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RESEARCH ARTICLE

Coarse and fine sediment transportation patterns and causes downstream of the Three Gorges Dam

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Abstract Reservoir construction within a basin affects the process of water and sediment transport downstream of the dam. The Three Gorges Reservoir (TGR) affects the sediment transport downstream of the dam. The impoundment of the TGR reduced total downstream sediment. The sediment group $d \leqslant 0.125$ mm (fine particle) increased along the path, but the average was still below what existed before the reservoir impoundment. The sediments group $d > 0.125$ mm (coarse particle) was recharged in the Yichang to Jianli reach, but showed a deposition trend downstream of Jianli. The coarse sediment in the Yichang to Jianli section in 2003 to 2007 was above the value before the TGR impoundment. However, the increase of both coarse and fine sediments in 2008 to 2014 was less than that in 2003 to 2007. The sediment retained in the dam is the major reason for the sediment reduction downstream. However, the retention in different river reaches is affected by riverbed coarsening, discharge, flow process, and conditions of lake functioning and recharging from the tributaries. The main conclusions derived from our study are as follows: 1) The riverbed in the Yichang to Shashi section was relatively coarse, thereby limiting the supply of fine and coarse sediments. The fine sediment supply was mainly controlled by TGR discharge, whereas the coarse sediment supply was controlled by the duration of high flow and its magnitude. 2) The supply of both coarse and fine sediments in the Shashi to Jianli section was controlled by the amount of total discharge. The sediment supply from the riverbed was higher in flood years than that in the dry years. The coarse sediment tended to deposit, and the deposition in the dry years was larger than that in the flood years. 3) The feeding of the fine sediment in the Luoshan to Hankou section was mainly from the riverbed. The supply in 2008 to 2014 was more than that in 2003 to 2007. Around 2010, the coarse sediments transited from depositing to scouring that was probably caused by the increased duration of high flow days. 4) Fine sediments appeared to be deposited in large amounts in the Hankou to Jiujiang section. The coarse sediment was fed by the riverbed scouring, and much more coarse sediments were recharged from the riverbed in the flood years than in the dry years. 5) In the Jiujiang to Datong section, the ratio of fine sediments from the Poyang Lake and that from the riverbed was 1: 2.82. The sediment from the riverbed scouring contributed more to the coarse sediment transportation. The contribution was mainly affected by the input by magnitude and duration of high flows.

Keywords grouped sediments, genetic analysis, Three Gorges reservoir, transportation characteristics, middle and lower reaches of Yangtze River

1 Introduction

A reservoir has the powerful capability of regulating river runoff by the joint use of cascade reservoirs. The reservoir plays a substantial role that changes the natural hydrological cycle and the sediment transport process downstream (Benn and Erskine, 1994). Although a difference exists among rivers regarding the regulation of reservoirs, distribution of tributary and lakes, status of riverbed scouring, and adjustment of river types, sediment transportation along the river is increased after dam develop-

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ment. However, the total amount is still less than the average amount before the development of reservoirs. The saturation parameter in the saturation recovery coefficient regaining curve for the heterogeneous sediment downstream of the reservoir could generally be 10^{-3}–10^{-1}, which reduces with the diameter of the sediment, increases with the duration of the riverbed erosion, and shows a declining trend with the riverbed coarsening (Ge et al., 2011). The sediment transportation downstream of the Danjiangkou reservoir was reported to regain after build-up of the dam, in which the increase in 1980 to 1985 was stronger than that in 1970 to 1979 because of the high discharge in 1980 to 1985. However, the sediment transported had not reached the amount transported in pre-reservoir time (HBCWRC, 2002). The sediment group $d \leqslant 0.05$ mm downstream of the Sanmenxia Dam on the Yellow River increased along the river. The sediments with 0.05 mm $< d \leqslant 0.10$ mm also increased along the river, but decreased beyond a certain distance. Meanwhile, the sediment group $d > 0.10$ mm increased down the Huayuankou and was probably contributed by the tributary in the concerned river reach (Chen et al., 2002). In summary, the fine sediment downstream of the river could be regained to a certain degree after the development of the reservoir, which is also affected by river discharge, riverbed composition, and characteristics of the river networks concerning the discharge input and output.

Downstream the dam, the sediment transportation shows a decreasing trend after the impoundment of the reservoir (Yang et al., 2014, 2015b, c), which is consistent with the behavior of the sediment transportation from global studies on large reservoirs (Liu et al., 2013). The factors affecting the sediment transportation downstream of the Three Gorges Dam (TGD) are the impoundment of the reservoir, soil and water conservation practices, and characteristics of the river and lake networks, among others (Dai et al., 2011; Yang et al., 2015a). It was predicted based on the study on transportation characteristics of fine and coarse sediment that the transported sediment for each size groups would be retained, but the total sediments transported could not reach the pre-reservoir averages (Li et al., 2003). In 2003 to 2011, the sediment downstream along the river increased, agreeing with the prediction (Chen and Li, 2009; Guo et al., 2014). In 2003 to 2007, the observed data showed riverbed scouring for a relatively long distance near the dam section. The scouring was caused by inadequate fine sediment supply from the riverbed (Chen and Li, 2009). In 2003 to 2011, the sediments in the group $d \leqslant 0.125$ mm were gradually retained along the river. The retention for sediment group $d > 0.125$ mm was more efficient within 200 km downstream from the dam. The strong scouring after the reservoir impoundment occurred in the Jingjiang section (Guo et al., 2014). The scouring and silting in the river channel of the Yichang to Wuhan (Hankou) section on the Yangtze River (Zhu et al., 2012) and Sanmenxia to Lijin reach of the Yellow River (Xu et al., 2009) were both reported to respond differently to the sediment groups. The relationship between scouring to silting amount and sediment transportation was stronger for the coarse sediment groups. The change in the sediment source rate caused strong scouring and silting in the riverbed. In other words, the riverbed scouring and silting depended on both the sediment sources and sediment size distribution. The impounding of the Three Gorges increased the water level from 135 m to 175 m, altering the runoff in wet and dry seasons (Li et al., 2011), decreasing the flood discharge and duration (Jiang et al., 2014), and further changing the capacity of sediment transportation by runoff and that of scouring to the river bed. The riverbed in the middle and lower parts of Yangtze tended to be coarsening. The coarsening within 0 to 200 km down the dam was more obvious (Luo et al., 2012; Yang et al., 2016; Zhang et al., 2017). At the same time, the sediment transportation in the Yangtze mainstream was affected by the runoff relations with the lakes and the tributaries. The current understanding on the characteristic of the sediment transportation downstream the TGD is inadequate, particularly under the integrated impact from adjustments to discharge process, riverbed composition, and runoff relations between lakes and tributaries caused by impounding of the Three Gorges Reservoir (TGR). Therefore, further studies on the characteristics of the sediment transportation downstream of the TGD are needed.

In this study, we collected hydrological and sediment data from 1987 to 2014 for the reservoir and downstream river, carefully considering the relationship between the scouring and silting characteristics of the sediment and measured particle size groups, and riverbed scouring and silting (Zhu et al., 2012; Yang et al., 2016; Zhang et al., 2017). We used $d = 0.125$ mm as the critical size for the sediment particle differentiation. We then analyzed the characteristics of the sediment transportation in the mainstream downstream the dam for different sediment size groups and discussed the causes and the spatial–temporal distribution of sediment transporting.

2 Study area, data source, and hydrological and sedimentary characteristics

2.1 Study area

The river section from Yichang to Datong is 1183 km long. The Yichang to Dabujie section is 116.4 km long with a sand–cobble riverbed. The Dabujie to Datong section is 1066.6 km long with a sand bed (Fig. 1). The study area has hydrological stations, including Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Jiujiang, and Datong, among others. The water of the Dongting Lake drains into Songzikou, Taipingkou, and Ouchikou. These three rivers are collectively known as Sankou. The hydrological control stations for input from the Dongting Lake, Han

