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Sedimentation in the Three Gorges Dam and the future trend of Changjiang (Yangtze River) sediment flux to the sea

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Abstract. The Three Gorges Dam (TGD) on the upper Changjiang (Yangtze River), China, disrupts the continuity of Changjiang sediment delivery to downstream and coastal areas. In this study, which was based on 54 years of annual water and sediment data from the mainstream and major tributaries of Changjiang, sediment deposition induced by the TGD in 2003–2008 was quantified. Furthermore, we determined the theoretical trapping efficiency of the cascade reservoir upstream of the TGD. Its impact on Changjiang sediment flux in the coming decades is discussed. Results show that about 172 million tons (Mt) of sediment was trapped annually by the TGD in 2003–2008, with an averaged trapping efficiency of 75%. Most of the total sediment deposition, as induced by the TGD (88%), accumulated within the region between the TGD site and Cuntan. However, significant siltation (12% of the total sediment deposition) also occurred upstream of Cuntan as a consequence of the upstream extended backwater region of the TGD. Additionally, the Changjiang sediment flux entered a third downward step in 2001, prior to operation of the TGD. This mainly resulted from sediment reduction in the Jinshajiang tributary since the late 1990s. As the cascade reservoir is put into full operation, it could potentially trap 91% of the Jinshajiang sediment discharge and, therefore, the Jinshajiang sediment discharge would most likely further decrease to 14 Mt/yr in the coming decades. Consequently, the Changjiang sediment flux to the sea is expected to continuously decrease to below 90 Mt/yr in the near future, or only 18% of the amount observed in the 1950s. In the presence of low sediment discharge, profound impacts on the morphology of estuary, delta and coastal waters are expected.

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1 Introduction

Rivers are conveyor belts for terrestrial material delivery to the oceans (Walling and Fang, 2003; Walling, 2006), and they annually transport a 15–20 Gt sediment load to the global oceans (Milliman and Meade, 1983; Milliman and Syvitski, 1992). These large amounts of sediment play an important role in the global geological cycle, the global geochemical cycle, the coastal ecosystems and the evolution of deltas. However, dam construction interrupts the continuity of a river system in transporting sediments to downstream and coastal regions (Kondolf, 1997). During the latter half of the 20th century, about 45 000 large dams over 15 m high and an estimated 800 000 small dams had been built worldwide, representing nearly an order of magnitude increase compared to the year 1950 (WCD, 2000). It is estimated that more than 30% of the global sediment flux is trapped in reservoirs (Vörösmarty et al., 2003), and approximately 0.5% to 1% of the world's total reservoir volume is lost each year as a result of sedimentation (WCD, 2000). Subsequently, the global sediment flux from the rivers to the sea has decreased significantly (Milliman, 1997; Syvitski et al., 2005).

The Changjiang (Yangtze River) of China is a world-class river, it ranks fifth in terms of water discharge (920 km^3/yr) and historically is fourth in terms of sediment load (480 Mt/yr) (Milliman and Meade, 1983; Milliman and Syvitski, 1992). During the past five decades, the Changjiang water discharge has remained almost unchanged; however, the Changjiang sediment flux to the sea has experienced a distinct reduction. According to Yang et al. (2006b), the Changjiang displayed three phases of sediment reduction since the 1950s, including: following the Danjiangkou Reservoir on the Hanjiang in 1968 and after the construction of numerous dams and soil conservation projects in the Jialingjiang Basin in 1985. As the Three Gorges Dam (TGD)
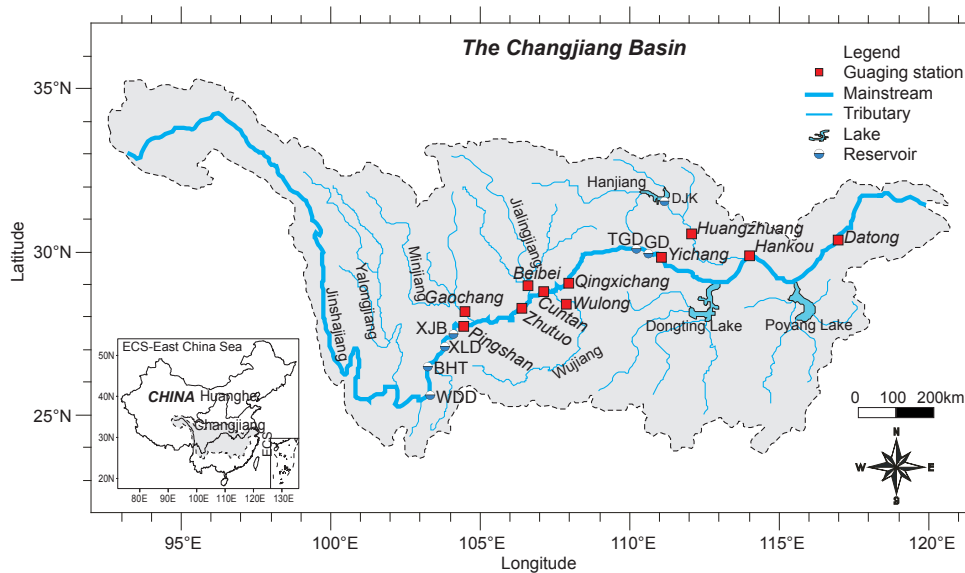
Fig. 1. The Changjiang drainage basin (DJK, Danjiangkou Reservoir; TGD, Three Gorges Dam; GD, Gezhouba Dam; XJB, Xiangjiaba Reservoir; XLD, Xiluodu Reservoir; BHT, Baihetan Reservoir; WDD, Wudongde Reservoir).

began operations in 2003, the Changjiang sediment flux entered a third downward step. This anti-phase relationship between the Changjiang water and sediment discharge illustrates the predominant impact of human activities on the sediment yield, transport and storage in this large river system (Yang et al., 2002, 2006b; Chen et al., 2005; Zhang et al., 2009). Of human activities, dam construction is the dominant factor (88%) contributing to the reduction in Changjiang sediment flux to the sea (Dai et al., 2008). Here, we mainly focused on the TGD (Fig. 1), which is the largest dam in the world. It is located at the end of the upper Changjiang. The water storage capacity of the TGD will be 39 km^3 by 2009, which is approximately 4.3% of the long-term annual water discharge at Datong (903 km^3 in 1950–2005).

