

Papers published in *Hydrology and Earth System Sciences Discussions* are under open-access review for the journal *Hydrology and Earth System Sciences*

Sedimentation in the Three Gorges Dam and its impact on the sediment flux from the Changjiang (Yangtze River), China

B. Q. Hu, Z. S. Yang, H. J. Wang, X. X. Sun, and N. S. Bi

College of Marine Geosciences, Ocean University of China, 238 Songling Rd., Qingdao 266100, China

Received: 17 July 2009 – Accepted: 27 July 2009 – Published: 29 July 2009

Correspondence to: B. Q. Hu (bangqihu@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

5177

Abstract

After the operation of the Three Gorges Dam (TGD) in 2003, the mean annual sediment load at Yichang station, 44 km downstream of the TGD, decreased drastically by 84% of that in the pre-TGD period (1986–2002). Annually, about 162 million tons (Mt) sediment was trapped by the TGD in 2003–2007, of which 92% was deposited within the region from Cuntan to TGD site; the remaining 8% deposited in the upstream of Cuntan owing to the effect of the extended backwater region of TGD. The theoretical trapping efficiency of the cascade reservoir on the lower Jinshajiang was calculated and its impact on the Changjiang sediment in the coming decades discussed. The results show that the cascade reservoir will trap up to 91% of the sediment discharge coming from the Jinshajiang tributary, and then the sediment discharge from the Changjiang to the sea will continuously decrease to less than 90 Mt/yr in the coming decades. In the presence of low sediment discharge, profound impacts on the morphology of estuary, delta and coastal sea are expected.

1 Introduction

Rivers are the conveyor belt for the delivery of terrestrial materials to the oceans (Walling and Fang, 2003; Walling, 2006), which annually transport 15–20 billion metric tons of sediment to the global oceans (Milliman and Meade, 1983; Milliman and Syvitski, 1992). These huge sediments 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 the river system for transporting the 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 greater number than that in 1950 (WCD, 2000). It is estimated that more than 30% of the global sediment flux was trapped in reservoirs (Vörösmarty et al., 2003)

5178

and 0.5%~1% of the world's total reservoir volume **was** lost each year as a result of sedimentation (WCD, 2000). Subsequently, the global sediment flux from the rivers to the sea **significantly decreased** (Milliman, 1997; Syvitski et al., 2005).

The Changjiang (Yangtze River) of China is a world-class river, it ranks 5th in terms of water discharge (920 km³/yr,) and historically 4th in terms of sediment load (480 Mt/yr) (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Since late 1960s, the water discharge from the Changjiang to the sea has remained almost unchanged; however, the Changjiang sediment discharge has experienced a distinct stepwise reduction, illustrating a predominated impact of human activities on the sediment yield, transport and storage in this large river system (Yang et al., 2002, 2006b). Of the human activities dam construction is the dominant factor (88%) contributing to the reduction in sediment discharge from the Changjiang to the sea (Dai et al., 2008).

The Three Gorges Dam (TGD), with its huge storage capacity of 39.3 km³, located at the end of the upper Changjiang, just 44 km upstream from the Yichang station (Fig. 1). Although the Changjiang sediment discharge had decreased by ~30% before the impoundment of the TGD in 2003 (Yang et al., 2006b), the impact of the TGD was more immediate and sharp. **After the TGD, the mean annual sediment load at Yichang declined to 67 Mt/yr in 2003–2007 of the post-TGD period, or 16% of that in 1986–2002.** Since the sediment discharge passing Yichang contributed most of the sediment flux from the Changjiang to the sea (Chen et al., 2001), a loss of 84% of sediment discharge at Yichang could drastically reduce the river's sediment discharge to downstream after Yichang and to the Sea. The possible consequences would be not only the downstream riverbed erosion, delta degradation, and wetlands loss (Yang et al., 2003, 2005, 2006a, 2007a, b; Chen et al., 2008; Xu and Milliman, 2009), but also a great threat to the downstream and coastal ecosystems (Xie et al., 2003; Shen and Xie, 2004). Therefore, the change of the Changjiang sediment caused by the impoundment of TGD after 2003 has garnered increasing attention and concern.

Sedimentation in reservoirs results in a progressive reduction of the storage capacity and triggers a series of physical, chemical and ecological impact on the environment.

5179

One key to assess its environment impacts is quantitative study on the reservoir sedimentation. Previous studies have estimated the annual deposition rate in the TGD by the method of sediment budget, however, the reported values were quite different with each other (IRTCES, 2003, 2004, 2005, 2006, 2007; 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 considering the influence of the sediment from the ungauged areas and 3) whether or not considering the sediment erosion within the channel between the TGD site and Yichang. Thus, for better understanding scientific and management issues of this giant reservoir related to watershed sediment budgets, depositional processes and reservoir operations, it is necessary to recalculate the sedimentation in the TGD by a thorough quantification study.