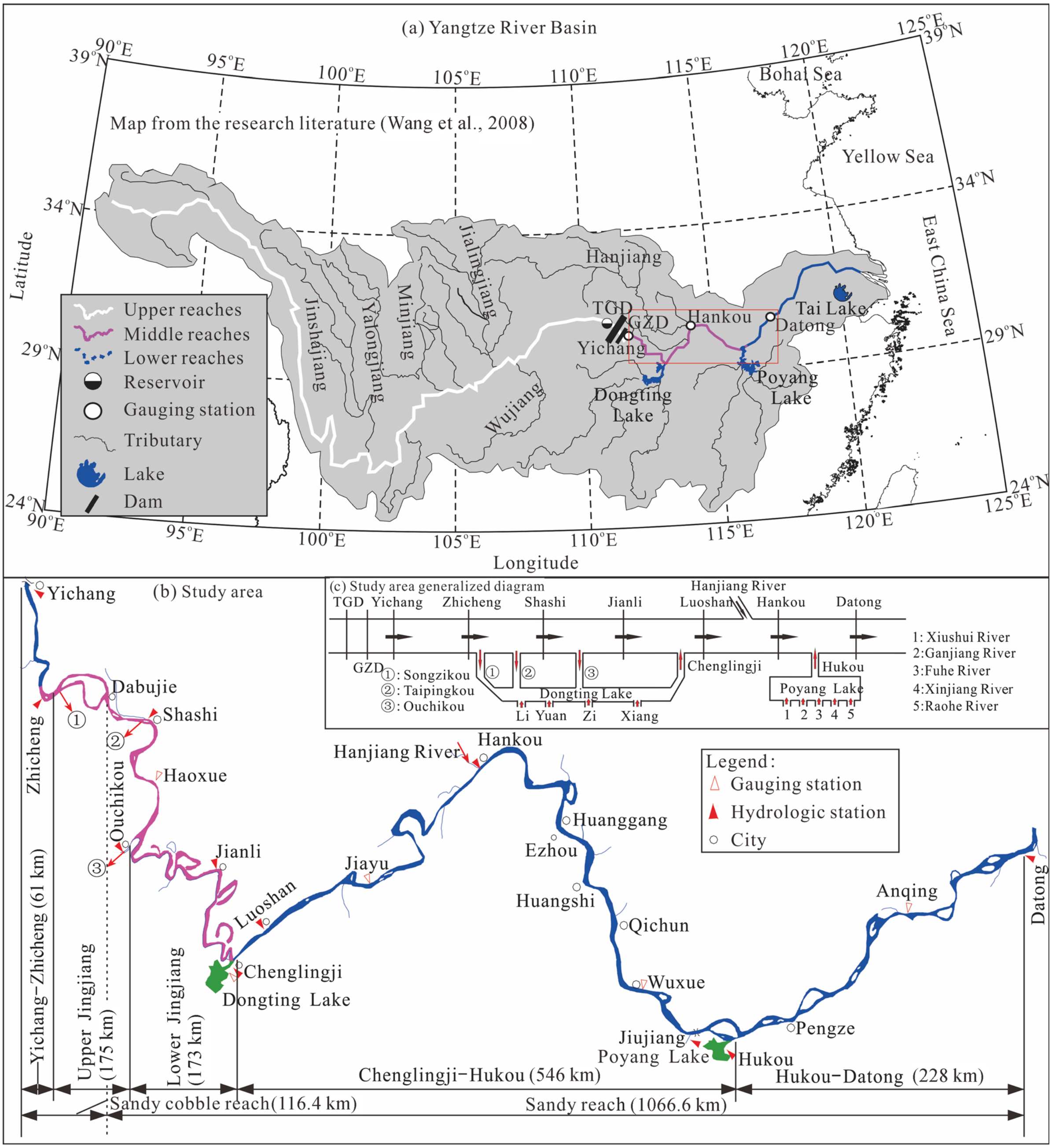

Fig. 1 Schematic diagram of the mainstream downstream the TGD. (a) Yangtze River Basin; (b) study area; (c) study area generalized diagram.

River, and Poyang Lake are the Chenglingji, Huangzhuang, and Hukou stations, respectively.

2.2 Data sources

The runoff, sediment, and size distribution for the suspended sediment in 1987 to 2014 were collected for the mainstream, tributaries, and lakes downstream the TGD. Table 1 shows the details. The particle information for the deposited sediment in the riverbed from Yichang to Datong was also collected. This information, including the yearly, monthly, and daily average runoff, flow rate, and sediment load data, as well as the annual average sediment gradation data, were collected by mainstream hydrological stations. The annual average runoff, flow rate, and sediment load data were collected by the tributary hydrological stations of the Dongting and Poyang lakes. The riverbed surface sediment grain size data were collected during the period October–November in 2003, 2007, and 2010. The TGR began impoundment in June 2003. Therefore, year 2003 was used as the demarcation year between the two periods, 1987 to 2002 and 2003 to

Table 1 Source of sediment and hydrological data downstream the TGD

Number	Hydrologic station	Content	Time characteristics	Year	Sources
1	Yichang, Zhicheng, Shashi, Jianli, Luoshan, Hankou, Jiujiang, Datong	Water, Sediment, Flow Sediment gradation	Day, Month, Year Year	1987–2014	Regional hydrological yearbook of the middle and lower reaches of the Yangtze River Changjiang Water Resources Commission
2	Songzikou, Taipingkou, Ouchikou	Water, Sediment, Flow	Month, Year	1987–2014	Changjiang Water Resources Commission
3	Chenglingji Hukou Jiujiang	Water, Sediment, Flow, Sediment gradation	Year	2003–2014 2006–2014 2009–2012	
4	Yichang to Datong	Bed sand grading	October	2003, 2007, 2010	Yangtze River Waterway Planning and Design Institute

2014. Two periods (i.e., 2003 to 2007 and 2008 to 2014) were further differentiated because of the difference in the water level after the impoundment and the varying degree of its influence on the water and sediment regulation. The period from 1987 to 2014 was divided into three time intervals, namely 1987–2002, 2003–2007, and 2008–2014. The division facilitated the comparison of the extent of influence and variability with respect to the sediment transport process before and after the reservoir impoundment.

2.3 Runoff regulation process of the TGR

The TGR began impoundment in June 2003, reaching an impoundment level of 175 m in the following three separate stages (Zhao et al., 2015): June 2003–September 2006, October 2006–September 2008, and October 2008 to present, which were distinguished as the cofferdam, initial, and pilot impoundment stages, with corresponding water retention levels of 135–139 m, 144–156 m, and 145–175 m, respectively (Fig. 2). The TGR regulation method was based on the flood peak reduction and drought flow recharge. During flood season, the upstream flood peak is drastically reduced to alleviate the pressure of downstream flood prevention. During drought season, the discharge is supplemented with the goal of alleviating downstream drought conditions while increasing the channel depth and improving its ecology. Since reaching the 175 m pilot retention stage in 2009, the flood peak reduction during flood season and the runoff recharge for drought season have exerted a more prominent influence. For example, in 2010, the maximum reduction of the flood peak flow rate reached 30,000 m^3/s, which ensured that the reservoir discharge rate did not exceed 40,000 m^3/s. The number of drought season runoff recharge days has increased every year since 2009. It reached 189 days during the period between 2015 and 2016, which suggested that the flow recharge regulation lasted for more than half of the year (Table 2).

2.4 Hydrological and sedimentary characteristics

In 2003 to 2014, the discharge and the sediment from the hydrological stations on the lower reaches of the dam were less than the average values in 1987 to 2002, in which the decrease of the discharge and the sediment in the 2008 to 2014 period was larger than that in 2003 to 2007 (Fig. 3). The decrease of the discharge and sediment in the 2003 to 2014 period was 3.5%–13.0% and 53.5%–93.5%, respectively. Moreover, the amount of the decline kept rising for

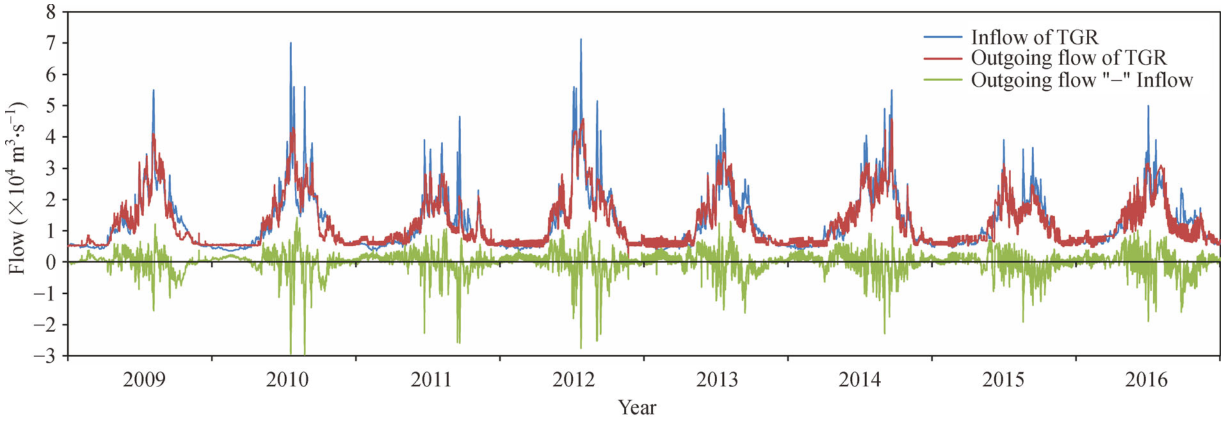

Fig. 2 175 m impoundment of the Three Gorges reservoir (runoff regulation process) (2009–2016).