After the TGD began to impound water and trap sediment in June 2003, the mainstream of the Changjiang has been disrupted in two parts, both upstream and downstream of the TGD (Dai et al., 2006; Yang et al., 2007a). Upstream of the TGD, the primary consequence is sedimentation. Sedimentation in reservoirs results in a progressive reduction in storage capacity and triggers a series of physical, chemical and ecological impacts on the environment. One key to assess its environment impacts is the quantitative study of reservoir sedimentation. Previous studies have estimated the annual sedimentation in the TGD by the sediment budget method; however, the reported values have been quite different from each other (Bulletin of Changjiang Sediment, 2003–2008; Dai et al., 2006; Yang et al., 2006b, 2007b; Chu and Zhai, 2008; Xu and Milliman, 2009). These differences are mainly caused by: (1) the different stations that were used as the upstream limit of the TGD (e.g., Qingxichang vs. Cuntan, see Fig. 1); (2) whether or not the influence of sediment from

ungauged areas was considered; and (3) whether or not sediment erosion within the channel between the TGD site and Yichang was considered. Thus, to better understand the scientific and management issues of this giant reservoir, it is necessary to recalculate the sedimentation rate in the TGD by undertaking a thorough quantification study.

Although the Changjiang sediment flux had decreased by approximately 30% before the impoundment of the TGD in 2003, the impact of the TGD on downstream sediment transport was more immediate and sharp (Yang et al., 2006b, 2007a; Hu et al., 2009; Xu and Milliman, 2009). The consequences of TGD trapping were downstream erosion, delta degradation and wetlands loss (e.g., Yang et al., 2003, 2005, 2006a, 2007a, 2007b; Chen et al., 2008; Xu and Milliman, 2009). It also posed a great threat to the downstream and coastal ecosystems (Xie et al., 2003; Shen and Xie, 2004). Therefore, changes in the Changjiang sediment flux caused by the impoundment of TGD after 2003 have garnered increasing attention and concern.

Several studies (Yang et al., 2002, 2003, 2005, 2006b) have estimated the Changjiang sediment flux (recorded at Datong), after the TGD implementation, based on the estimated sediment load out of TGD (Yichang) and the correlation between sediment data at Yichang and Datong before TGD. However, Chen et al. (2008) have argued that these above estimates appear to overestimate the sediment discharge entering the TGD in the post-TGD period. Xu et al. (2007) also indicated that the correlation between sediment load at Yichang and Datong, after TGD, has been fundamentally changed. More recently, by considering the impact of the cascade reservoir that is located on the upstream side of the TGD (Fig. 1), Yang et al. (2006a, 2007a, b)

Table 1. Detailed hydrological records of stations at the mainstream and major tributaries of the Changjiang. Data series are 1950s–2005.

Rivers		Stations	Area (10^4 km^2)	Water discharge (km^3/yr)	Sediment load (Mt/yr)
Tributary	Jinshajiang	Pingshan	45.86	145	249
	Jialingjiang	Beibei	15.61	66	111
	Minjiang	Gaochang	13.54	50	26
	Wujiang	Wulong	8.30	86	48
	Hanjiang	Huangzhuang	14.21	47	52
Changjiang Mainstream	Upper	Zhutuo	69.47	269	302
		Cuntan	86.66	348	418
		Yichang	100.55	436	470
	Mid-Lower	Hankou	148.80	712	384
		Datong	170.54	903	414

suggest that the Changjiang sediment flux will decrease to about 100–150 Mt/yr in the next six decades. Similarly, Chen et al. (2008) indicate that the Changjiang sediment flux over the post-TGD period will possibly vary from 112 Mt/yr to 132 Mt/yr or less in ordinary years. Nevertheless, these results (Yang et al., 2006a, 2007a, b; Chen et al., 2008) are still under debate, due to the impact of the cascade reservoir, which was only partly or qualitatively discussed.

In this paper, we will discuss the effect of the TGD on the Changjiang hydrographic regime, through its two parts that are separated by the TGD site. The upper part is the mainstream from Pingshan to Yichang and the lower part is from Yichang to Datong (Fig. 1). Hydrological data were temporally separated into two periods according to the TGD operation in 2003, including: the pre-TGD period and the post-TGD period. The main objectives of this paper are: (1) to estimate the sedimentation rate in the TGD through analysis of the sediment data, both upstream and downstream of the TGD; (2) to give a quantified evaluation of the cascade reservoir's effect by estimating its theoretical trapping efficiency; and (3) to discuss the future trend of the Changjiang sediment flux into the sea in the coming decades.

2 Physical setting

The Changjiang originates from the Qinghai–Tibetan Plateau at an elevation of 5400 m and extends eastward 6300 km before debouching into the East China Sea (ECS) (Fig. 1). The Changjiang basin covers a drainage area of 1.81×10^6 km^2, accounting for about 19% of China's national area (Chen et al., 2001). This large watershed is home to a population of more than 400 million, or 6.6% of the world's population (UNDES, 2001). The climate of the Changjiang basin is typically subtropical, wet and warm in summer, and moist and cool in winter. The annual mean temperature increases from below 4°C in the source area to approximately 5–15°C in the

mountainous areas and approximately 16–18°C in the middle and lower reaches (Chen et al., 2002). The average precipitation and evaporation in the Changjiang basin are 1000–1400 mm/yr and 700–800 mm/yr, respectively (Shen, 1986).

The upper Changjiang, with a drainage area of about 1.00×10^6 km^2, extends 4500 km from the source to Yichang station. It is characterized by mountains and hills, with an average gradient of 1.1% (Yang et al., 2007a). Four major tributaries (Jinshajiang, Jialingjiang, Minjiang, and Wujiang) join the mainstream of the upper Changjiang (Fig. 1 and Table 1). The mid-lower Changjiang flows 1880 km from Yichang to Datong, with a drainage area of 0.8×10^6 km^2. It flows through extensive fluvial plains, with several lakes (e.g., Dongting and Poyang Lakes, see Fig. 1) linked with the mainstream. Both of the two large lakes trap most of the sediment from their own drainage basins and greatly regulate the Changjiang sediment flux to the sea (Dai et al., 2005; Yang et al., 2007a; Chen et al., 2008). The Hanjiang is the largest tributary in the mid-lower Changjiang. Downstream of Datong, the river is tidally influenced. Therefore, the Datong water and sediment records are generally used to represent the mass flux of the Changjiang that is discharged into the sea, though it is over 600 km upstream from the river mouth. Within the Changjiang basin, the water and sediment distribution pattern is quite uneven. Most of the Changjiang sediment discharge to the sea mainly originates from the upper reaches, whereas water discharge from the upper reaches accounts for only 50%, compared to that of Datong (Chen et al., 2001; Wang et al., 2008).