Otherwise, several studies (Yang et al., 2002, 2003, 2006b) estimated the sediment flux from the Changjiang to the sea (recorded at Datong station) after the TGD, on the basis of the estimated sediment load out of TGD at Yichang and the relationship between sediment data at Yichang and Datong in the pre-TGD period. **However, Chen et al. (2008) argued that these above estimates appear to overestimate the sediment discharge entering the TGD in the post-TGD period, and Xu et al. (2007) also indicated that the sediment correlation between Yichang and Datong during the post-TGD period have been fundamentally changed as a consequence of the decline of sediment diversion into the Dongting Lake and the changed sediment dynamics in the mid-lower Changjiang.** More recently, by considering the other impact factors, especially the impact of the proposed cascade reservoir on the lower **Jinshajiang** (Fig. 1), Yang et al. (2007a, b) suggested that the sediment flux from the Changjiang to the sea will decrease to about 100–150 Mt/yr in the coming six decades; and Chen et al. (2008) indicated that the annual sediment load at Datong over the post-TGD period will possibly vary from 112 Mt to 132 Mt or less in ordinary years. However, these results are still under debate due to the impact of the cascade reservoir on the lower Jinshajiang

5180

was only partly or qualitatively discussed.

In this paper, the sedimentation rate in the TGD is firstly calculated through a quantitative analysis of the sediment data upstream and downstream of the reservoir, followed by estimating the theoretical trapping efficiency of the proposed cascade reservoir on the lower Jinshajiang. Finally, the paper discusses the variation of the sediment flux from the Changjiang to the sea in the coming decades.

2 Physical setting

The Changjiang is one of the largest rivers in the world, which originates from the Qinghai-Tibetan Plateau at an elevation of 5400 m, with a drainage area of 1 810 000 km², accounting for about 19% of China's national area (Chen et al., 2001). The Changjiang basin 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, and 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 100×10^4 km², extends 4500 km from the source to Yichang station. The upper Changjiang basin 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 in the mainstream of the upper Changjiang (Fig. 1). The mid-lower Changjiang flow 1880 km through the extensive fluvial plains with several lakes from Yichang to Datong stations, with an average riverbed gradient of 0.03% (Chen et al., 2007). Downstream of Datong station the river is tidally influenced, therefore the Datong water and sediment records are generally used to represent the Changjiang's mass flux discharged to 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 sediment load from the Changjiang to the sea mainly originated from the upper reaches, whereas the water

5181

discharge from the upper reaches accounts for only 50% of that at Datong (Chen et al., 2001; Wang et al., 2008).

The TGD, with 181 m in height, 2335 m in length, and a storage capacity of 39.3 km³ (Zhao et al., 2000), is the largest dam in the world (Nilsson et al., 2005). It began trapping sediment and storing water from the upper reaches in June 2003. In addition, four large hydropower dams (Wudongde, Baihetan, Xiluodu and Xiangjiaba) have been planned taking the advantage of a 730 m drop over 770 km of river in the lower Jinshajiang (Fig. 1 and Table 2). The Xiluodu and Xiangjiaba are now under construction and will be put into operation in 2013 and 2012, and the other two dams, Wudongde and Baihetan, will be started construction in 2010 and planned for put into operation in 2020s (Liu, 2007; Yang et al., 2007b). The total storage capacity of the cascade reservoir on the lower Jinshajiang would be around 41.4 km³, which is about one third of the current annual water discharge of 145 km³ from the Jinshajiang.

3 Data collection and methods

3.1 Data collection

Water and sediment data used in this study are mainly provided by the Changjiang Water Conservancy Committee (CWCC) and partly from the River Sediment Bulletin of China (IRTCES, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007) published by the Ministry of Water Resources, China. Bed load is not included in the present study since its contribution to total load is less than 2% in the Changjiang (Yang et al., 2002; 2003). The locations and the detailed hydrological records of stations are presented in Fig. 1 and Table 1.

3.2 Estimates of the sediment deposition caused by TGD

Yichang station, located 44 km downstream from the TGD site, is mainly fed by four major tributaries of the upper Changjiang, i.e. Jinshajiang, Jialingjiang, Minjiang and

5182

Wujiang (Fig. 1). These four major tributaries totally contribute 80% of water discharge and 93% of 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 transform sediment discharge from the four major tributaries into the total sediment entering the TGD during the post-TGD period. However, the sediment load at Yichang displayed a distinct decreasing trend since the mid-1980s due to the intensifying human activities (dams and soil conservation) in the upper Changjiang basin (Xu et al., 2006; Yang et al., 2006b). Therefore, the sediment data in the period of 1986–2002 may be more representative of the condition just before the TGD than the whole period (1950s–2002) used in the previous studies. 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 (2003–2007). Accordingly, two methods can be used to estimate the sedimentation in the TGD: one is through establishing the correlation between sediment load at Yichang station and that from the four major tributaries of the upper reaches during the pre-TGD period to restore the scenario of sediment load at Yichang in the post-TGD period, and the differences between the restored values and the measured values at Yichang are assumed to be equal to the annual reservoir sedimentation, the other one is based on the method of sediment budget, which has been used in the previous studies (e.g. Yang et al., 2007b).