Table 2 Benefit analysis of the Three Gorges reservoir

Year	Maximum peak	Occurrence date (Day/Month)	Maximum discharge flow/($m^3 \cdot s^{-1}$)	Times of flood storage	Water storage /(10^8 m^3)	Compensation days	Make-up water /(10^8 m^3)	Dry water level increase/m
2003	46,000	4/9	0	0	0	0	0	0.74
2004	60,500	8/9	3700	1	4.95	11	8.8	
2005	46,000	22/7	0	0	0	0	0	
2006	29,500	10/7	0	0	0	0	0	0.38
2007	52,500	30/7	5100	1	10.43	80	35.8	0.33
2008	41,000	15/8	0	0	0	63	22.5	1.03
2009	55,000	5/8	16,300	2	56.5	101	56.6	1.00
2010	70,000	20/7	30,000	7	266.3	141	139.7	1.13
2011	46,500	21/7	25,500	5	187.6	164	215	1.31
2012	71,200	24/7	28,200	4	228.4	150	215	1.29
2013	49,000	21/7	14,000	5	118.37	146	177.9	1.26
2014	55,000	20/9	22,900	10	175.12	180	244	1.26
2015	39,000	1/7	8000	3	75.4	189	291	1.26
2016	50,000	1/7	19,000	4	227			

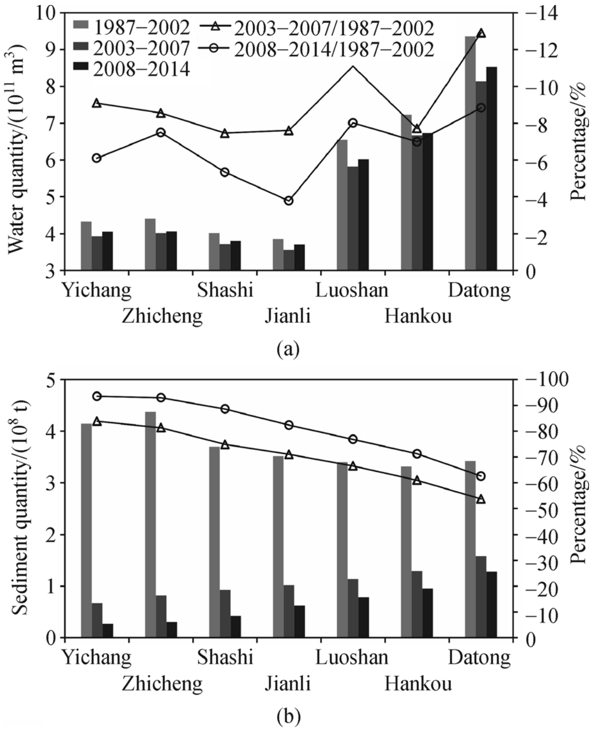

Fig. 3 Changes of discharge and flux downstream the TGD. (a) Change of water quantity; (b) change of sediment quantity.

the discharge and became gentle for the sediment. The comparison of the 2003–2012 period with the 1993–2002 period showed that the contribution to the water reduction from precipitation, urban water consumption, Three Gorges Dam, other dams, and soil and water conservation practices were 61%, 2%, 3%, 5%, and 9%, respectively. Furthermore, the contribution to the sediment reduction was 14%, 1%, 65%, 1%, and 10%, respectively (Yang et al., 2015a).

Figure 4 shows that the percentage of water and sediment in the Sankou station to the total water and sediment amount in Zhicheng denoted a declining trend.

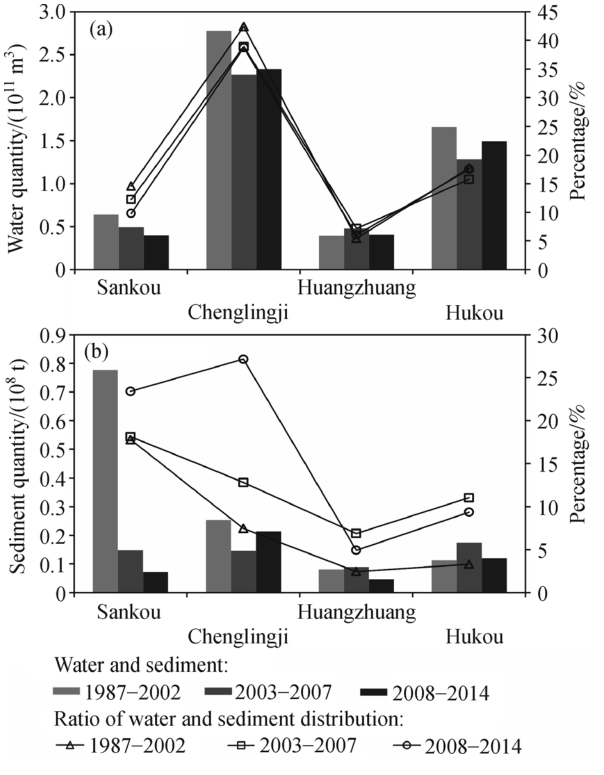

Fig. 4 Changes of discharge and flux in the lakes and tributary downstream the TGD. (a) Water; (b) sediment.

The water and the sediment from the Chenglingji station both decreased at first, and then increased. The share of water to the amount in the Luoshan station decreased, whereas the share of sediment increased. The water and the sediment from the Han River to the Yangtze River and its percentage to the values from the Hankou Station all increased first, and then decreased. The share of water from the Hukou station to the amount in the Datong station first decreased, and then increased, whereas that of sediment first increased, and then decreased.

The median diameter of the suspended sediment downstream of the dam in the periods of 1987 to 2002, 2002 to 2007, and 2008 to 2014 first increased, and then decreased, in which the median diameter of the suspended sediment after the TGD impoundment showed a peak in the Jianli station (Fig. 5). In the perspective of the inter-annual variability of the median diameter of the suspended sediment in the concerned stations, the key points are as follows:

a) The Yichang station increased with decrease at first;

b) The Zhicheng station slightly decreased;

c) The Shashi, Jianli, and Luoshan stations all increased first, and then decreased;

d) Slight increases were observed in the Hankou and Datong stations;

e) The Dongting lake station and the Sankou station increased with decrease at first;

f) The Chenglingji station kept increasing, and the Huangzhuang station on the Han River decreased after first increasing;

g) The median diameter of the suspended sediment in the Huangzhuang station on the Han river was larger than that in the Hankou station, but the difference of the value in the Hankou station to the stations upstream was relatively small because of the slight sediment contribution of the Huangzhuang station to the total sediment amount in the Hankou station; therefore, the effect on the value of the median diameter of the suspended sediment in Hankou was limited.

Meanwhile, the influence was further weakened by the deposition by coarse sediments and eroded for fine sediment in the riverbed between the Huangzhuang station and the entrance gate.

3 Transport patterns of sediments with different-sized groups downstream the TGD

3.1 Transport processes for sediment groups with different particle sizes

The sediments were cataloged into five groups according to their particle size: sediment groups $d \leqslant 0.031$ mm, $0.031 \text{ mm} < d \leqslant 0.063$ mm, $0.063 \text{ mm} < d \leqslant 0.125$ mm, $0.125 \text{ mm} < d \leqslant 0.25$ mm, and $d > 0.25$ mm (Fig. 6). Figure 5 shows the spatial characteristics of the transport processes. The sediment amount for the sediment group $d \leqslant 0.031$ mm showed a pattern of increase–decrease–increase for the river section of Yichang to Zhicheng to Luoshan to Datong in 1987 to 2002. The same result was obtained showed for the river section of Yichang to Zhicheng to Jianli to Datong in 2003 to 2007. The sediment amount between Yichang and Datong also increased in 2008 to 2014. Similarly, the sediment amount for the sediment group with $0.031 \text{ mm} < d \leqslant 0.063$ mm increased along both river sections of Yichang to Zhicheng to Luoshan and Luoshan to Hankou to Datong in 1987 to 2002. An increasing–decreasing–increasing process along the river section of Yichang to Jianli to Luoshan to Datong was observed in both periods of 2003 to 2007 and 2008 to 2014. The sediment amount for the sediment group with $0.063 \text{ mm} < d \leqslant 0.125$ mm first decreased, and then increased along the river sections of Yichang to Zhicheng to Luoshan and Luoshan to Hankou to Datong in 1987 to 2002. The sediment along the Yichang to Hankou to Datong section increased, and then decreased in 2003 to 2007, and kept increasing all along the river in 2008 to 2014. The sediment amount for the sediment group with $0.125 \text{ mm} < d \leqslant 0.25$ mm first decreased, and then increased along the river section of Yichang to Zhicheng to Jianli and in the Jianli to Luoshan to Hankou to Datong section in 1987 to 2002. This pattern showed a decreasing–increasing–decreasing process. The sediment along the Yichang to Hankou to Datong section first increased, and then decreased in 2003 to 2007. Meanwhile, the sediment amount along the river in 2008 to 2014 first increased, and then decreased for both sections of Yichang to Jianli to Luoshan and Luoshan to Hankou to Datong. The sediment