The TGD, at 181 m in height, 2335 m in length, and with a storage capacity of 39.3 km^3 (Zhao et al., 2000), is the largest dam in the world (Nilsson et al., 2005). The TGD is a multifunctional hydroelectric facility used for flood control, hydropower generation and navigation. The dam began storing water and trapping sediment in June 2003. In addition, four large hydropower dams (Wudongde, Baihetan, Xiluodu and

Table 2. The cascade reservoir on the lower Jinshajiang of the upper Changjiang (see Fig. 1 for locations, adapted from Liu, 2007).

Dam site	Elevation (m)	Watershed area (10^4 km^2)	Average inflow (km^3/yr)	Total storage (km^3)	Active storage (km^3)	Install capacity (MW)	Annual energy (GWh)
Wudongde	723	39.6	120	5.86	2.62	8 700	39.5
Baihetan	550	41.7	130	19.01	10.44	1 305	57.7
Xiluodu	370	44.0	139	11.57	6.46	1 260	57.4
Xiangjiaba	220	44.5	141	4.98	0.9	600	30.8

Xiangjiaba) have been planned, taking advantage of a 730 m drop over 770 km of the river in the lower Jinshajiang (Fig. 1 and Table 2). The Xiluodu and Xiangjiaba Dams are now under construction and will be put into operation in 2013 and 2012, respectively. The other two dams, Wudongde and Baihetan, will start construction in 2010 and be put into operation in the 2020s (Liu, 2007; Yang et al., 2007b). The total storage capacity of the cascade reservoir on the lower Jinshajiang would be around 41.4 km^3, which is about one third of the current annual water discharge of 145 km^3 from the Jinshajiang tributary.

3 Data collection and methods

3.1 Data collection

Water and sediment data used in this study were mainly provided by the Changjiang Water Resources Commission (CWRC) and partly from the Bulletin of Changjiang Sediment (2000–2008), published by the CWRC (available in http://www.cjh.com.cn/). Bed load is not included in the present study, as its contribution to total load is less than 2% in the Changjiang (Yang et al., 2002, 2003). The locations and detailed hydrological records of stations are presented in Fig. 1 and Table 1.

3.2 Estimates of sediment deposition caused by the TGD

Yichang station is located 44 km downstream from the TGD site and, thus, it can act as the TGD output station. The water and sediment discharges of Yichang are mainly fed by Jinshajiang, Jialingjiang, Minjiang and Wujiang (Fig. 1). These four major tributaries collectively contribute 80% of the water discharge and 93% of the sediment load at Yichang station (Table 1). Fu et al. (2006) established a correlation between sediment load at Yichang and that from the four major tributaries in the pre-TGD period (1950s–2002). This correlation was also used by Chen et al. (2008) to calculate the total sediment entering the TGD during the post-TGD period. However, the sediment load at Yichang has displayed a distinct decreasing trend since the mid-1980s, as a result of intensi-

fying human activity (e.g., dams and soil conservation) in the upper Changjiang basin (Fig. 2a) (Xu et al., 2006; Yang et al., 2006b; Xiong et al., 2009). Therefore, the sediment data for the period of 1986–2002 may be more representative of the condition just before the TGD than the whole period (1950s–2002).

In this study, the time series of the sediment data were divided into two periods: the pre-TGD period (1986–2002) and the post-TGD period (2003–2008). Accordingly, two methods were used to estimate the sedimentation rate in the TGD. (1) First, we established the correlation between sediment load at Yichang and that from the four major tributaries during the pre-TGD period (1986–2002) (Fig. 2b). This correlation was used to restore the scenario of sediment load at Yichang in the post-TGD period. Differences between the restored and measured sediment load at Yichang in 2003–2008 were assumed to be equal to the reservoir sedimentation. (2) The other method was based on a sediment budget, which has been used in previous studies (e.g., Dai et al., 2006; Yang et al., 2007b, Chu and Zhai, 2008).

3.3 Computing the theoretical trapping efficiency (*TE*) of reservoirs

The theoretical trapping efficiency (*TE*) of the large reservoirs (>0.5 km^3) can be approximated using the empirical relationship originally developed by Brune (1953):

$$TE = 1 - \frac{0.05}{\sqrt{\Delta\tau_R}} \tag{1}$$

where $\Delta\tau_R$ is the local residence time change calculated with Eq. (2):

$$\Delta\tau_R = \frac{\sum_{i}^{n} V_i}{Q} \tag{2}$$

where V_i is the storage capacity of the i-th reservoir (km^3) and Q is the annual water discharge (km^3/yr) at the dam site.

The theoretical *TE* of the cascade reservoirs was calculated separately for each individual dam, using the results of annual water discharge at each dam site and the storage volume of the individual dam. With regard to the total cascade

Table 3. Sediment budgets of the mainstream from Pingshan to Yichang (Unit: Mt/yr).

