the sandy river beach.

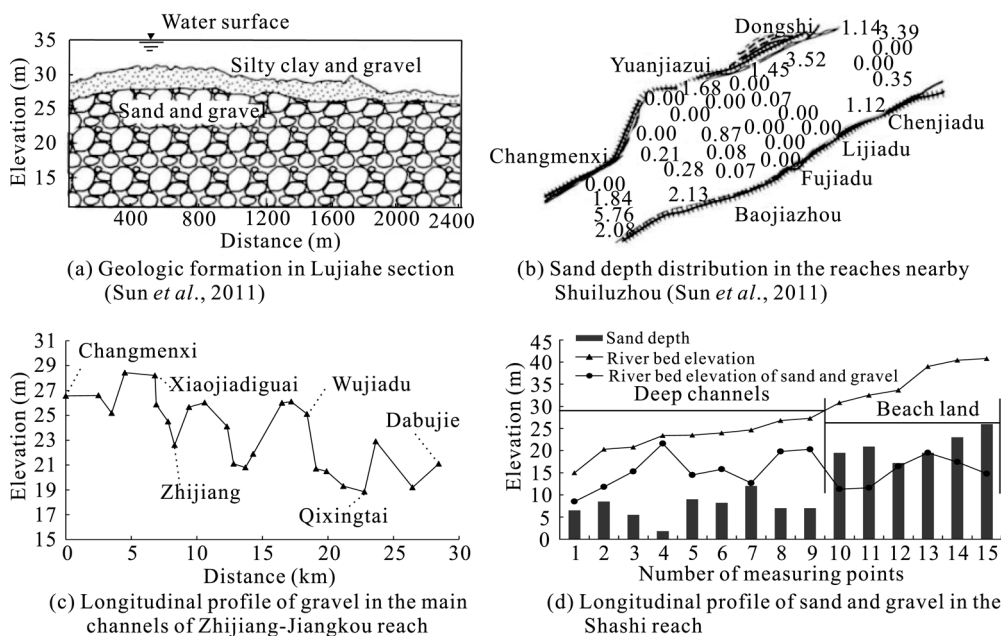


Figure 11 Geological composition of the riverbed in the middle reaches of the Yangtze River

4.3 Relationship of riverbed adjustment and suspended sediment restoration with riverbed compensation

Downstream reaches of the TGP comprise: Yichang to Zhicheng, Upper Jingjiang (Zhicheng to Ouchikou), lower Jingjiang (Ouchikou to Chenglingji), Chenglingji to Hankou, Hankou to Hukou, and Hukou to Datong. Channel erosion and deposition intensity per unit river length in the above river reaches is shown in Figure 12. The main conclusions are as follows:

Yichang to Zhicheng reach (YZR).

Erosion was recorded in four periods of 1987–2002, 2003–2007, and 2008–2014. Erosion intensity was higher after impoundment than before, and was weaker in 2008–2014 than 2003–2007. The main reason was the great degree of armoring of the sand/gravel riverbed. As a result, the $d < 0.125$ mm sediment component

of the riverbed was almost zero, causing a shortage in the suspended sediment compensation for this size group. Meanwhile, both the duration and average flood discharge were decreased, leading to reduced erosion of the $d > 0.125$ mm component of the riverbed. Therefore, the suspended sediment compensation capacity of the riverbed for this size range was reduced, which also contributed to erosion.

Upper Jingjiang reach (UJR), between Zhicheng Station and Jianli Station. Riverbed erosion intensity showed an increasing trend and $d > 0.125$ mm suspended sediment was gradually restored. The divergence and convergence at Dongting Lake had little effect on suspended sediment restoration of this size group, indicating that the increase in $d > 0.125$ mm sediment load in this reach was mainly from riverbed erosion. The $d < 0.125$ mm sediment was also gradually restored, suggesting that there was erosion of both coarse and fine sand from the riverbed in the upper Jingjiang reach. This made it a region with concentrated, and relatively high degree, of erosion compared to other reaches after impoundment.