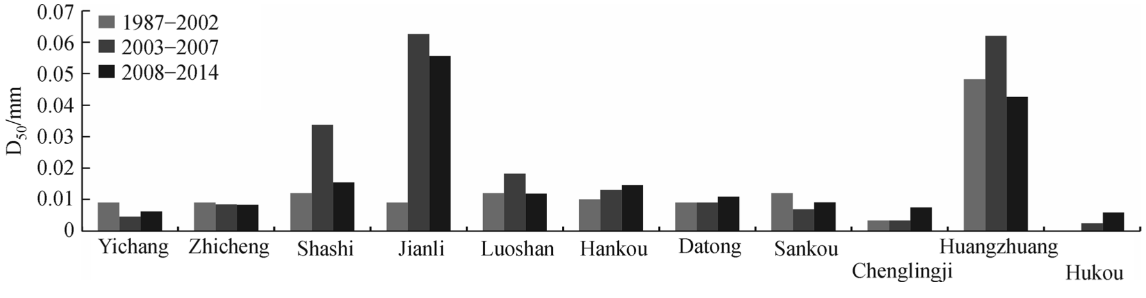

Fig. 5 Change of the median diameter of the suspended sediment downstream the TGD (1987 to 2014).

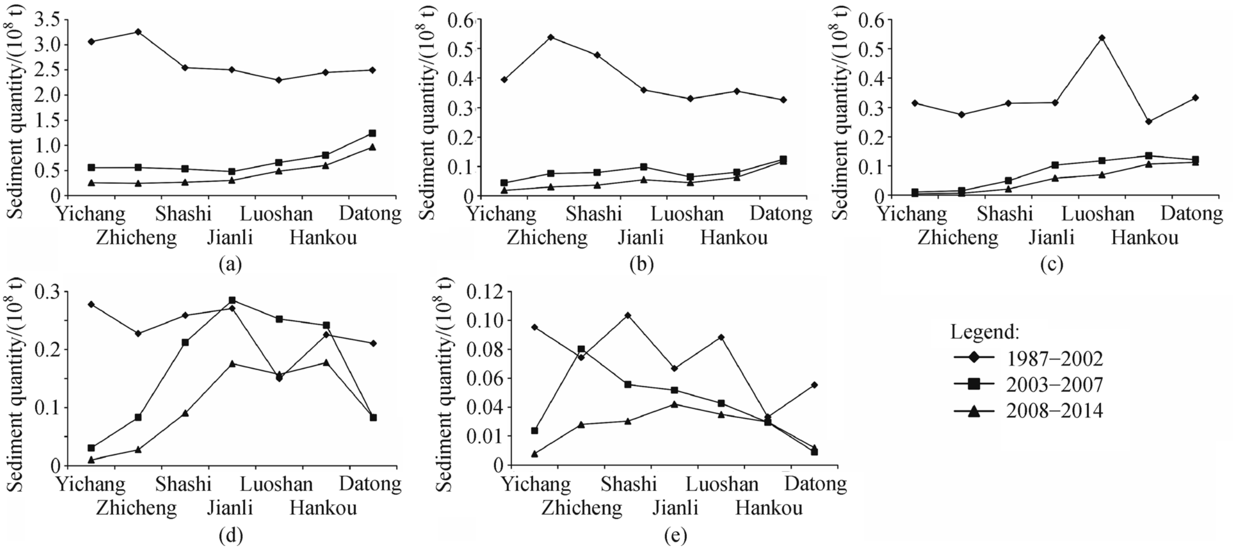

Fig. 6 Transport process of different particle sizes of the sediment downstream the TGD. (a) $d \leqslant 0.031$ mm; (b) 0.031 mm $< d \leqslant 0.063$ mm; (c) 0.063 mm $< d \leqslant 0.125$ mm; (d) 0.125 mm $< d \leqslant 0.25$ mm; (e) $d > 0.25$ mm.

amount for the sediment group $d > 0.25$ mm first decreased, and then increased along the river sections of Yichang to Zhicheng to Shashi, Shashi to Jianli to Luoshan, and Luoshan to Hankou to Datong in 1987 to 2002. The sediment along Yichang to Zhicheng to Datong increased, and then deceased in 2003 to 2007. In 2008 to 2014, the sediment amount along Yichang to Jianli to Luoshan first increased, and then decreased.

The sediment amounts were temporally ranked in ascending order for groups $d \leqslant 0.125$ mm by year for the periods of 2008 to 2004, 2003 to 2007, and 1987 to 2002. The sediment amount for the sediment group with 0.125 mm $< d \leqslant 0.25$ mm in the stations of Jianli, Luoshan, and Hankou in 2003 to 2007 was higher than that in 1987 to 2002 and, in 2008 to 2014, had values less than those in 2003 to 2007 and 1987 to 2002. The sediment amount for the sediment group $d > 0.25$ mm in the Zhicheng stations in 2003 to 2007 was higher than that in 1987 to 2002 and, in 2008 to 2014, had values less than those in 2003 to 2007 and 1987 to 2002, except for the observations in the Datong station.

3.2 Transport processes for the coarse and fine sediments in representative runoff years

Years 2006 and 2011 were representative low-flow years (Fig. 7(a)). We compared the sediment and discharge data for 2006 and 2011. The sediment concentrations for the sediment groups $d \leqslant 0.125$ mm in 2006 were larger than those in 2011 in the Yichang, Zhicheng, Shashi, Luoshan, and Datong stations. The result obtained for the Jianli and Hankou stations was in contrast to those of the sediment concentrations in 2011, which were larger than those in 2006. The sediment concentrations for the sediment groups $d > 0.125$ mm in 2006 were larger than those in 2011 in all the involved stations. Moreover, the discharges in 2011 were larger than those in 2006 in the Yichang, Zhicheng, Shashi, and Jianli stations. The changes were not significant in the Luoshan, Hankou, and Datong stations.

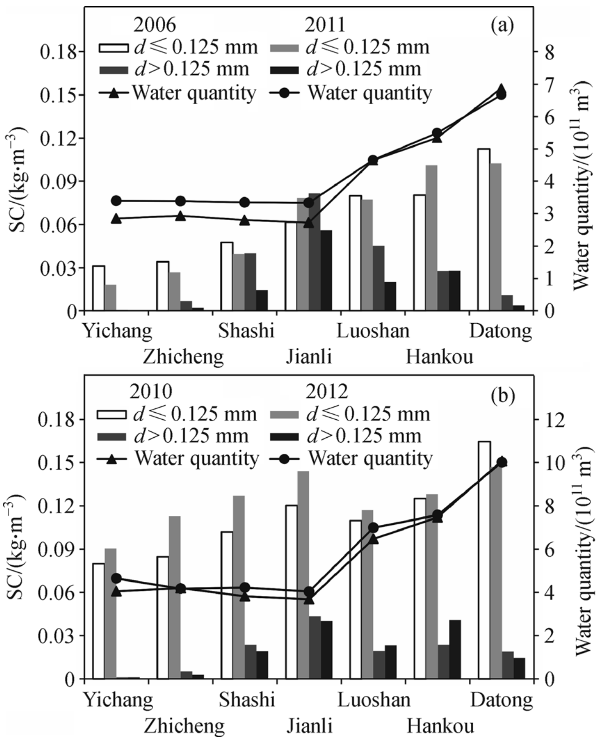

Fig. 7 Transport process of different particle sizes of sediments downstream the TGD in the representative runoff years. (a) Dry years; (b) flood years.

Years 2010 and 2012 were representative high-flow years (Fig. 7(b)). We compared the sediment and discharge data for 2006 and 2011. The sediment concentrations for the sediment groups $d \leqslant 0.125$ mm in 2012 were larger than those in 2010 in all stations from Yichang to Hankou. These results were in contrast with the data for the Datong stations. The sediment concentrations for the sediment groups $d > 0.125$ mm in 2012 were lower than those in 2010 in the Yichang, Zhicheng, Shashi, and Datong stations. Moreover, the sediment concentrations for the Luoshan and Hankou station in 2012 were larger than those in 2010. The discharges were slightly larger in 2012 than those in 2010 in all the involved stations along the river.