Periods	Jinshajiang (Pingshan)	Minjiang (Gaochang)	Jialingjiang (Beibei)	Wujiang (Wulong)	Cuntan	Yichang	Sediment from the ungauged area			Sediment deposition(+)/erosion(−)		
							Cuntan-Pingshan	Yichang-Cuntan	Yichang-Pingshan	Cuntan-Pingshan	Yichang-Cuntan	Yichang-Pingshan
2003	156	48	31	14	206	98	32	11	43	61	133	194
2004	148	34	18	11	173	64	22	7	29	49	127	176
2005	188	59	42	4	270	110	37	11	48	56	175	231
2006	90	21	3	3	109	9	10	2	12	15	105	120
2007	150	31	27	10	210	53	25	9	34	23	176	199
2008	204	15	14	4	212	32	32	5	37	53	189	242
2003–2008	156	35	23	8	197	61	26	8	34	43	151	194
1956–2002	254	48	115	28	430	492	41	33	74	28	−1	27
Sediment deposition caused by TGD										15	152	167

Cuntan and Yichang are two mainstream stations for the upper Changjiang, and Jinshajiang, Minjiang, Jialingjiang and Wujiang are four major tributaries delivering sediment discharges into the mainstream (Fig. 1). The data of sediment from the ungauged areas are after Dai et al. (2006) and Yang et al. (2007a, b) or calculated by the same method. Sediment deposition(+)/erosion(−) from Yichang to Pingshan was calculated by subtracting Yichang from the sum of Jinshajiang, Minjiang, Jialingjiang, Wujiang and the ungauged area in Yichang-Pingshan. The budgets for Yichang-Cuntan and Cuntan-Pingshan were calculated in a similar way. The differences of sediment deposition between 1956–2002 and 2003–2008 were assumed to the TGD-induced.

reservoir, the volumes of each dam were summarized, and the annual water discharge used was the long-term mean water discharge at the aftermost station (Pingshan station).

Brune's method for calculating the theoretical *TE*, originally developed for reservoirs in the United States, is widely used for reservoirs in other parts of the world as well. This method can provide reasonable estimation of long-term and mean *TE* of large reservoirs (e.g., Vörösmarty et al., 1997, 2003; Morris and Fan, 1998; Kummu and Varis, 2007).

4 Results

4.1 Sediment deposition caused by the TGD

On the basis of the annual sediment data at Yichang ($Q_S Y$) and that from the four major tributaries ($Q_S T$) of the upper Changjiang, linear regression equations in the pre-TGD (1986–2002) and post-TGD (2003–2008) periods were obtained as follows (Fig. 2):

Pre-TGD: $Q_S Y = 1.125 Q_S T - 20$ (3)

Post-TGD: $Q_S Y = 0.554 Q_S T - 61$ (4)

The coefficients of determination, R^2, for the above correlations were 0.85 and 0.71, respectively, at a significance level of $P < 0.01$. Mean annual sediment load at Yichang was estimated at 228 Mt for 2003–2008 by Eq. (3) (in the case of non-TGD). These estimated values can be viewed as the total sediment load entering the TGD (Chen et al., 2008) (Fig. 3). Thus, the differences between the estimated (non-TGD) and measured (with TGD operation) sediment load at Yichang were assumed equivalent to sediment deposition caused by the TGD. The mean annual sediment trapped by the TGD was 168 Mt/yr in 2003–2008, with the maximum sediment deposition (215 Mt) occurring in 2008 and the minimum (103 Mt) occurring in 2006 (Fig. 3).
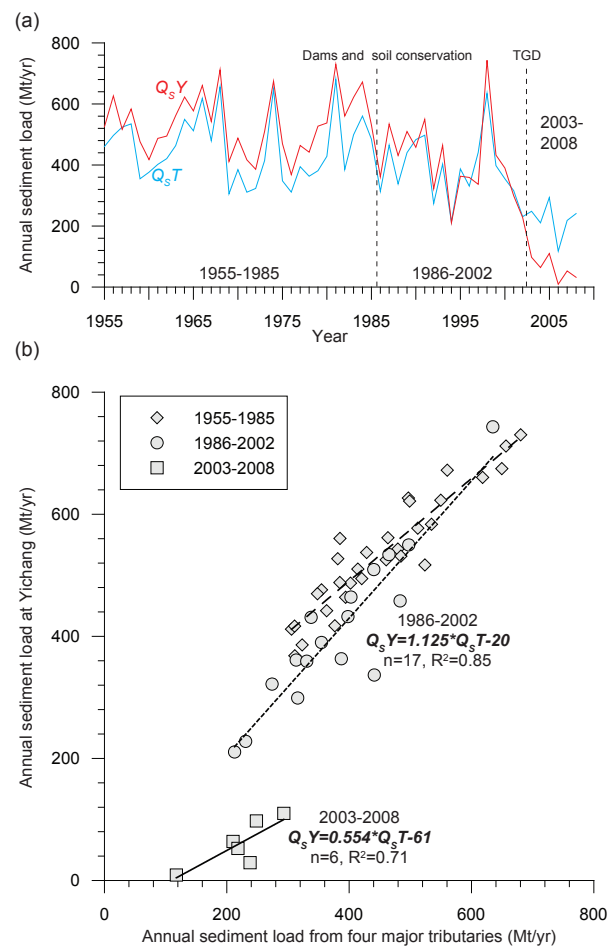

Fig. 2. Time series of annual sediment load at Yichang ($Q_S Y$) and that from the four major tributaries ($Q_S T$) from 1955–2008; **(b)** The correlations between $Q_S Y$ and $Q_S T$ in the pre-TGD (1986–2002) and post-TGD (2003–2008) periods.
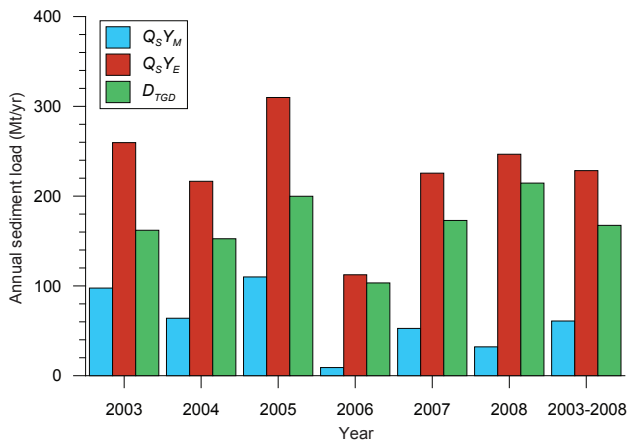
Fig. 3. Annual sediment load at Yichang and the sediment deposition caused by TGD in 2003–2008. The sediment deposition caused by TGD (D_{TGD}) was assumed to be the differences between the measured ($Q_S Y_M$, with the TGD operation) and the estimated ($Q_S Y_E$, non-TGD) sediment load at Yichang.

Table 4. The theoretical trapping efficiency for the cascade reservoir on the lower Jinshajiang and the TGD with different water levels.