Lower Jingjiang Reach (LJR), between Jianli Station and Luoshan Station. The degree of suspended sediment restoration decreased. During 1987–2002, 2003–2007, and 2008–2014, the $d > 0.125$ mm sediment load at Luoshan Station was lower than that at Jianli Station. Deposition of $d > 0.125$ mm sediment occurred during all three time periods, suggesting that this fraction was restored to a level similar to that before impoundment. There is convergence of tributaries at Dongting Lake. The differences in $d < 0.125$ mm sediment load in reaches between Luoshan Station, Chenglingji Station and Jianli Station were -2680×10^4 t/y, 150×10^4 t/y, and 60×10^4 t/y during 1987–2002, 2003–2007, and 2008–2014, respectively. Thus, the pattern changed from erosion and deposition before impoundment, to just erosion after impoundment. In the lower Jingjiang reach, both coarse and fine sand showed erosion and deposition in 1987–2002, but this changed to coarse sand deposition and fine sand erosion in 2003–2007 and 2008–2014. A shortage in fine sand compensation was due to the reduced flood discharge and duration at Jianli Station, and riverbed armoring. The combined effect was that erosion intensity in the lower Jingjiang reach was lower during 2008–2014 as compared with 2003–2007.

Chenglingji to Hankou reach (CHR), between Luoshan Station and Hankou Station. The trend here was for riverbed erosion in 1987–2002, 2003–2007, and 2008–2014. The $d > 0.125$ mm component of suspended sediments showed a trend of erosion in 1987–2002, deposition in 2003–2007 and erosion in 2008–2014. The number and duration of $Q > 35000$ m³/s floods increased during 2008–2013 as compared to 2003–2007, which changed the characteristics of erosion and deposition during the two time periods. This is different from

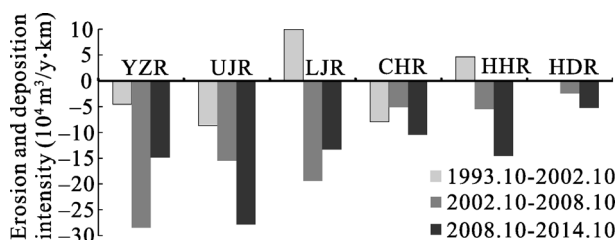


Figure 12 Variations in erosion and deposition intensity in downstream reaches of the TGP

the findings in previous studies, and is mainly due to the fact that data used in previous studies were from 2007 and earlier (Chen *et al.*, 2010), or data from 2003–2011 were analyzed as a whole (Guo *et al.*, 2014), which minimized the impact of flow flux. When the erosion/deposition relationship is calculated at Hankou Station, the inflow from Hanjiang needs to be taken into account as the confluence of the Hanjiang River is located 1.15 km above the Station. Therefore, the sediment load from Hanjiang into the Yangtze River at Huangzhuang Station needs to be excluded from sediment balance calculations in the river reaches between Chenglingji and Hankou. The differences of $d < 0.125$ mm sediment load at Hankou, Hanjiang Huangzhuang and Luoshan Stations during 2003–2007 and 2008–2014 were -1890×10^4 t/y, 890×10^4 t/y, and 1240×10^4 t/y, respectively. The trend was for erosion and deposition before impoundment, changing to just erosion after impoundment. The pattern of erosion and deposition in reaches from Chenglingji to Wuhan was coarse sand erosion and fine sand deposition in 1987–2002 before impoundment, changing to coarse sand deposition and fine sand erosion in 2003–2007, and coarse and fine sand erosion in 2008–2014. This led to variations in erosion and deposition of both coarse and fine sands. Due to the impact of combined flow flux at Dongting Lake and the main stream Yangtze River, flood duration increased at Luoshan Station, but with a slightly lower average flow level. As a result, the total flood season water discharge had an increasing trend. This increased erosion power, which caused the transition from “coarse sand deposition fine sand erosion” in 2003–2007 to “both coarse and fine sand erosion” in 2008–2014. Due to the increase in flood discharge at Luoshan Station, and the sandy riverbed from Chenglingji and Hankou, there was sufficient sediment compensation from the riverbed. Therefore, erosion intensity was higher during 2008–2014 than during 2003–2007.