3.3 Computing the theoretical trapping efficiency (TE) of reservoirs

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

$$TE = 1 - \frac{0.05}{\sqrt{\Delta\tau_R}} \quad (1)$$

5183

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

$$\Delta\tau_R = \frac{\sum_i^n V_i}{Q} \quad (2)$$

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 for individual dam separately, using the data of annual water discharge at each dam's site and the storage volume of individual dam. With regard to the total cascade reservoir, the volumes of each dam were summarized, and the annual water discharge used is the long-term mean water discharge at the aftermost station (Pingshan station).

The Brune's method for calculating the theoretical TE, originally developed for the reservoirs in the United States, is widely used for the reservoirs in the other parts of the world as well and found to provide reasonable estimation of long-term and mean trapping efficiency (Vörösmarty et al., 1997, 2003; Morris and Fan, 1998; Kummur and Varis, 2007).

4 Results and Discussion

4.1 Sedimentation in 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 (2003–2007) periods were obtained as follows (Fig. 2):

$$\text{Pre - TGD} : Q_S Y = 1.125 Q_S T - 20 \quad (3)$$

$$\text{Post - TGD} : Q_S Y = 0.598 Q_S T - 64 \quad (4)$$

5184

The coefficients of determination, R^2 , for the above correlations are 0.85 and 0.94, respectively, at a significance level of $P < 0.01$. Mean annual sediment load at Yichang was estimated as 225 Mt in the post-TGD period in the case of no-TGD, and the difference between the estimated and measured sediment load at Yichang is assumed equivalent to the sediment deposition caused by the TGD. The results show that the mean annual sediment trapped by TGD was 158 Mt/yr in 2003–2007, and the maximum sediment deposition (200 Mt) occurred in 2005, the minimum (103 Mt) in 2006 (Table 3).

To validate the above estimated results, we established the sediment budgets of the mainstream reaches from Pingshan to Yichang, which was subdivided into two sections: the lower section from Yichang to Cuntan and the upper section from Cuntan to Pingshan (Fig. 1). The results show that the sediment deposited in the whole mainstream reaches from Pingshan to Yichang has increased from 27 Mt/yr in 1956–2002 to 184 Mt/yr in 2003–2007, indicating that the TGD-induced sediment deposition was averaged 157 Mt/yr in 2003–2007 (Table 4). It is very close to the above estimated result of 158 Mt/yr by our formula (Table 3). The sediment budgets of each sub-sections also provided insight to the distribution pattern of the sediment deposition caused by the TGD, indicating that 144 Mt/yr of the sediment deposition caused by TGD deposited in the lower section from Yichang to Cuntan, and the remaining 13 Mt/yr deposited in the upper section from Cuntan to Pingshan.

It is noticeable that the mainstream reaches between the TGD site and Yichang station suffered from serious erosion after the TGD operation (IRTCS, 2003; Yang et al., 2007a, b), thus the sediment trapping effect of the TGD would be underestimated by both of the two methods as discussed above. The sediment load passing Huanglingmiao station, just 13 km downstream of the TGD, was averaged 63 Mt/yr in 2003–2007, which increased to 67 Mt/yr at Yichang (44 km downstream of the TGD), that is, annually averaged 4 Mt/yr of sediment was eroded from the 31 km length channel from Huanglingmiao to Yichang, with a sediment erosion rate of 0.12 Mt/km/yr. Given the sediment erosion rate of 0.12 Mt/km/yr for the whole channel from TGD to

5185

Yichang (44 km channel length), the total sediment erosion in the channel between the TGD site and Yichang was calculated as about 5 Mt/yr in 2003–2007, which should be added to the sediment deposition in the lower section from Cuntan to Yichang. In conclusion, the total sediment trapped by TGD would be averaged 162 Mt/yr in 2003–2007, of which 92% was trapped in the lower section from Yichang to Cuntan, the remaining 8% deposited in the upper section from Cuntan to Pingshan. The sediment trapping efficiency (TE) of the TGD estimated in the present study was averaged 75% in 2003–2007, which is close to the designed values (70–80%) (Yang et al., 2002), but 8% higher than that published by CWCC (IRTCS, 2003, 2004, 2005, 2006, 2007).

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 in the TGD (Table 5). However, the significant siltation in the upstream of Cuntan (13 Mt/yr in 2003–2007) was underestimated or neglected in the previous studies. This siltation in the upstream of Cuntan may be related to the upstream extended backwater region of TGD. When sediment deposited in the backwater region as a result of the current velocity and sediment carrying capacity is reduced, it would bring a feedback mechanism allowing the depositional environment to propagate much farther upstream than the initial hydraulic backwater curve might suggest (Goodwin et al., 2001). This extended backwater region was observed in numerous dam systems, including the Aswan High Dam on Nile River in Egypt (El-Manadely et al., 2002), the Sardar Sarovar Dam on the Narmada River in India (Bettess, 1993), and the Sanmenxia reservoir on the Yellow River in China (Wang et al., 2007b).