Dam	Q^a (km³/yr)	V^b (km³)	$\Delta\tau_R^c$	TE^d
Wudongde	120	5.9	0.05	77%
Baihetan	130	19.0	0.15	87%
Xiluodu	139	11.6	0.08	83%
Xiangjiaba	141	5.0	0.04	73%
Cascade	145	41.4	0.29	91%
	436	13.6 (139 m)	0.03	72%
TGD	436	23.1 (156 m)	0.05	78%
	436	39.3 (175 m)	0.09	83%

[a] Annual water Discharge at the dam locations (Liu, 2007).
[b] Storage volume (Liu, 2007; Yang et al., 2005).
[c] Local residence time, Eq. (2).
[d] TE calculated using the Brune's method, Eq. (1).

To validate the above estimated results, we also established the sediment budgets of the mainstream reaches from Yichang to Pingshan, which was subdivided into two sections: (1) the lower section from Yichang to Cuntan and (2) the upper section from Cuntan to Pingshan. Results of the sediment budgets show that sediment deposition from Yichang to Pingshan has increased from 27 Mt/yr in 1956–2002 to 194 Mt/yr in 2003–2008, indicating that the TGD-induced sediment deposition averaged 167 Mt/yr in 2003–2008 (Table 3). This is very close to the above estimated result of 168 Mt/yr, by our formula (Fig. 3). The sediment budgets also provided insight into the distribution pattern of the sediment deposition caused by the TGD. The data suggest that 152 Mt/yr of the sediment deposition caused by TGD was deposited in the lower section from Yichang to Cuntan, and the remaining 15 Mt/yr was deposited in the upper section from Cuntan to Pingshan (Table 3).

As the mainstream channel between the TGD site and Yichang suffered from serious erosion after the TGD operation (Bulletin of Changjiang sediment, 2003; Yang et al., 2007a, b), the sediment trapping effect of the TGD would be underestimated by both methods, as discussed above. In 2003–2008, sediment load increased from 58 Mt/yr at Huanglingmiao (just 13 km downstream of the TGD) to 61 Mt/yr at Yichang (44 km downstream of the TGD) (Bulletin of Changjiang sediment, 2003–2008). Because there are no small tributaries joining the mainstream between the TGD site and Yichang, this increase of 3 Mt/yr in sediment can be attributed to the riverbed erosion between the two stations, with a sediment erosion rate of 0.1 Mt/km/yr. Given this sediment erosion rate for the whole channel, from the TGD site to Yichang (44 km channel length), the total sediment erosion between the TGD site and Yichang was calculated as

4.4 Mt/yr in 2003–2008. This amount of sediment should be added to the sediment deposition in the lower section, from the TGD site to Cuntan. In conclusion, the total sediment trapped by the TGD averaged 172 Mt/yr in 2003–2008, of which 88% was trapped in the lower section, from the TGD site to Cuntan, and the remaining 12% was deposited upstream of Cuntan. In 2003–2008, the estimated sediment TE of the TGD averaged 75%.

4.2 Theoretical trapping efficiency of the reservoirs

Four large dams, Wudongde, Baihetan, Xiluodu and Xiangjiaba, with a total storage capacity (41.4 km³) greater than the TGD, are now under construction or will be constructed upstream of the TGD (Fig. 1 and Table 2). To evaluate the impact of the whole cascade reservoir on the Changjiang sediment flux in the coming decades, the theoretical TE was calculated using Brune's method. The theoretical TE for the individual dams of the cascade reservoir varies from 73% to 87%. On completion of the cascade reservoir, it would be theoretically capable of trapping 91% of the sediment discharge coming from the Jinshajiang basin (Table 4). The theoretical TE of the TGD was 73% and 78%, with a water elevation of 139 m and 156 m, respectively (Table 4). This approximates the real TE of 75% in 2003–2008, when the water elevation varied from 139 m to 156 m. As the water elevation of TGD rises to 175 m after 2009, the theoretical TE of the TGD will be up to 83%, which is much more than the value of 69% estimated by Yang et al. (2005).

The theoretical TE values for the Xiluodu and Xiangjiaba Reservoirs, calculated herein, are similar to the results of previous studies (Huang and Huang, 2002; Hu et al., 2003; Tang and He, 2003). These results suggest that Brune's method can be used to estimate the TE of reservoirs in the upper Changjiang basin. Otherwise, it should be noted that actual

Table 5. Summary of the estimated sedimentation rate in the TGD (Unit: Mt/yr).

Sedimentation rate (Mt/yr)	Time scale	Reference
110	2003–2004	Yang et al., 2006b
118	2003–2006	Xu and Milliman, 2009
122	2003–2004	Dai et al., 2006
125	2003	Chu and Zhai, 2008
138	2003–2008	CWRC, 2003–2008
151	2003–2005	Yang et al., 2007b
172	2003–2008	This study

sediment trapping in the reservoir was constrained by not only the local residence time related to its storage capacity, but also the sediment supply from the upstream basin. For example, although the Baihetan Reservoir has the highest theoretical *TE* of 87% in the Jinshajiang cascade reservoirs, it probably would not trap much sediment as a result of the upstream Wudongde Reservoir's sediment buffering effect.

By contributing around 60% of the total sediment discharge from the upper reaches into the TGD, the Jinshajiang became the major sediment source of the Changjiang, both pre- and post-TGD. After the cascade reservoir on the lower Jinshajiang is put into full operation in the 2020s, the sediment passing Pingshan will most likely decrease sharply to ca. 14 Mt/yr (9% of 156 Mt/yr in 2003–2008). If the sediment discharge from other sub-basins maintains present levels (99 Mt/yr in 2003–2008) (Table 3), the total sediment discharge entering the TGD will decrease to 113 Mt/yr in the next decade, which is less than half of that in 2003–2008. Given that the *TE* of the TGD, with its water elevation at 175 m after 2009, is 83% (Table 4), the sediment discharge passing Yichang would be only around 19 Mt/yr in the coming decades.