Hankou to Datong reach (HDR), between Hankou Station and Datong Station. The period 1987–2002 showed a small scale deposition trend, and the scouring intensity during 2008–2014 was higher than that during 2003–2007. As sediment from Poyang Lake is mainly composed of fine suspended sediment, it was excluded from erosion and deposition calculations of $d > 0.125$ mm sediment between Hankou and Datong. The differences in $d > 0.125$ mm suspended sediment load at Datong Station, Hukou Station and Hankou Station were 100×10^4 t/y, -1800×10^4 t/y, and -700×10^4 t/y, respectively, in 1987–2002, 2003–2007, and 2008–2014. The pattern was small scale erosion before impoundment, becoming erosion and deposition after impoundment. As for the change of erosion and deposition of $d > 0.125$ mm suspended sediments, previous research has shown that the $d > 0.125$ mm sediment deposition was caused by the decrease in runoff after impoundment (Chen *et al.*, 2010). The differences in $d < 0.125$ mm suspended sediment load at Datong Station, Hukou Station, and Hankou Station were -130×10^4 t/y, 2950×10^4 t/y, and 3120×10^4 t/y during 1987–2002, 2003–2007, and 2008–2014. The trend was for small scale deposition before impoundment and erosion after impoundment. In general, erosion and deposition of sediments in river reaches from Hankou to Datong was minor before impoundment, and kept in balance. After impoundment, it changed to erosion. We used the sediment balance method to calculate erosion and deposition intensity in reaches from Hankou to Datong. Average annual erosion and deposition during 1987–2002, 2003–2007, and 2008–2014 was -600×10^4 , 1200×10^4 , and 2100×10^4 t/y, respectively. Erosion was higher during 2008–2014 than 2003–2007, which corresponds to the period of erosion intensity associated with the geological composition of

the riverbed. There were clear differences in erosion intensity in reaches between Hankou to Hukou and Hukou to Datong. From Hankou to Hukou, fine sand erosion had, to a certain degree, been restored. Inflow of fine sand from Poyang Lake increased the amount of sediment in unsaturated water in reaches from Hukou to Datong, which reduced riverbed erosion intensity. Under their combined influences, erosion and deposition intensity was lower from Hukou to Datong than from Hankou to Hukou.

From the above analysis, it can be seen that there was a good correlation between the amount of sediment and riverbed erosion and deposition intensity in reaches between Yichang and Datong. Combined with post-impoundment changes in flood amount and duration, erosion and deposition variations during 2003–2007 and 2008–2014 could be explained. However, there were relatively large differences between the amount of sediment erosion and deposition and the amount of riverbed erosion and deposition. This was probably caused by the combined effect of instream sand mining, waterway dredging, and other factors. Instream sand mining can, to a certain extent, exacerbate riverbed erosion, channel widening, and stream gradient adjustment. The “keeping fine sand and leaving gravel” technique in operation during sand mining accelerates the process of sand bed coarsening (Hu *et al.*, 2015). Instream sand mining data in the main stream reaches of the Yangtze River for 2003–2011 is summarized in Table 2. It can be seen that sand mining had a large impact, for example, it accounted for 63.2% of the total sediment load at Datong Station in 2009. However, not all sand mining was below the bankfull channel, and its proportion will decrease. In addition, the river waterway departments in the middle and lower reaches of the Yangtze River conducted large scale dredging. The amount of dredging was relatively large, even during the unfavorable years (Table 3). Due to the impact of sand mining and dredging, riverbed erosion and deposition intensities calculated using topographic survey and discharge balance methods were not consistent, and could be quite different.