According to the design scheme of TGD, 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. 3a, IRTCS, 2003, 2004, 2005, 2006, 2007). However, Wang et al. (2007a) indicated that the backwater region of TGD has extended upstream farther than the Qingxichang station in 2003 and Dai et al. (2006) also noticed a significant siltation in the upstream of Qingxichang in 2003

5186

and 2004. Furthermore, the variation of sediment load at the stations along the upper Changjiang before and after the TGD demonstrated the impact of the extend backwater region of the TGD on the sediment transport in the upper Changjiang in 2003–2007 (Fig. 3b). As shown in Fig. 3b, 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 or riverbed erosion. After the TGD put into operation, the sediment load began decreasing from Qingxichang in 2003, from Cuntan in 2004 and 2005, and from Zhutuo in 2006. This indicates that the backwater region of TGD has extended gradually upstream direction from Qingxichang (470 km upstream of the TGD) to Zhutuo (760 km upstream of the TGD), accompanying with sediment deposited in these regions. As the water elevation of the TGD increases to 175 m after 2009, the backwater region of TGD may be extended further upstream, consequently more sediment trapped within the backwater region is expected, and its impact on the local environment should attract more attention.

4.2 The theoretical trapping efficiency of the reservoirs

Four large dams, i.e. Wudongde, Baihetan, Xiluodu and Xiangjiaba, with a total storage capacity (41.4 km^3) greater than the TGD, are now under construction or will be constructed on the lower Jinshajiang (Fig. 1 and Table 2). To evaluate the impact of the whole cascade reservoir on the sediment discharge of the Changjiang in the coming decades, the theoretical trapping efficiency (TE) is calculated using the Brune's method. The theoretical values of TE for the individual dams of the cascade reservoir on the lower Jinshajiang vary from 73% to 87%, on completion of the cascade reservoir it would be theoretically capable to trap up to 91% of the sediment discharge coming from the Jinshajiang basin (Table 6). The theoretical TE for the Xiluodu and Xiangjiaba Dams calculated here are similar with the results of the previous studies (Huang and Huang, 2002; Hu et al., 2003; Tang and He, 2003). These results suggest that the Brune's method can be used to estimate the TE of the reservoirs on the upper Changjiang basin. Otherwise, it should be noted that the actual sediment trapping in

5187

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 its upstream Wudongde reservoir's sediment buffering effect.

The calculated theoretical TE of the TGD was 73% and 78% with its water elevation of 139 m and 156 m, respectively (Table 6), which is also close to the real TE of 75% in 2003–2007 when its 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 TGD will be up to 83%, much more than the value of 69% estimated by Yang et al. (2005).

4.3 Sediment flux from the Changjiang to the sea in the future

After the TGD put into operation in 2003, about 75% of the sediment discharge delivered from the upper Changjiang was retained behind the dam, which led to corresponding sediment reduction at Datong (represented as the sediment flux from the Changjiang to the sea) in 2003–2007 (Fig. 4a). However, based on the regression equation of the pre-TGD period (1986–2002) of Yang et al. (2006b) (Fig. 4b) and the estimated sediment load at Yichang in 2003–2007 (Table 3), mean annual sediment load at Datong had decreased by 92 Mt/yr from 352 Mt/yr in 1986–2000 to 260 Mt/yr in 2001–2007 in the case of non-TGD. This suggests that the third phase of the sediment reduction from the Changjiang to the sea happened even earlier before the TGD, and the TGD-induced sediment reduction at Datong was estimated as averaged 92 Mt/yr in 2003–2007. This prior sediment reduction can be ascribed to the increased reforestation in the lower Jinshajiang basin since the later 1990s (Xu et al., 2006).

By contributing 58% or 146 Mt/yr of the sediment discharge from the upper reaches into the TGD (Table 4), the Jinshajiang becomes the major sediment source of the Changjiang in and after TGD periods. After the cascade reservoirs on the lower Jinshajiang are put into full operation in the next decade, most of the sediment entering the cascade reservoir will be trapped, and the sediment passing Pingshan would most

5188

likely decrease sharply to ~15 Mt/yr (9% of 146 Mt/yr in 2003–2007). If the sediment discharge from other sub-basins maintained their present level (2003–2007), the total sediment discharge entering the TGD in the next decade will decrease to 119 Mt/yr or nearly half of that in 2003–2007. Given the TE of TGD with its water elevation of 175 m after 2009 is 83% (Table 6), the sediment discharge passing Yichang station would be only 20 Mt/yr in the coming decades.