3.3 Characterizations of the sediment transportation for coarse ($d > 0.125$ mm) and fine ($d \leqslant 0.125$ mm) sediment groups

An obvious difference was observed in the characteristics of the sediment transportation between groups of $d > 0.125$ mm and $d \leqslant 0.125$ mm. Hence, a further analysis was made for these two groups. Temporally (Figs. 8(a) and (c)), the sediment amount and concentration for the sediment group $d \leqslant 0.125$ mm in periods of 2003 to 2007 and 2008 to 2014 were smaller than those in the 1987 to 2002 period. The sediment amount and concentration for the sediment group $d > 0.125$ mm were gradually retained along the Yichang to Jianli stations in 2003 to 2007. The values reached or exceeded those of the records in 1987 to 2002. The sediment amount and concentration in the Yichang to Jianli station were retained in 2008 to 2014. However, these values were still lower than those in 1987 to 2002 and 2003 to 2007. Spatially (Figs. 8(b) and (d)), the result obtained is presented as follows: the sediment amount for the sediment group $d \leqslant 0.125$ mm increased, and then decreased from Yichang to Zhicheng to Shashi in 1987 to 2002. Meanwhile, the change from Shashi to Datong was not obvious. The sediment amount in the periods of 2003 to 2007 and 2008 to 2014 gradually increased along the river. The sediment concentration increased from Yichang to Jianli, slightly decreased from Jianli to Luoshan, and kept increasing from Luoshan to Datong. The sediment amount and concentration for the sediment group $d > 0.125$ mm in the 1987–2002 period decreased from Yichang to Jianli. The sediment increased after the reservoir impoundment. However, the sediment in the Jianli to Datong section decreased after the reservoir impoundment.

4 Causes of variability for the fine and coarse sediment transportation downstream the TGD

The direct factor influencing the sediment transportation downstream of the TGD was the sediment detention by the reservoir, while the indirect factors were riverbed coarsening, total water, flow process, and water distributing and confluence by tributaries and lakes.

4.1 Impact of sediment detention by the reservoir

Since 2003, the outbound sediments from the TGR for the sediment group $d \leqslant 0.125$ mm kept on decreasing as the

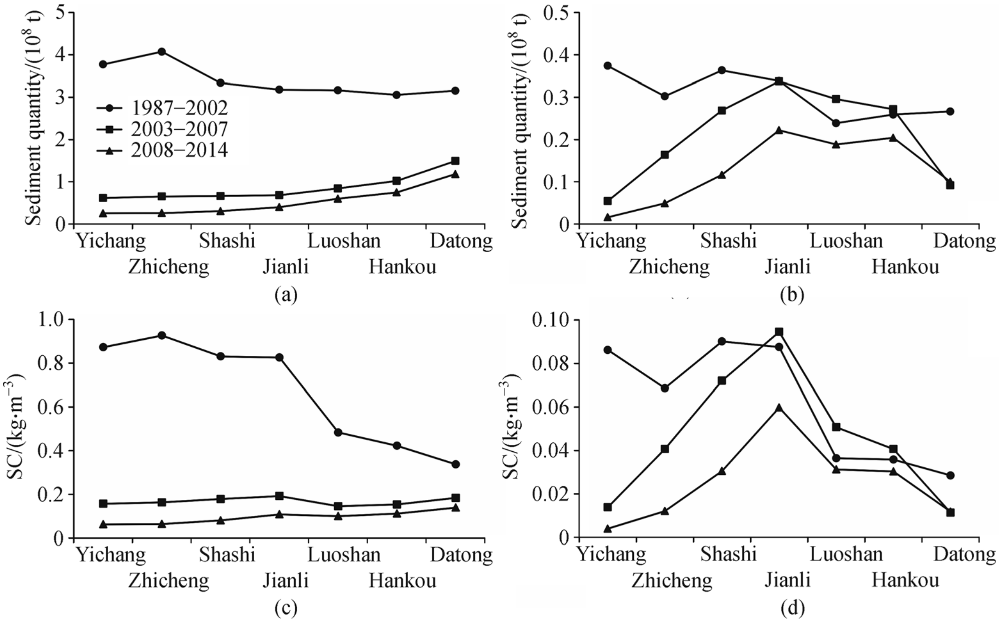

Fig. 8 Changes of the sediment load of (a) $d \leqslant 0.125$ mm and (b) $d > 0.125$ mm and concentration (SC) of (c) $d \leqslant 0.125$ mm and (d) $d > 0.125$ mm downstream the TGD.

sedimentation ratio of the reservoir increases. In other words, the sediments in the sediment group $d > 0.125$ mm were mainly deposited in the reservoir, or less sediment, overall, was deposited in the reservoir area (Fig. 9). The inbound sediments to the TGR did not show any obvious change, but the decreased outbound sediment resulted in the increase in the sedimentary area. The sedimentary area increased to 97.2% in 2005 to 2012. From this, it could be deduced that the sediments in the sediment group $d > 0.125$ mm were mainly detained in the reservoir area (Fig. 9). Therefore, the sediment detention by the reservoir was the main reason for the sediment reduction downstream.

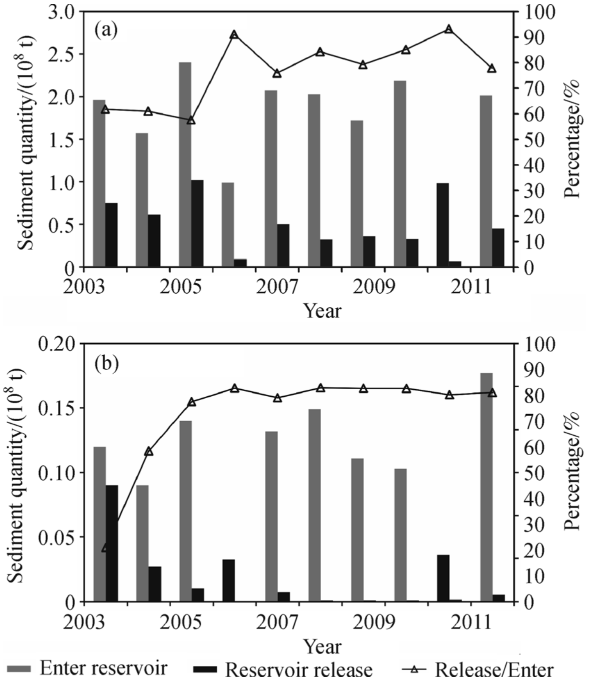

Fig. 9 Ratios of the inflow sediment to the outflow sediments with particle sizes grouped as (a) $d \leqslant 0.125$ mm and (b) $d > 0.125$ mm.

The coarse sediment discharge in the river reach near the dam in the Yichang station was 0.054×10^8 t/yr and 0.016×10^8 t/yr in 2003 to 2007 and 2008 to 2014, respectively. The amount in the Jianli station was 0.337×10^8 t/yr and 0.221×10^8 t/yr in 2003 to 2007 and 2008 to 2014, respectively, in which the sediment from the riverbed was 85.3% in 2003 to 2007 and 92.8% in 2008 to 2014. The fine sediment discharge in the Yichang station was 0.62×10^8 t/yr and 0.25×10^8 t/yr in 2003 to 2007 and 2008 to 2014, respectively. The amount in the Jianli station was 0.66×10^8 t/yr and 0.41×10^8 t/yr in 2003 to 2007 and 2008 to 2014, respectively, in which the sediment discharge from the riverbed was 0.04×10^8 t/yr, thereby accounting for 6.1% in 2003 to 2007 and 0.16×10^8 t/yr for 39.0% in 2008 to 2014.

In conclusion, the contribution of the sediments from the riverbed in the Jianli station increased. However, the coarse sediments led to a decrease, whereas the fine sediments contributed to an increase. These results were probably related to the variability in the riverbed composition and the flow processes.

4.2 Impact of riverbed coarsening

Figure 10 shows the coarsening trend of the riverbed in 2003, 2007, and 2010. Herein, a strong coarsening process occurred in the Yichang to Zhicheng section, and the riverbed generally coarsened from Zhicheng to Luoshan. The coarsening decreased with the riverbed only being slightly coarsened down from the Luoshan station.

Sand deposited downstream of the dam because of the increase in the riverbed roughness (Table 2). The overall resistance showed an increasing trend, considering the influence of the longitudinal shape resistance and the river regime adjustment resistance (Han, 2015). The increase of the resistance will weaken the intensity of the sediment supply from the riverbed concerning both fine and coarse sediments. A sandy bed will generally show a low level of coarsening, and coarsening has less effect on the supply of suspended sediments.