5 Discussion

5.1 The upstream extending backwater region of the TGD in 2003–2008

By considering the influences of the sediment source from the ungauged area and the riverbed erosion within the channel between the TGD site and Yichang, Yang et al. (2007b) reported the highest sedimentation rate of 151 Mt/yr in the TGD (Table 5). However, the significant siltation in the upstream area of Cuntan (15 Mt/yr in 2003–2008) was underestimated or neglected in previous studies. This siltation may be related to the upstream extended backwater region of the TGD. When sediment deposited in the backwater region, as a result of the decreased current velocity and sediment carrying capacity, it brings a feedback mechanism. This allows the depositional environment to propagate much farther upstream than the initial hydraulic backwater curve might sug-
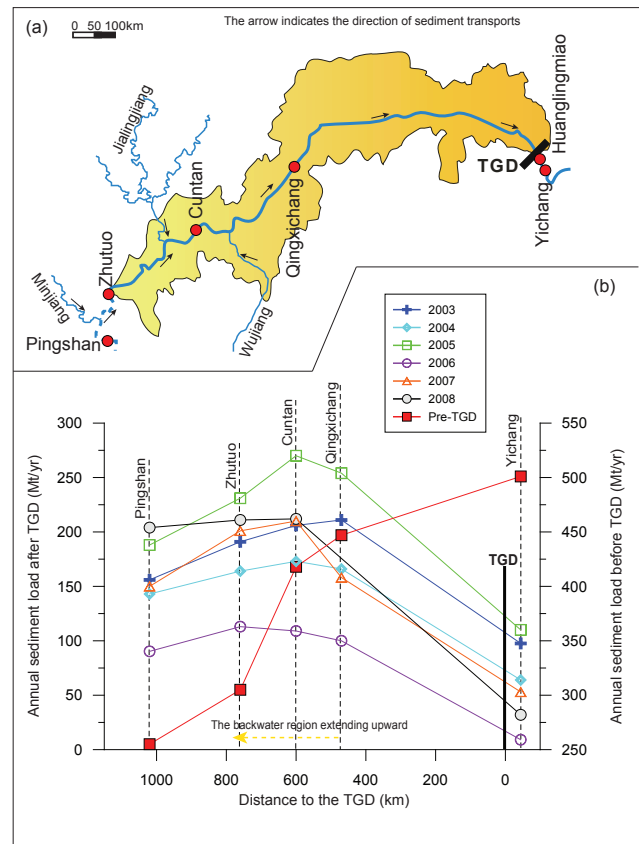

Fig. 4. (a) The sketch map of the Three Gorges Dam (TGD); **(b)** The annual sediment load after the impoundment of the TGD in comparison with the long-term average values (Pre-TGD, 1950s–2000) at the stations along the upper Changjiang. It is suggested that the backwater region of TGD has upstream extended beyond Zhutuo station in 2006 (760 km upstream of the TGD site). Note that the sediment load at Qingxichang in 2008 is not available.

gest (Goodwin et al., 2000). This extended backwater region was observed in numerous dam systems, including the Aswan High Dam on the Nile River in Egypt (El-Manadely et al., 2002), the Sardar Sarovar Dam on the Narmada River in Indus (Bettess, 1993), and the Sanmenxia reservoir on the Yellow River in China (Wang et al., 2007b). This phenomenon of the upstream extended backwater region appears to occur in the TGD as well.

According to the TGD design scheme, the upstream limit of the backwater region was Qingxichang when its water elevation was 139 m in 2003–2005, Cuntan for 156 m in 2006–2008 and Zhutuo for 175 m after 2009 (Fig. 4a). However, Wang et al. (2007a) indicated that the backwater region of the TGD extended upstream farther than the Qingxichang in 2003. Dai et al. (2006) also noticed a significant siltation in the upstream of Qingxichang in 2003 and 2004. Furthermore, the variation of sediment load at the stations along the upper Changjiang demonstrated the impact of the extended TGD backwater region on sediment transport in the upper

Changjiang in 2003–2008. As shown in Fig. 4b, sediment load along the upper Changjiang increased from 254 Mt/yr at Pingshan to 492 Mt/yr at Yichang during the pre-TGD period, indicating an additional sediment input of the tributaries and/or riverbed erosion. After the TGD was put into operation, however, the sediment load began decreasing from Qingxichang in 2003, from Cuntan in 2004 and 2005, and from Zhutuo after 2006. This indicates that the backwater region of the TGD has extended gradually upstream from Qingxichang (470 km upstream of the TGD) to Zhutuo (760 km upstream of the TGD), accompanied by sediment deposition in these regions. As the water elevation of the TGD increases to 175 m after 2009, the backwater region of the TGD may be extended further upstream. Consequently, the trapping of more sediment within the extended backwater region is expected. The impact of this on local environments should attract more attention.

Due to the short-term data of the post-TGD period, as well as the rough sediment budgets, a rigorous upstream limit of the TGD backwater region cannot be obtained at present. Otherwise, the sedimentation rate of the TGD calculated herein reflects only the suspended sediment load. Undoubtedly all of the bed loads coming from the upper reaches of the TGD are trapped as well, though the amounts of bed loads are unclear. These bed loads are most likely deposited in the backwater region of the TGD, owing to the reduced current velocity and sediment carrying capacity in this region. In addition, landslides and debris flows, taking place around the margins of the new TGD-induced high lake, will also contribute large amounts of sediment into the TGD, especially when the TGD water level fluctuates during floods and drawdowns. Both of these would increase the sedimentation rate of the TGD. Therefore, more in-situ investigations are required for future studies. These investigations should include repeat bathymetric surveys and/or coring at key locations, as suggested by Snyder et al. (2004), which may provide more detail about depositional processes and the history of the TGD.