Table 2 Annual sand mining limits in the middle and lower reaches of the Yangtze River (Wang *et al.*, 2014)

Year	2004	2005	2006	2007	2008	2009	2010	2011
Sand mining controlled amount (10 ⁴ t)	1186	1602	1240	1690	5140	7020	4430	4407

Table 3 Dredging amounts in the Yichang-Datong section (Huang *et al.*, 2015)

Year	2008	2009	2010	2011	2012	2013
Dredging amount (10 ⁴ m ³)	25.9	69.9	51.5	466.7	147.5	608.9

4.4 Discussion on the trend of sediment load change in middle and lower reaches of the TGP after the operation of cascade reservoirs

TGP intercepts a large amount of sediment. Clear water discharge causes water bodies downstream of the dam to be under long-term unsaturated conditions. Due to the restoration of suspended sediments, reaches downstream of the dam are under long-term erosion. Fine sand in the riverbed of the reaches between Yingchang and Zhicheng was completely washed away. The coarse grain transport capacity, especially of gravel, was weakened due to the reduced flood discharge. Meanwhile, the surface gravel layer concealed the underneath riverbed, which enhanced the anti-erosion capability of the riverbed. Large or catastrophic

floods promote coarse sand transport and increase riverbed erosion intensity, although with limited transport distance. In sandy river reaches, there is a large amount of $d > 0.125$ mm coarse sand and a limited amount of $d < 0.125$ mm fine sand in the riverbed. As a result, the restoration of fine suspended sediments in sandy river reaches is limited. Although $d > 0.125$ mm suspended sediment recovery was relatively fast, recovery was lower during 2008–2013 compared with 2003–2007. Upper Jingjing reaches experienced the largest erosion during 2003–2007. Erosion had advanced to the downstream reaches in 2008–2014; preliminary findings showed erosion had reached the lower Jingjiang region. With cascade reservoirs in the upper reaches of Changjian being put into operation successively, it will further exacerbate clear water discharge. As time goes by, the area of major erosion will move to downstream reaches. Because of the large amount of $d > 0.125$ mm sediments in the sandy river reaches, the $d > 0.125$ mm sediment load will continue to recover. However, due to flow leveling, especially the relative decrease in flood duration and amount, the sediment load of this size group will decrease. According to a recent plan, the TGP will implement small and medium flood regulation, which could further increase the flow leveling amplitude (Zheng, 2015). The $d > 0.125$ mm suspended sediment showed a relatively large degree of restoration at Jianli Station, Luoshan Station, and Hankou Station. The largest sediment load was observed at Jianli Station. Therefore, Jianli Station was chosen as representative hydrologic station for predicting downstream coarse sediment load after the joint operation of the TGP and upstream cascade reservoirs. During 2003–2004, the maximum $d > 0.125$ mm sediment load at Jianli Station was 5300×10^4 t/y. Using the difference between Yichang Station and Shankou Station as the riverbed supply amount between Yichang and Jianli, the maximum sediment compensation was calculated at 4400×10^4 t/y, with an average of 3000×10^4 t/y

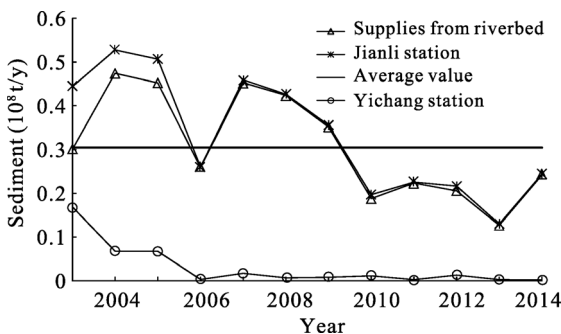


Figure 13 Changes in sediment with grain size $d > 0.125$ mm in the Yichang to Jianli reach from 2003 to 2014

(Figure 13). In summary, after the operation of TGP and upper stream cascade reservoirs, the maximum $d > 0.125$ m suspended sediment load did not exceed 5300×10^4 t/y in the middle and lower reaches of the Yangtze River due to the impact of small and medium flood regulation by TGP, riverbed coarsening, and other factors. Because of the substantial decrease in $d > 0.125$ mm sediment in the riverbed, riverbed compensation did not exceed 4400×10^4 t/y (annual average from 2003–2007).

5 Conclusions

The effect of the TGP impoundment on sediment load in downstream reaches has become apparent. In this paper, we analyzed data from 1987–2014 for the middle and lower reaches of the Yangtze River, and revealed mechanisms of suspended sediment restoration and riverbed compensation. The main conclusions are as follows:

- (1) After the TGP impoundment, flood duration and amount were substantially reduced in

downstream reaches. Sediment load was close to clear water discharge, and gradually restored along the downstream reaches over time. However, the sediment load did not exceed the annual average before impoundment.