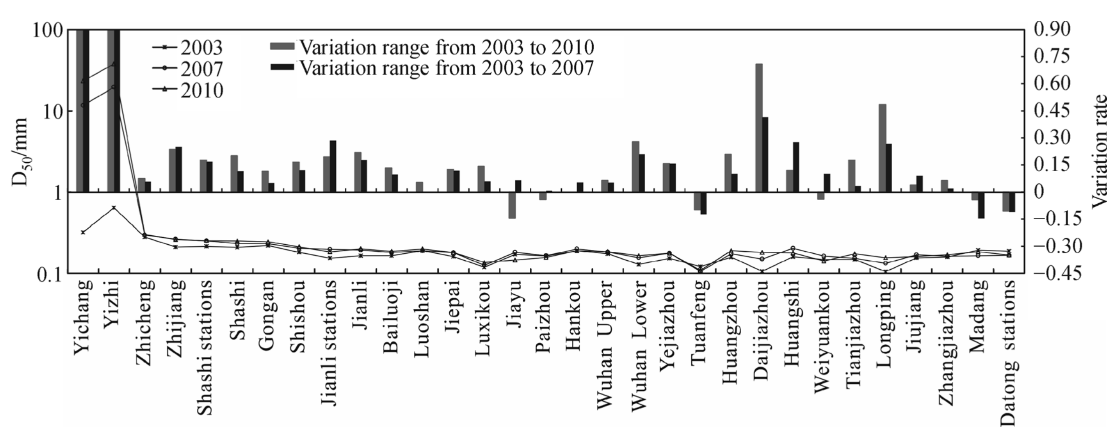

Fig. 10 Change of median diameters for riverbed sediment in the downstream of the TGD.

Table 3 Roughness change caused by the riverbed coarsening (Han, 2015)

River bed composition	Sandy gravel	Sandy gravel–Sandy	Sandy	
Reach	Yichang to Zhicheng	Zhicheng to Dabujie	Dabujie to Chenglingji	Chenglingji to Hukou
Increasing multiples	1.91	1.65	1.03	1.02

4.3 Impact of the flow process

The maximum sediment concentration is always obtained in the period of high flow for both fine and coarse sediments. The number of days with $Q > 15{,}000$ m^3/s in the Shashi station was 26 in 2006 and 76 in 2011, showing an obvious increase on the time duration (Fig. 11). However, the sediment amount for groups $d > 0.125$ mm and $d \leqslant 0.125$ mm both showed a decreasing trend. The maximum discharges in the Shashi station in 2006 and 2011 were less than 25,000 m^3/s, and there was almost no flow through the higher part of the bed. Moreover, the flow intensively scoured the riverbed with a flat bank. Therefore, the sediments in the sediment group $d \leqslant 0.125$ mm were rare in the deep bank, and the amount of fine sediments in 2011 was less than that in 2006. The long high flow duration in 2011 helped in supplying sediments from the riverbed for the sediment group $d > 0.125$ mm. However, the sediment amount for the sediment group $d > 0.125$ mm was less in 2011 than that in 2006 because the riverbed coarsening strengthened channel resistance and weakened riverbed scouring.

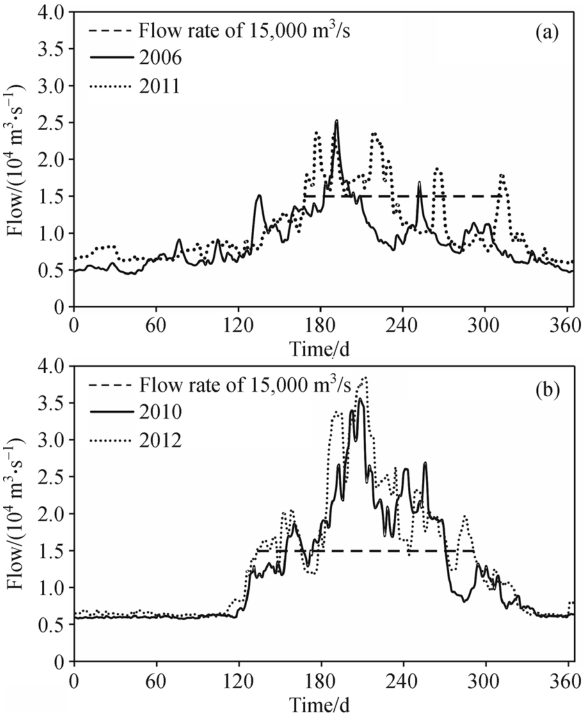

Fig. 11 Discharge changes in the representative hydrological years in the Shashi hydrological station after the TGR impoundment. (a) Dry years; (b) flood years.

The comparison of the data for 2010 and 2012 in the Shashi station showed that the number of days with $Q > 15{,}000$ m^3/s was 110 and 132, indicating that the time duration increased in 2010 and 2012 (Fig. 11). The sediment amount for the sediment group $d > 0.125$ mm in the reach from Yichang to Shashi was higher in 2010 than that in 2012 because the riverbed coarsening strengthened channel resistance and weakened riverbed scouring. In the same section of the river, the sediment amount for the sediment group $d \leqslant 0.125$ mm was lower in 2010 than that in 2012 because the water along with high flow over the higher bank kept it unsaturated for a relatively long time, thereby enhancing channel scouring.

The river from Yichang and Shashi contains a sand–pebble section and a section transiting to sand pebble. The sandy bed only covers a short reach. The riverbed coarsening increased the surface resistance and limited the flow ability for riverbed scouring in both dry and flood years. Therefore, the riverbed contribution to the decrease of sediment group $d > 0.125$ mm. In the flood year, the riverbed contributed more to the sediment group $d \leqslant 0.125$ mm, which was mainly from scouring of the shallow bank by overflow. The magnitude also depended on the flood duration.

The flood discharge was determined as $Q \geqslant 1.5 \times 10^4$ m^3/s for the river section from Yichang to Jianli, $Q \geqslant 2.5 \times 10^4$ m^3/s for the Luoshan station, $Q \geqslant 3.0 \times 10^4$ m^3/s for the Hankou station, and $Q \geqslant 3.5 \times 10^4$ m^3/s for the Datong station (Fig. 12).

The number of days with discharge above the flood discharge and the averaged discharge in the period in 2008 to 2014 in the Yichang, Zhicheng, Shashi, Jianli, and Hankou stations were all larger than those in 2003 to 2007. The values in the Luoshan and Datong stations in 2008 to 2014 were larger than those in 2003 to 2007. In 2008 to 2014, the sections without input from tributary or lakes had sediment amounts smaller than those in 2003 to 2007. This result was consistent with the number of high flow days and flow magnitude.

4.4 Impact of exchange with lakes and input from tributaries

The river reach from Yichang to Datong was divided into six sections. The impact of the exchange with lakes and the input from the tributaries on the sediment concentration is discussed for each section as follows:

1) Yichang to Shashi section: the sediment amount in the

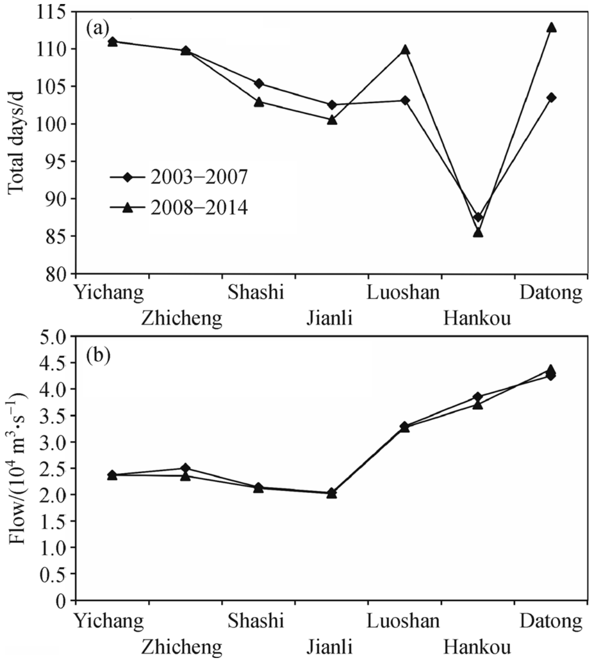

Fig. 12 Change of flood discharge and duration downstream the TGD. (a) Flow last days; (b) average flow in the days.

Yichang station after the TGD impoundment was higher than that in the Shashi station for sediment groups $d > 0.125$ mm and $d \leqslant 0.125$ mm. This result indicates that the sediment supply exceeded the consumptions flowing out to Songlike and Hukou rivers. In other words, the sediment supply in the section was mainly fed by the riverbed scouring (Fig. 13). The sediment supply for the sediment group $d \leqslant 0.125$ mm in 2008 to 2014 was higher than that in 2003 to 2007, which was consistent with the changing pattern of total water amount. A statistical analysis showed that the area of marginal and in-between banks in the river section from Yichang to Shashi decreased (Zhu et al., 2015). Therefore, it is inferred that the fine sediment supply from the riverbed was mainly from the marginal and in-between banks. The sediment supply for the sediment group $d > 0.125$ mm in 2008 to 2014 was less than that in 2003 to 2007, which was also consistent with the changing pattern for the level of riverbed coarsening and duration of high-flow days. In summary, the fine sediment supply was mainly from the marginal and in-between banks and affected by the total water amount and the duration of overflow on the marginal banks. The coarse sediment supply was controlled by the duration of high-flow days and magnitude of the high flow.