According to the regression equation of the post-TGD period (2003–2007) in Fig. 4b, the sediment load at Datong will decrease to 96 Mt/yr when the sediment load at Yichang further decreased to 20 Mt/yr in the next decade (as shown above). Moreover, several other factors will cause further reduction in sediment flux from the Changjiang to the sea in the near future as detailed below. First, the South to North Water Diversion Project (SNWDP) will be put into full operation in 2030s, from then on it will divert about 5% or 45 km³ of the Changjiang annual water discharge through three passages to the dry northern China, leading to 3%–5% of the river sediment loss (Yang et al., 2002); Second, 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 over 9×10⁴ km² with an increasing rate of 5000 km²/yr. The WSCP has partly accounted for the sediment reduction of the Jialingjiang in 1990s and the Jinshajiang in 2000s (Xu et al., 2006; Yang et al., 2006b), and then around 15% of the total sediment reduction at Datong from 504 Mt/yr in 1956–1965 to 320 Mt/yr in 1993–2002 was attributed to the effects of WSCP (Dai et al., 2008). The Chinese government has approved a plan to protect and recover an additional area of 7.5×10⁴ km² within the Changjiang basin in the next decade. Therefore, the WSCP would to a great extent further decrease sediment discharge from the Changjiang to the sea in the next decade. Last, sediment availability downstream of the TGD will be a limiting factor influencing sediment recovery in the downstream of the TGD (Lu, 2002; Yang et al., 2007b; Chen et al., 2008). Therefore, the sediment discharge from the Changjiang to the sea is conservatively expected to be <90 Mt/yr in the coming decades. This values is not only much lower than most of the values predicted by the previous studies (Yang

5189

et al., 2002, 2003, 2006b), but also lower than the minimum values gave by Yang et al. (2007a) and Chen et al. (2008).

5 Conclusions

Our study shows that the TGD annually trapped about 163 Mt of sediment coming from the upper Changjiang in 2003–2007, which is higher than the values published by the CWCC and that estimated by the previous studies. These differences are mainly resulted from the underestimation or by neglecting of the siltation in the backwater region of TGD. The sediment budgets show that 92% of the total sediment trapped by TGD deposited in the lower section from TGD site to Cuntan, the remaining 8% deposited in the upstream of Cuntan as a result of the effect of the extended backwater area of the TGD.

As a result of the reduction of sediment discharge coming from the Jinshajiang since 2000, the sediment discharge from the Changjiang to the sea had entered the third downward step in 2001 ahead of the TGD operation. Moreover, the proposed cascade reservoir on the lower Jinshajiang will trap 91% of the sediment coming from the Jinshajiang basin when it put into full operation in the next decade. Consequently, the sediment discharge from the Changjiang to the sea will most likely decrease to less than 90 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.

Acknowledgements. We are grateful to the Changjiang Water Conservancy Committee for the access to valuable data sets. This work was financially supported by National Natural Science Foundation of China (NSFC) (Grant No. 90211022, 40876019)

5190

References

- Bettess, R.: Sediment and backwater aspects of Sardar Sarovar Project, HR Wallingford, Report EX2761, 1993.
- Brune, G. M.: Trap efficiency of reservoirs, *Transactions of the American Geophysical Union*, 34, 407–418, 1953.
- Chen, X. Q., Yan, Y., Fu, R. S., Dou, X., and Zhang, E. F.: Sediment transport from the Yangtze River, China, into the sea over the Post-Three Gorge Dam Period: A discussion, *Quaternary Int.*, 186, 55–64, 2008.
- Chen, Z. Y., Li, J. F., Shen, H. T., and Wang, Z. H.: Yangtze River of China: historical analysis of discharge variability and sediment flux, *Geomorphology*, 41, 77–91, 2001.
- Chen, Z. Y., Chen, D., Xu, K. Q., Zhao, Y., Wei, T., Chen, J., Li, L., and Watanabe, M.: Acoustic Doppler current profiler surveys along the Yangtze River, *Geomorphology*, 85, 155–165, 2007.
- Chu, Z. X. and Zhai, S. K.: Yangtze River Sediment: In Response to Three Gorges Reservoir (TGR) Water Impoundment in June 2003, *J. Coastal Res.*, 24, 30–39, 2008.
- Dai, S. B., Yang, S. L., and Li, P.: Regulation of the main river channel to the sediment discharge of Yangtze catchment, *Acta Geographica Sinica*, 61, 461–470, 2006.
- Dai, S. B., Lu, X. X., Yang, S. L., and Cai, A. M.: A preliminary estimate of human and natural contributions to the decline in sediment flux from the Yangtze River to the East China Sea, *Quaternary Int.*, 186, 43–54, 2008.
- El-Manadely, M. S., Abdel-Bary, R. M., El-Sammany, M. S., and Ahmed, T. A.: Characteristics of the delta formation resulting from sediment deposition in Lake Nasser, Egypt: Approach to tracing lake delta formation, *Lakes & Reservoirs: Research and Management*, 7, 81–86, 2002.
- Fu, R. S., Qi, M. L., Fang, H. W., and Chen, X. Q.: Influence of hydro-engineering projects in the upper Yangtze River on the changes of water and sediment output from Yichang Station, *Journal of Hydroelectric Engineering*, 24, 103–110, 2006.
- Goodwin, P., Falte, M., and Betts, A. D. K.: Managing for unforeseen consequences of large dam operations, Working Paper of the World Commission on Dams, Vlaeberg, Cape Town, South Africa, 4–5, 2001.
- Hu, Y. F., Wu, W. M., and Chen, Z. H.: Reservoir sediment computation of Xiangjiaba hydropower plant, *Yangtze River*, 34, 36–38, 2003.