(2) During 2003–2014, the $d > 0.125$ mm suspended sediment in downstream reaches recovered to a certain degree. The level of restoration was the highest at Jianli Station, which was close to the pre-impoundment level, and erosion and deposition characteristics were consistent to that before impoundment. The degree of recovery was lower during 2008–2014 than during 2003–2007.

(3) In 2003–2007 and 2008–2014, the $d < 0.125$ mm suspended sediment load in downstream reaches of the TGP was restored to a certain degree. However, the total amount did not exceed the average amount before impoundment. The level of restoration during 2008–2014 was lower than during 2003–2007.

(4) The restoration of $d > 0.125$ mm sediment mainly came from riverbed erosion after the TGP impoundment. However, the supply did not exceed 4400×10^4 t/y, which was limited by average flood flow and duration. The effect of upper reach main stream, tributaries, and lakes was less important. The restoration of $d < 0.125$ mm suspended sediments was controlled by upper reach main stream, tributaries, lakes, and riverbed compensation. Due to armoring, the riverbed compensation capability for suspended sediments decreased.

(5) After TGP impoundment, the $d > 0.125$ mm and $d < 0.125$ mm sediment erosion and deposition characteristics varied in different river reaches. During the time periods of 2003–2007 and 2008–2014, the Yichang to Zhieng reach in upper Jingjiang recorded coarse and fine sand erosion, lower Jingjiang recorded coarse sand deposition and fine sand erosion. Chenglingji to Hankou was characterized by coarse sand deposition and fine sand erosion in 2003–2007, and erosion in 2008–2014. This difference was controlled by flood amount and duration at Luoshan Station. The Kankou to Datong reach recorded coarse sand deposition and fine sand erosion.

References

- Ban Xuan, Jiang Liuzhi, Zeng Xiaohui *et al.*, 2014. Quantifying the spatio-temporal variation of flow and sediment in the middle Yangtze River after the impoundment of the Three Gorges. *Advances in Water Science*, 25(5): 650–657. (in Chinese)
- Benn Patrick C, Erskine Wayne D, 1994. Complex channel response to flow regulation: Cudgegong River below Windermere Dam, Australia. *Applied Geography*, 14(2): 153–168. doi: 10.1016/0143-6228(94)90058-2.
- Chen Fei, Li Yitian, Tang Jinwu *et al.*, 2010. Analysis of group-sized sediment transports downstream a reservoir. *Journal of Hydroelectric Engineering*, 9(1): 164–170. (in Chinese)
- Chen Jianguo, Zhou Wenhao, Yuan Yuping, 2002. Transportation and adjustment of different grain sized sediment along the Lower Yellow River under typical operation modes of Sanmenxia Reservoir. *Journal of Sediment Research*, (2): 15–22. (in Chinese)
- Dai S B, Lu X X, Yang S L *et al.*, 2008. A preliminary estimate of human and natural contributions to the decline in sediment flux from the Yangtze River to the East China Sea. *Quaternary International*, 186(1): 43–54. doi: 10.1016/j.quaint.2007.11.018.
- Dai S B, Yang S L, Li M, 2009. The sharp decrease in suspended sediment supply from China's rivers to the sea: Anthropogenic and natural causes. *Hydrological Sciences Journal*, 54(1): 134–146. doi: 10.1623/hysj.54.1.135.
- Dai Zhijun, Chu Ao, Stive Marcel *et al.*, 2011. Is the Three Gorges Dam the cause behind the extremely low sus-