2) Shashi to Jianli section: the sediment amount in the Jianli station after the TGD impoundment was higher than that in the Zhicheng station for sediment groups $d > 0.125$ mm and $d \leqslant 0.125$ mm, thereby indicating that the sediment supply exceeded consumption flowing out to the Ouchi River. In other words, the sediment supply in the section was mainly fed by riverbed scouring (Fig. 14). The sediment supply in 2008 to 2014 was higher than that in 2003 to 2007 for sediment groups $d > 0.125$ mm and $d \leqslant 0.125$ mm. This result was consistent with the changing pattern of the total water amount and closely related with factors, such as level of riverbed coarsening, high-flow days, and magnitude of the high flow. The overall supply in this section was controlled by the total water amount.

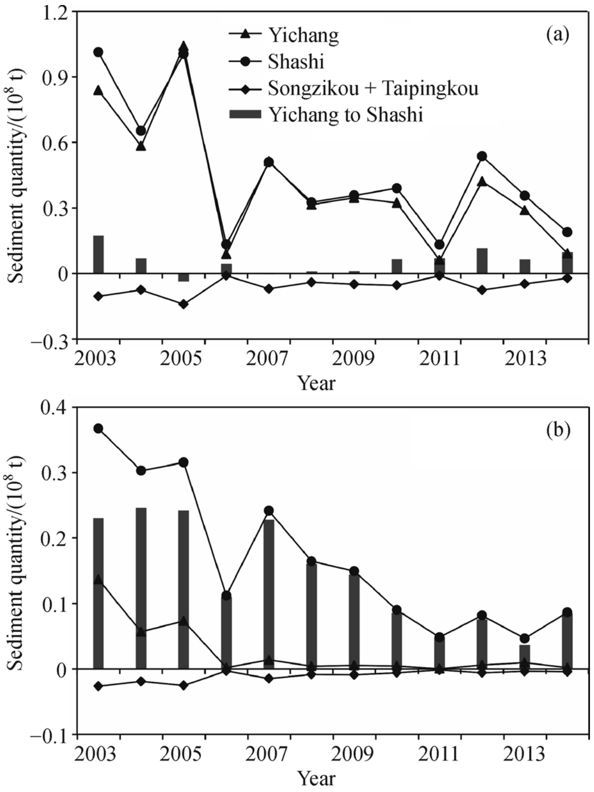

Fig. 13 Change of quantity of scouring and sedimentation for (a) fine ($d \leqslant 0.125$ mm) and (b) coarse ($d > 0.125$ mm) sediments in the Yichang to Shashi section.

3) Jianli to Luoshan section: Figure 15(a) shows the impact of confluence from Dongting Lake on the sediment transporting process of the sediment group $d \leqslant 0.125$ mm in the Jianli to Luoshan section. The sediment input from the lake was positively correlated with the sediment transportation in the river. The sediment supply in the median flood year was larger than that in the median dry year. The sediment supply in the river section exceeded the value in the upstream controlling station (Chenglingji Station) in approximately 2/3 of the total studied years. The sediment supply for the sediment group $d \leqslant 0.125$ mm for the average value of 2003 to 2014 increased to 9.4% in the river section from Jianli to Luoshan. In other words, the sediment supply in this section was mainly from the Dongting Lake, and the contribution from the riverbed was secondary. The sediment in this section for the sediment group $d > 0.125$ mm tended to deposit, except in 2003. The deposition in the median flood years was less than that

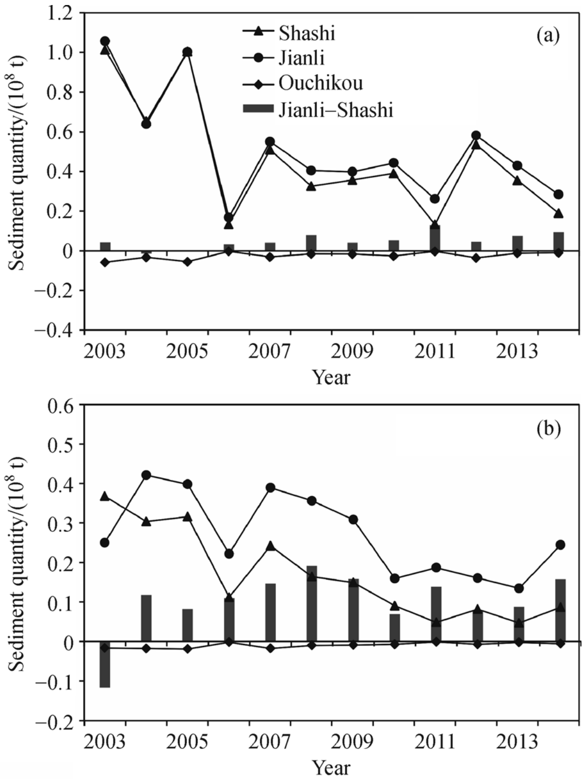

Fig. 14 Change of quantity of scouring and sedimentation for (a) fine ($d \leqslant 0.125$ mm) and (b) coarse ($d > 0.125$ mm) sediments in the Shashi to Jianli section.

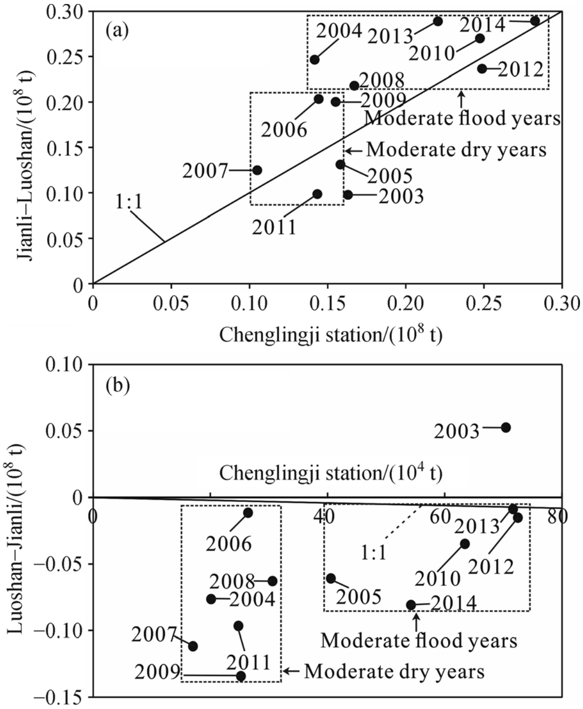

Fig. 15 Impact of confluence from Dongting Lake on the sediment transporting process in the Jianli to Luoshan section (note: the discharges in the Luoshan station after the TGR impoundment were sorted, and the averaged values were applied to determine the moderate dry and flood years. Years 2004, 2006, 2007, 2009, 2011, and 2013 were determined to be moderate dry years, while year's 2003, 2005, 2008, 2010, 2012, and 2014 were moderate flood years). (a) $d \leqslant 0.125$ mm; (b) $d > 0.125$ mm.

in the median dry years. In other words, the flood was able to carry more coarse sediments ($d > 0.125$ mm), as shown in Fig. 15(b).

4) Luoshan to Hankou section: an intersection with the Han River exists in this section. The intersection location is 1.5 km up the Hankou station, and the effect of the input from the Han River is insignificant and negligible. Therefore, we took off the input amount of sediment from the Han River in the analysis that follows. Figure 16 shows the sediment transportation for both coarse and fine sediments in the Luoshan to Hankou section. The riverbed supplied sediments for transporting for the sediment group $d \leqslant 0.125$ mm in 2003 to 2014, in which the supply in 2008 to 2014 was slightly lower than that in 2003 to 2007. Depositing trends in this section were observed for the sediment group $d > 0.125$ mm from 2003 to 2009. Moreover, the riverbed scouring dominated from 2010 to 2014. The sediments in this section were depositing dominated before the TGR impoundment. The trend continued in 2003 to 2007 with a decreasing magnitude of the deposition (Chen and Li, 2009). However, since 2010, the riverbed became scoured and mainly affected by the flow process. Referring to the result in Section 3.3, the number of days with high flows was $Q \geqslant 2.5 \times 10^4$ m^3/s, and the averaged high-flow values both increased in 2008 to 2014. Under the condition of continued sediment reduction in the Luoshan station, the increased duration and magnitude of high flow caused an intensive scouring to the riverbed and has turned deposition to scouring since 2010.

5) Hankou to Jiujiang section (Fig. 17): Figure 17 shows the analysis result for this section. The sediment transportation in the Jiujiang station for the sediment group $d \leqslant 0.125$ mm was lower than that in the Hankou station from 2007 to 2012. Hence, the fine sediment tended to deposit in this section. The sediment transportation in the Jiujiang station for the sediment group $d > 0.125$ mm was higher than that in the Hankou station. Therefore, the riverbed fed the sediment transportation in this section. The coarse sediments tended to deposit, and the fine sediment was scoured from the riverbed. Regarding amount , the deposition of fine sediments in the high-flow years was higher than that in the low-flow years. The coarse sediment scouring in the high-flow years was greater than that in the low-flow years.