5191

- Huang, Y. and Huang, Y. L.: Assessment on impact of Xiluodu on sediment deposition in Three Gorges Reservoir, *China Three Gorges Construction*, 9, 16–19, 2002.
- IRTCS: River sediment bulletin of china (2000), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), Beijing, 2000.
- IRTCS: River sediment bulletin of china (2001), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), Beijing, 2001.
- IRTCS: River sediment bulletin of china (2002), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), Beijing, 2002.
- IRTCS: River sediment bulletin of china (2003), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), Beijing, 2003.
- IRTCS: River sediment bulletin of china (2004), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), Beijing, 2004.
- IRTCS: River sediment bulletin of china (2005), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), Beijing, 2005.
- IRTCS: River sediment bulletin of china (2006), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), 2006.
- IRTCS: River sediment bulletin of china (2007), in, Ministry of Water Resources Conservancy. Available from: <http://www.irtces.org/database.asp> (in Chinese), 2007.
- Kondolf, G. M.: Hungry Water: Effects of Dams and Gravel Mining on River Channels, *Environmental Management*, 21, 533–551, 1997.
- Kummu, M. and Varis, O.: Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River, *Geomorphology*, 85, 275–293, 2007.
- Liu, F.: Introduction of the planed hydroelectric engineering on the lower Jinshajiang Construction of Water Resources and Hydroelectric Engineering, 3, 153–155, 2007.
- Lu, J. Y.: Impact of downstream erosion of the Three Gorges Dam on protective bank structures, *Yangtze River*, 33, 23–25, 2002.
- Milliman, J. D. and Meade, R. H.: World-Wide Delivery of River Sediment to the Oceans, *J. Geol.*, 91, 1–21, 1983.
- Milliman, J. D. and Syvitski, J. P. M.: Geomorphic/tectonic control of sediment transport to the ocean: the importance of small mountainous rivers, *J. Geol.*, 100, 525–544, 1992.
- Milliman, J. D.: Blessed dams or damned dams?, *Nature*, 386, 325–327, 1997.
- Morris, G. L. and Fan, J.: Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use, McGraw-Hill Professional, 1998.

5192

- Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C.: Fragmentation and Flow Regulation of the World's Large River Systems, *Science*, 308, 405–408, 2005.
- Shen, C. Y.: A pandect of China climate, China Science Press, Beijing, 1986.
- Shen, G. Z. and Xie, Z. Q.: Three Gorges Project: Chance and Challenge, *Science*, 304, 681, 2004
- Syvitski, J. P. M., Vorosmarty, C. J., Kettner, A. J., and Green, P.: Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean, *Science*, 308, 376–380, 2005.
- Tang, J. and He, X. P.: Impoundment of the Xiluodu Reservoir and its impact on the lower reaches, *Design of Hydroelectric Power Station*, 19, 60–63, 2003.
- UNDES: United Nations Department of Economic and Social Affairs, New York, 2001.
- Vörösmarty, C. J., Meybeck, M., Fekete, B., and Sharma, K.: The potential impact of neo-castorization on sediment transport by the global network of rivers, in: *Human impact on erosion and sedimentation*, edited by: Walling, D. and Probst, J.-L., IAHS Press, Wallingford, UK, 261–272, 1997.
- Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J. P. M.: Anthropogenic sediment retention: major global impact from registered river impoundments, *Global Planet. Change*, 39, 169–190, 2003.
- Walling, D. E. and Fang, D.: Recent trends in the suspended sediment loads of the world's rivers, *Global Planet. Change*, 39, 111–126, 2003.
- Walling, D. E.: Human impact on land-ocean sediment transfer by the world's rivers, *Geomorphology*, 79, 192–216, 2006.
- Wang, H. J., Yang, Z. S., Wang, Y., Saito, Y., and Liu, J. P.: Reconstruction of sediment flux from the Changjiang (Yangtze River) to the sea since the 1860s, *J. Hydrol.*, 349, 318–332, 2008.
- Wang, J., Zhang, O. Y., and Xiong, M.: The impact of initial water impoundment on sediment transport of Three Gorges Reservoir, *Journal of Hydroelectric Engineering*, 26, 98–108, 2007a.
- Wang, Z. Y., Wu, B. S., and Wang, G. Q.: Fluvial processes and morphological response in the Yellow and Weihe Rivers to closure and operation of Sanmenxia Dam, *Geomorphology*, 91, 65–79, 2007b.
- WCD: Dams and Development: A New Framework for Decision-making, Earthscan, London and Sterling, VA, 2000.
- Xie, P., Wu, J. G., Huang, J. H., and Han, X. G.: Three-Gorges Dam: Risk to Ancient Fish,