5.2 Prior reduction of the Changjiang sediment flux before the TGD

As the Changjiang sediment flux is mainly supplied by the upper reaches (Chen et al., 2001), the correlation of sediment load between Yichang and Datong was well established during the pre-TGD period (Fig. 5). As indicated by Yang et al. (2006b), the correlation between Yichang and Datong gradually became significant (Fig. 5b). For the period of 1953–1968, before the impoundment of the Danjiangkou Reservoir, the Hanjiang was the largest sediment contributor to the mainstream of Changjiang below Yichang. Additionally, the Dongting Lake plays an important role in regulating the Changjiang sediment flux (Dai et al., 2005; Yang et al., 2007a). In 1953–1968, a large amount (35%) of sediment coming from Yichang was deposited in the Dongting
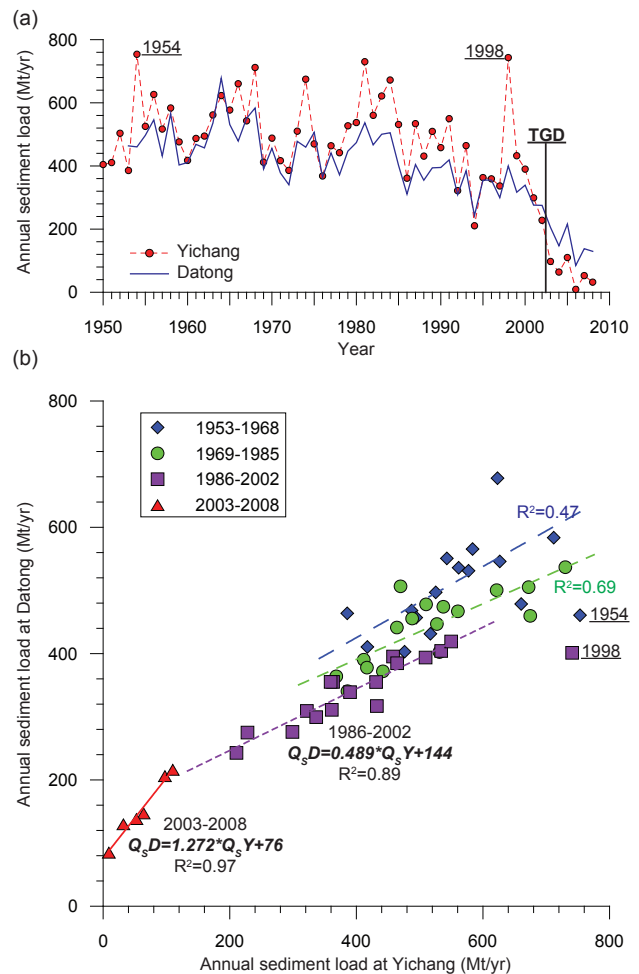

Fig. 5. (a) Comparison with the sediment load at Yichang and Datong from 1950–2008. In the extreme floods years of 1954 and 1998, about 100 Mt of sediments were lost in the middle reaches through the river breaches and overbank flows (Yang et al., 2006b); **(b)** Correlations between sediment load at Yichang and Datong during the different periods (modified from Yang et al., 2006b, the extreme flood years of 1954, 1998 were excluded).

Lake (Dai et al., 2005; Xu et al., 2007). Therefore, for 1953–1968, the correlation between Yichang and Datong was low ($R^2 = 0.47$). In contrast, after the mid-1980s, the Hanjiang had almost stopped supplying sediment to the mainstream (10 Mt/yr in 1986–2002 vs. 122 Mt/yr in 1953–1968). In the same period of 1986–2002, the sediment depleted in Dongting Lake also decreased sharply to 47 Mt/yr, or 11% of that at Yichang (Xu et al., 2007). The correlation between Yichang and Datong in 1986–2002, therefore, became more significant ($R^2 = 0.89$). Thus, the correlation in 1986–2002 may well indicate the sediment transport process in the mid-lower Changjiang just before the TGD.

Based on the regression equation of 1986–2002 (Fig. 5b) and the estimated sediment load at Yichang in 2003–2008
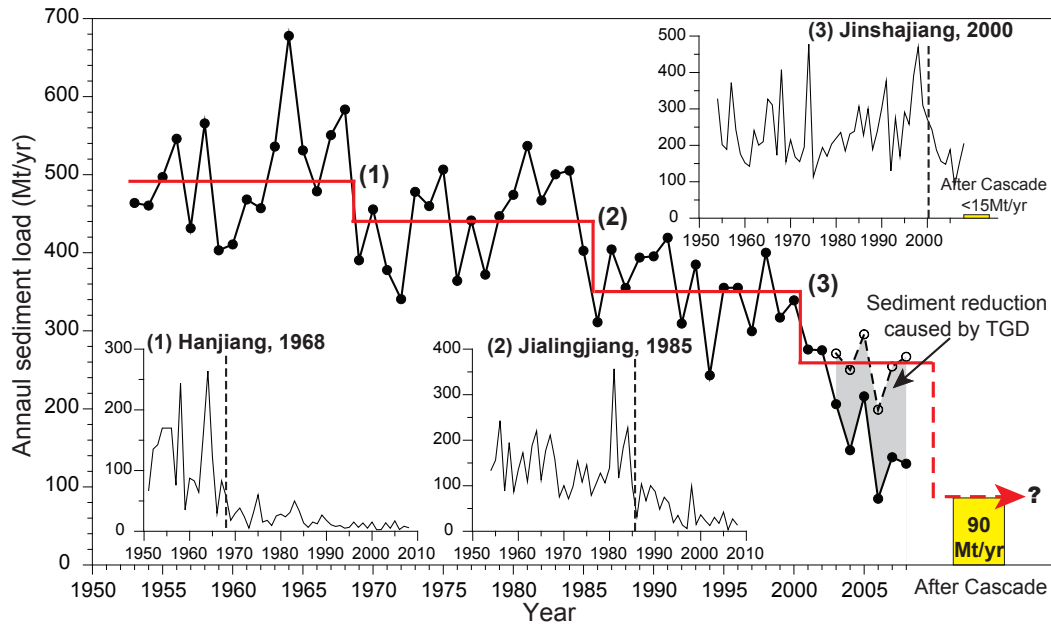
Fig. 6. Time series of the Changjiang sediment flux to the sea from 1953 to 2008. The black circle is the measured sediment load at Datong, and the open circle represents the estimated sediment load at Datong in 2003–2008 in the case of no-TGD. Three phases of sediment reductions are displayed with the red line. The averaged value for 2001-2008 was calculated in the case of no-TGD. The first and second phases are consistent with Yang et al. (2006b). However, the Changjiang sediment flux had entered the third downward step in 2001 ahead of the TGD operations, corresponding to the sediment reduction in the Jinshajiang since the late 1990s. After the cascade reservoir on the lower Jinshajiang put into full operation, the changjiang sediment flux possibly further decrease to below 90 Mt/yr. The grey region is the sediment reduction caused by TGD (102 Mt/yr in 2003–2008). See text for more detail.