6) Jiujiang to Datong section: Figure 18 shows the analysis result for this section. In this section, the fine sediment tended to be supplied, and the supply in the median flood years was higher than that in the median dry years. The riverbed supplied a higher amount of fine

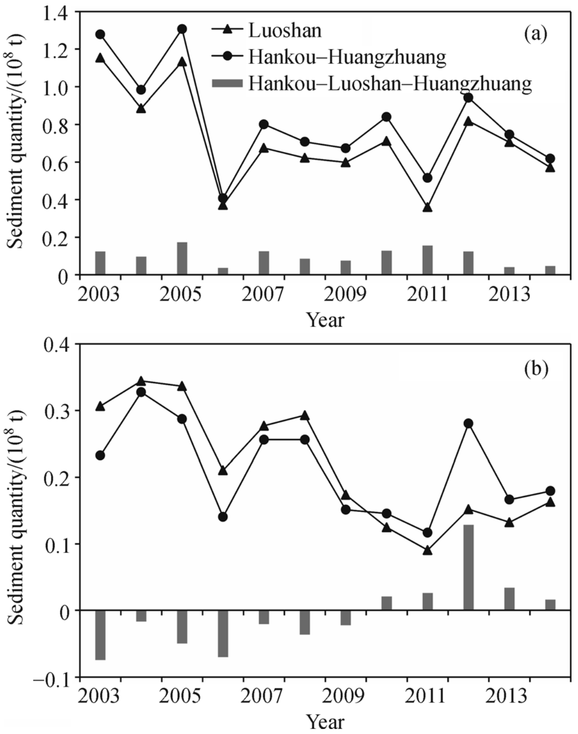

Fig. 16 Quantitative change of scouring and sedimentation for (a) fine ($d \leqslant 0.125$ mm) and (b) coarse ($d > 0.125$ mm) sediments in the Luoshan to Hankou section.

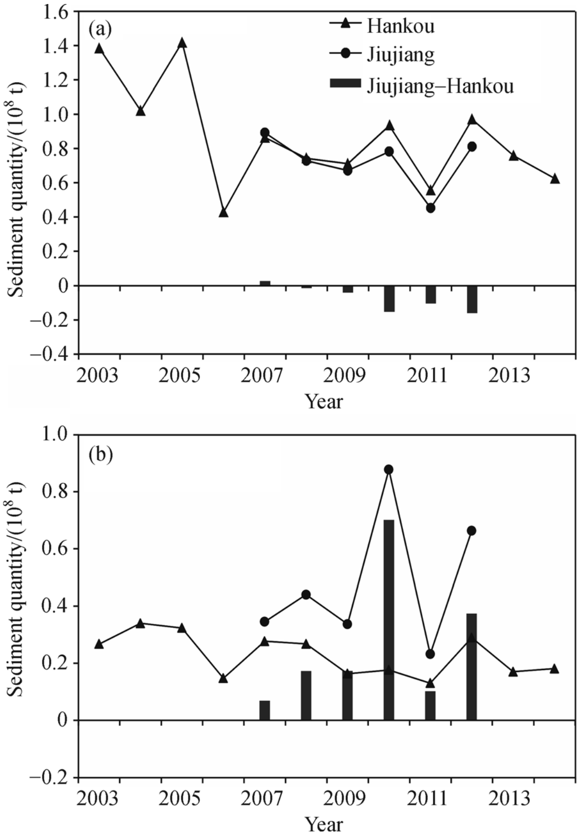

Fig. 17 Quantitative change of scouring and sedimentation for (a) fine ($d \leqslant 0.125$ mm) and (b) coarse ($d > 0.125$ mm) sediments in the Hankou to Jiujiang section.

sediments than the Poyang Lake. However, the sediment input from the lake was also a determining factor for the sediment supply in this section, which was in agreement with the conclusion from published studies (Chen and Li, 2009). The coarse sediment in this section was dominated by deposition. The input from the Poyang Lake was very limited, and the contribution was minimal. However, the deposition in the median flood years was less than that in the median dry years. The water from Poyang Lake increased the flow in the Datong station and showed high flow values. The duration of the high-flow days reduced the deposition, but did not change the overall patterns. The fine sediment input from Poyang Lake from 2007 to 2012 was 0.76×10^8 t, while that from the riverbed was 2.14×10^8 t. The radio of the fine sediment contribution from the lake and from the riverbed was 1:2.82.

5 Conclusions

In this study, we collected data including the input and output discharges in the TGR, riverbed information from 1987 to 2014, and sediment and its composition in the major hydrological station downstream the TGD on the Yangtze River. Based the data above, we studied the characteristics and variability of sediment transportation in the concerned river reach and its causes. The study focused on flow process, riverbed composition, lake and river relation, and tributary inputting, among others. The main conclusions are drawn as follows:

1) Characteristics of transportation for fine and coarse sediments

a) Since the TGR impoundment, the sediment transportations were all lower than the values before the impoundment for sediment groups $d \leqslant 0.031$ mm, $0.031\ \text{mm} < d \leqslant 0.063$ mm, and $0.063\ \text{mm} < d \leqslant 0.125$ mm along all the hydrological stations down the dam. The transportations in 2008 to 2014 were smaller than the values in 2003 to 2007. Spatially, the sediment transportation increased along the river.

b) The data for sediment group $d > 0.125$ mm since the impoundment showed that the sediment was fed by riverbed scouring in the river section from Yichang to Jianli. The value even exceeded that before the impoundment in the Jianli station. The retaining process weakened from 2008 to 2014, and the value in this period was below the pre-impoundment value.

2) Spatial and temporal variabilities of transportation for fine and coarse sediments and its causes

a) The riverbed in the Yichang to Shashi section was relatively coarse, which limited the supply of fine and

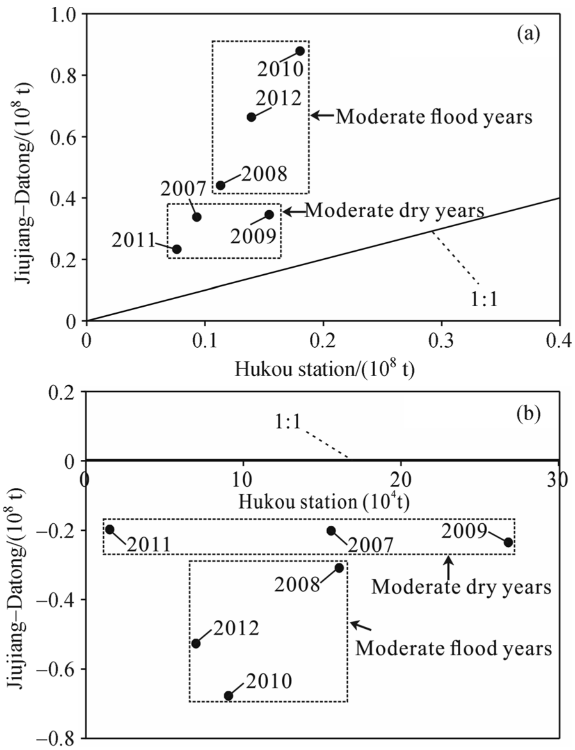

Fig. 18 Impact of confluence from the Poyang Lake on the quantity of scouring and sedimentation for the (a) fine ($d \leqslant 0.125$ mm) and (b) coarse ($d > 0.125$ mm) sediments in the Jiujiang to Datong section (note: the flood and dry years were determined according to the discharge data in the Datong station, and the determined dry years and flood years were the same as those determined by the data from the Luoshan station).

coarse sediments. The fine sediment supply was mainly controlled by the discharge, while the coarse sediment supply was controlled by the duration of high flow and its magnitude.

b) The supply of both coarse and fine sediments in the Shashi to Jianli section was controlled by the amount of total discharge.

c) The input from the Dongting Lake played the most important roles on sediment supply in the Jianli to Luoshan section. The sediment supply from the riverbed was higher in flood years than in dry years. The coarse sediment tended to deposit, and the deposition in dry years was larger than that in flood years.

d) The feeding of the fine sediment in the Luoshan to Hankou section was mainly from the riverbed. The supply in 2008 to 2014 was less than that in 2003 to 2007. Around 2010, the coarse sediments were transited from depositing to scouring, which was probably caused by the increased duration of high flow days.

e) Fine sediments appeared to deposit more in the Hankou to Jiujiang section. The coarse sediment was fed by the riverbed scouring, and more coarse sediments were recharged from the riverbed in flood years than in dry years.

f) The ratio of the fine sediments from the Poyang Lake to that from the riverbed in the Jiujiang to Datong section was 1:2.82. The sediment from the riverbed scouring contributed more to the coarse sediment transportation. The contribution was mainly affected by the input from the Poyang Lake.

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