- pended sediment discharge into the Yangtze (Changjiang) Estuary of 2006? *Hydrological Sciences Journal*, 56(7): 1280–1288. doi: 10.1080/02626667.2011.585136.
- Guo Xiaohu, Li Yitian, Qu Geng *et al.*, 2014. Analysis of sediment transport in Middle Yangtze River after filling of the Three Gorges Reservoir. *Journal of Sediment Research*, (5): 11–17. (in Chinese)
- Han Qiwei, 2003. Reservoir Siltation. Beijing: Science Press, 582–607. (in Chinese)
- Hu Chaoyang, Wang Erpeng, Wang Xinqiang, 2015. Analysis of channel evolution under combined action of reservoir and channel sand excavation. *Journal of Water Resources & Water Engineering*, 26(3): 178–183. (in Chinese) DOI:10.11705/j.issn.1672-643X.2015.03.37.
- Huang Zhaobiao, Li Ming, 2016. The prototype observation report of Yichang to Anqing reaches of the Yangtze River. Wuhan: Changjiang Waterway Planning Design and Research Institute, 15–16. (in Chinese)
- Hydrology Bureau, Changjiang Water Resource Commission (HB, CWRC), 2002. Analysis of river bed erosion downstream from Danjiangkou reservoir in period of retardation and period of water impoundment. In: Sediment Research of Three Gorge Project (Vol. 7). Beijing: Beijing Intellectual Property Press, 75–82. (in Chinese)
- Li Qiongfang, Yu Meixiu, Lu Guobin *et al.*, 2011. Impacts of the Gezhouba and Three Gorges reservoirs on the sediment regime in the Yangtze River, China. *Journal of Hydrology*, 403(3/4): 224–233. doi: 10.1016/j.jhydrol.2011.03.043.
- Li Yitian, Sun Zhaohua, Deng Jinyun, 2003. A study on riverbed erosion downstream from the Three Gorges Reservoir. *Journal of Basic Science and Engineering*, 11(3): 283–295. (in Chinese)
- Luo X X, Yang S L, Zhang J, 2012. The impact of the Three Gorges Dam on the downstream distribution and texture of sediments along the middle and lower Yangtze River (Changjiang) and its estuary and subsequent sediment dispersal in the East China Sea. *Geomorphology*, 179(1): 126–140. doi: 10.1016/j.geomorph.2012.05.034.
- Sun Zhaohua, Li Yitian, Ge Hua *et al.*, 2011. Channel erosion processes of transitional reach from gravel river bed to sand bed in middle Yangtze River. *Journal of Hydraulic Engineering*, 42(7): 789–797. (in Chinese)
- Wang Yangui, Liu Xi, Shi Hongling, 2014. Variations and influence factors of runoff and sediment in the Lower and Middle Yangtze River. *Journal of Sediment Research*, (5): 38–47. (in Chinese)
- Williams G P and Wolman M G, 1984. Downstream effects of dams on alluvial rivers. In: Geological Survey Professional Paper 1286 U. S. Government Printing Office, Washington, DC, v q83pp.
- Xia Junqiang, Zong Quanli, Deng Shanshan *et al.*, 2014. Seasonal variations in composite riverbank stability in the Lower Jingjiang Reach, China. *Journal of Hydrology*, 9(Part D): 3664–3673. doi: 10.1016/j.jhydrol.2014.10.061.
- Yang S L, Milliman J D, Xu K H *et al.*, 2014b. Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River. *Earth-Science Reviews*, 138: 469–486. doi: 10.1016/j.earscirev.2014.07.006.
- Yang S L, Xu K H, Milliman J D *et al.*, 2015b. Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes. *Scientific Reports*, 5:12581. doi: 10.1038/srep12581.
- Yang Yunping, Deng Jinyun, Zhang Mingjin *et al.*, 2015a. The synchronicity and difference in the change of suspended sediment concentration in the Yangtze River Estuary. *Journal of Geographical Sciences*, 25(4): 399–416. doi: 10.1007/s11442-015-1176-9.
- Yang Yunping, Li Yitian, Sun Zhaohua *et al.*, 2014a. Suspended sediment load in the turbidity maximum zone at the Yangtze River Estuary: The trends and causes. *Journal of Geographical Sciences*, 24(1): 129–142. doi: 10.1007/s11442-014-1077-3.
- Zheng Shouren, 2015. Risk analysis of implementing middle-small flood dispatch by Three Gorges Project and countermeasures. *Yangtze River*, 46(5): 7–12. (in Chinese)