(228 Mt/yr), mean annual sediment load at Datong had decreased by 91 Mt/yr, from 352 Mt/yr in 1986–2000 to 261 Mt/yr in 2001–2008 (non-TGD). This strongly implies that the third downward step in the Changjiang sediment flux happened even earlier, before the TGD. This can be mainly ascribed to increased reforestation and the construction of large hydraulic projects within the lower Jinshajiang basin since the late 1990s (Xu et al., 2006; Xiong et al., 2009). These human activities caused the Jinshajiang sediment discharge to sharply decline from 280 Mt/yr in 1986–2000 to 171 Mt/yr in 2001–2008 (Fig. 6). Sediment reduction induced by the TGD at Datong was estimated at 102 Mt/yr in 2003–2008 (gray region in Fig. 6), which is larger than the values given by Yang et al. (2007b).

5.3 Future trend of the Changjiang sediment flux to the sea

The correlation between sediment load at Yichang and Datong before the TGD was implemented has been applied to forecast the Changjiang sediment flux after the TGD in the previous studies (e.g., Yang et al., 2002, 2003, 2005, 2006b). However, it should be noted that the correlation between Yichang and Datong after the TGD has been fundamentally changed (Fig. 5b). This is mainly as a result of the changed sediment dynamics downstream of the TGD, such as

the changed sediment transport regimes, the transition from deposition to erosion and the shrinking Doting Lake (Xu et al., 2007, Yang et al., 2007a; Hu et al., 2009; Xu and Milliman, 2009). Thus, the correlation before the TGD may not represent the sediment transport process in the mid-lower Changjiang over the post-TGD period.

In spite of some uncertainties in the correlation between Yichang and Datong after TGD, owing to their relatively short period (2003–2008), it was applied to provide an insight into the future trend of the Changjiang sediment flux over the post-TGD period. According to the regression equation for the post-TGD period (Fig. 5b), the sediment load at Datong will decrease to 100 Mt/yr when sediment load at Yichang is further decrease to 19 Mt/yr in the next decade. Moreover, several other factors will cause further reduction in the Changjiang sediment flux to the sea in the near future, as detailed below.

First of all, the South to North Water Diversion Project (SNWDP) will be put into full operation in the 2030s. From then on it will divert about 5%, or 45 km^3, of the Changjiang annual water discharge through three passages to dry northern China, leading to 3%–5% of river sediment loss (Yang et al., 2002). Secondly, the Water and Soil Conservation Project (WSCP) has been implemented in the Changjiang basin since 1988. By 2008, the total area under control was

estimated at over $90 \times 10^3 \, \text{km}^2$, with an increasing rate of $5000 \, \text{km}^2/\text{yr}$. The WSCP has partly accounted for the sediment reduction of the Jialingjiang in the 1990s and the Jinshajiang in the 2000s (Xu et al., 2006; Yang et al., 2006b). Around 15% of the total sediment reduction at Datong, from $504 \, \text{Mt/yr}$ in 1956–1965 to $320 \, \text{Mt/yr}$ in 1993–2002, was attributed to the effects of the WSCP (Dai et al., 2008). The Chinese government has approved a plan to protect and recover an additional area of $75 \times 10^3 \, \text{km}^2$ within the Changjiang basin in the next decade. Therefore, the WSCP would, to a great extent, further decrease the Changjiang sediment flux to the sea in the next decade.

Last, in response to the TGD trapping, the downstream reaches of the TGD have suffered from severe erosion (Dai et al., 2006; Yang et al., 2006b, 2007a, b; Xu et al., 2006; Chen et al., 2008; Xu and Milliman, 2009). About $70 \, \text{Mt/yr}$ of sediment was eroded from the channel between Yichang and Datong in 2003–2008 (data in 2003–2006 were after Xu and Milliman (2009)). These channel erosion sediments accounted for 45% of the Changjiang sediment flux to the sea in 2003–2008. The erosion magnitude decreased along the downstream direction in 2003–2008, when the sediment erosion rate was $0.1 \, \text{Mt/km/yr}$ for the TGD site-Yichang, $0.07 \, \text{Mt/km/yr}$ for Yichang-Hankou, and $0.05 \, \text{Mt/km/yr}$ for Hankou-Datong. The erosion capacity will decrease with an increase in water depth, and the maximum erosion depth will extend downstream from the TGD site to Datong within 60 years (Lu, 2002; Yang et al., 2007a, b). Thus, sediment availability will be a limiting factor influencing sediment recovery downstream of the TGD on a long-term time scale (Yang et al., 2007b; Chen et al., 2008).

Taking the above-mentioned factors into account, the Changjiang sediment flux to the sea is conservatively expected to be less than $90 \, \text{Mt/yr}$ in the coming decades, when the cascade reservoir upstream of the TGD is put into full operation (Fig. 6). This value is not only much lower than most of the values predicted by previous studies (e.g., Yang et al., 2002, 2003, 2006b), but also lower than the minimum values given by Yang et al. (2007a) and Chen et al. (2008). Furthermore, for a longer time scale, when sediment entrainment downstream of the TGD is exhausted, the Changjiang sediment flux to the sea will possibly decrease further.

6   Conclusions

Our study shows that the TGD annually trapped about 172 Mt of sediment coming from the upper Changjiang in 2003–2008, which is higher than the values published by the CWRC and those estimated by previous studies. These differences are mainly a result of the underestimation or neglect of siltation in the backwater region of the TGD. The sediment budgets show that 88% of the total sediment trapped by the TGD is deposited in the lower section, from the TGD site to Cuntan. The remaining 12% is deposited in the upstream

of Cuntan as a result of the effect of the extended backwater area of the TGD.

Owing to the sediment reduction of the Jinshajiang since 2000, the sediment discharge from the Changjiang to the sea entered a third downward step in 2001, ahead of the TGD operation. The proposed cascade reservoir on the lower Jinshajiang may potentially trap 91% of the sediment coming from the Jinshajiang basin when it is put into full operation in the next decade. Consequently, the sediment discharge from the Changjiang to the sea will probably decrease to less than $90 \, \text{Mt/yr}$ in the coming decades, or only 18% of that in the 1950s. In response to the lower sediment supply, the Changjiang subaqueous delta will be eroded extensively, and a series of profound geological, morphological, ecological, and biogeochemical responses will appear in the estuary, delta, and coastal sea.

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