5193

- Science*, 302, 1149–1151, 2003.
- Xu, K. and Milliman, J. D.: Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam, *Geomorphology*, 104, 276–283, 2009.
- Xu, K. H., Milliman, J. D., Yang, Z. S., and Wang, H. J.: Yangtze Sediment Decline Partly From Three Gorges Dam, *Eos Trans. AGU*, 87, 185–190, 2006.
- Xu, K. H., Milliman, J. D., Yang, Z. S., and Xu, H.: Climatic and Anthropogenic Impacts on Water and Sediment Discharges from the Yangtze River (Changjiang), 1950-2005, in: *Large Rivers*, edited by: Avijit, G., 609–626, 2007.
- Yang, S. L., Zhao, Q. Y., and Belkin, I. M.: Temporal variation in the sediment load of the Yangtze river and the influences of human activities, *J. Hydrol.*, 263, 56–71, 2002.
- Yang, S. L., Belkin, I. M., Belkina, A. I., Zhao, Q. Y., Zhu, J., and Ding, P. X.: Delta response to decline in sediment supply from the Yangtze River: evidence of the recent four decades and expectations for the next half-century, *Estuarine, Coastal and Shelf Science*, 57, 689–699, 2003.
- Yang, S. L., Zhang, J., Zhu, J., Smith, J. P., Dai, S. B., Gao, A., and Li, P.: Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response, *J. Geophys. Res.*, 110, F03006, doi:10.1029/2004jf000271, 2005.
- Yang, S. L., Li, M., Dai, S. B., Liu, Z., Zhang, J., and Ding, P. X.: Drastic decrease in sediment supply from the Yangtze River and its challenge to coastal wetland management, *Geophys. Res. Lett.*, 33, L06408, doi:10.1029/2005gl025507, 2006a.
- Yang, S. L., Zhang, J., Dai, S. B., Li, M., and Xu, X. J.: Effect of deposition and erosion within the main river channel and large lakes on sediment delivery to the estuary of the Yangtze River, *J. Geophys. Res.*, 112, F02005, doi:10.1029/2006jf000484, 2007a.
- Yang, S. L., Zhang, J., and Xu, X. J.: Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, *Yangtze River*, *Geophys. Res. Lett.*, 34, L10401, doi:10.1029/2007gl029472, 2007b.
- Yang, Z. S., Wang, H. J., Saito, Y., Milliman, J. D., Xu, K. H., Qiao, S. Q., and Shi, G. Y.: Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam, *Water Resour. Res.*, 42, W04407, doi:10.1029/2005wr003970, 2006b.
- Zhao, C. H., Zhu, Z. H., and Zhou, D. Z.: *Worldwide Rivers and Dams*, China Water Conservancy and Hydroelectr. Press, Beijing, 1059 pp., 2000.

5194

Table 1. Detailed hydrological records of stations at the mainstream and the major tributaries of the upper Changjiang. Datasets were 1950s–2006.

River	Stations	Area (10 ⁴ km ²)	Water discharge (km ³ /yr)	Sediment load (Mt/yr)
Jinshajiang	Pingshan	45.86	145	249
Jialingjiang	Beibei	15.61	66	111
Minjiang	Gaochang	13.54	50	26
Wujiang	Wulong	8.30	86	48
Mainstream	Zhutuo	69.47	269	302
	Cuntan	86.66	348	418
	Yichang	100.55	436	470
	Datong	170.54	903	414

5195

Table 2. The cascade reservoirs on the lower Jinshajiang River of the upper Changjiang (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	8700	39.5
Baihetan	550	41.7	130	19.01	10.44	1305	57.7
Xiluodu	370	44.0	139	11.57	6.46	1260	57.4
Xiangjiaba	220	44.5	141	4.98	0.9	600	30.8

5196

Table 3. Estimation of the annual sediment deposited in the Three Gorges Reservoir^a (Unit: Mt/yr).

Year	Q_{ST}	Q_{SY}	Q_{SY_E}	D_{TGD}
2003	249	98	260	162
2004	210	64	217	153
2005	293	110	310	200
2006	117	9	112	103
2007	218	53	226	173
Average	217	67	225	158

^a Q_{ST} , Q_{SY} and Q_{SY_E} are the annual total sediment load from the four major tributaries, annual measured and estimated sediment load at Yichang station, respectively. The estimated sediment load at Yichang station is calculated with Eq. (3); D_{TGD} is the sediment deposition caused by TGD, $D_{TGD}=Q_{SY_E}-Q_{SY}$.

Table 4. Sediment budgets of the different sections in the mainstream from Pingshan to Yichang^a (Unit: Mt/yr)

Periods	Q_{SP}	Q_{SG}	Q_{SB}	Q_{SC}	Q_{SW}	Q_{SY}	$Q_{SU_{P-C}}^b$	$Q_{SU_{C-Y}}^b$	$Q_{SU_{P-Y}}^b$	$Q_{SD_{P-C}}$	$Q_{SD_{C-Y}}$	$Q_{SD_{P-Y}}$
2003	156	48	31	206	14	98	32	11	43	61	133	194
2004	148	34	18	173	11	64	22	7	29	49	127	176
2005	188	59	42	270	4	110	37	11	48	56	175	231
2006	90	21	3	109	3.9	10	2	12	15	105	120	199
2007	150	31	27	210	10	53	25	9	34	23	176	199
Post-TGD (2003–2007)	146	39	24	194	8	67	25	8	33	41	143	184
Pre-TGD (1956–2002)	254	48	115	430	28	492	41	33	74	28	-1	27
Sediment deposition caused by TGD ^c										13	144	157

^a Q_{SP} , Q_{SG} , Q_{SB} , Q_{SC} , Q_{SW} and Q_{SY} are annual sediment load at Pingshan, Gaochang, Beibei, Cuntan, Wulong and Yichang stations, respectively; $Q_{SU_{P-C}}$, $Q_{SU_{C-Y}}$, $Q_{SU_{P-Y}}$ and $Q_{SD_{P-C}}$, $Q_{SD_{C-Y}}$, $Q_{SD_{P-Y}}$ are sediment from the ungauged areas and sediment deposited in the sections of the upstream of TGD (Pingshan-Cuntan), the TGD Regions (Cuntan-Yichang) and the whole upper part (Pingshan-Yichang), respectively; $(Q_{SD_{P-C}}=Q_{SP}+Q_{SG}+Q_{SU_{P-C}}-Q_{SC})$; $Q_{SD_{C-Y}}=Q_{SC}+Q_{SB}+Q_{SW}+Q_{SU_{C-Y}}-Q_{SY}$; $Q_{SD_{P-Y}}=Q_{SP}+Q_{SG}+Q_{SB}+Q_{SW}+Q_{SU_{P-Y}}-Q_{SY}$ ^b The data of sediment from the ungauged areas are after Dai et al. (2006) and Yang et al. (2007b) or calculated by the same method; ^c The difference of sediment deposition between the pre-TGD and post-TGD periods is assumed to be TGD-induced.

Table 5. Summary of the estimated sedimentation rate in the TGD.

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
128	2003–2007	IRTCES, 2003–2007
151	2003–2005	Yang et al., 2007b
162	2003–2007	This study

5199

Table 6. Results of the theoretical trapping efficiency calculations for individual dams and the cascade.

Dam	Q^a (km ³ /yr)	V^b (km ³)	$\Delta\tau_R^c$	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%
TGD	436	13.6 (139 m)	0.03	72%
	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).

5200

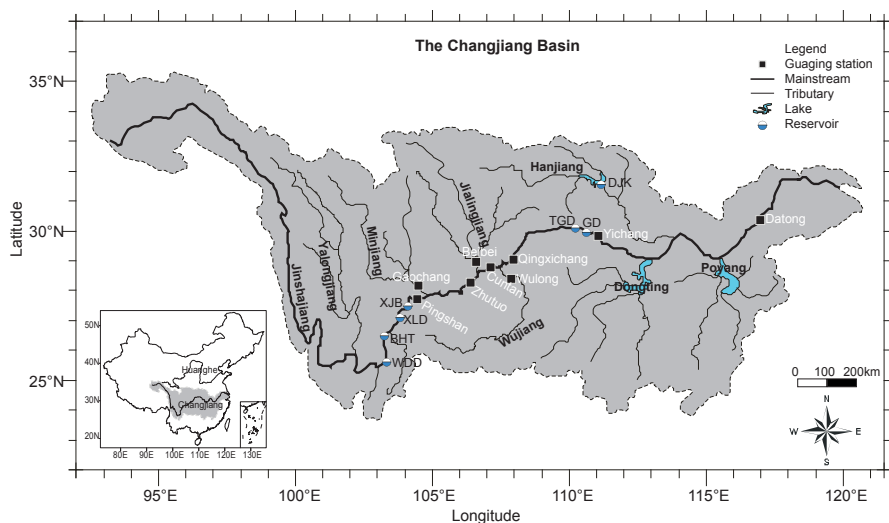


Fig. 1. The Changjiang drainage basin (DJK, Danjiangkou Reservoir; TGD, Three Gorges Dam; GD, Gezhouba Dam; XJB, Xiangjiaba Reservoir; XLD, Xiluodu Reservoir; BHT, Baihetan Reservoir; WDD, Wudongde Reservoir).

5201

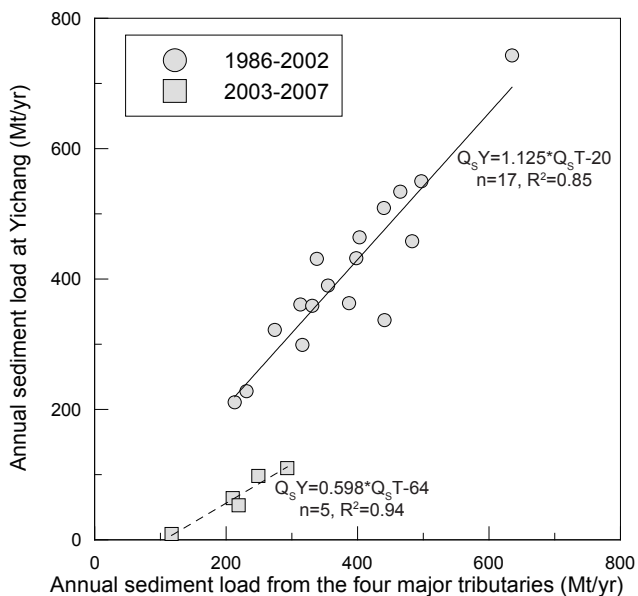


Fig. 2. The correlations between annual sediment load at Yichang and that from the four major tributaries during the pre-TGD and post-TGD periods.

5202

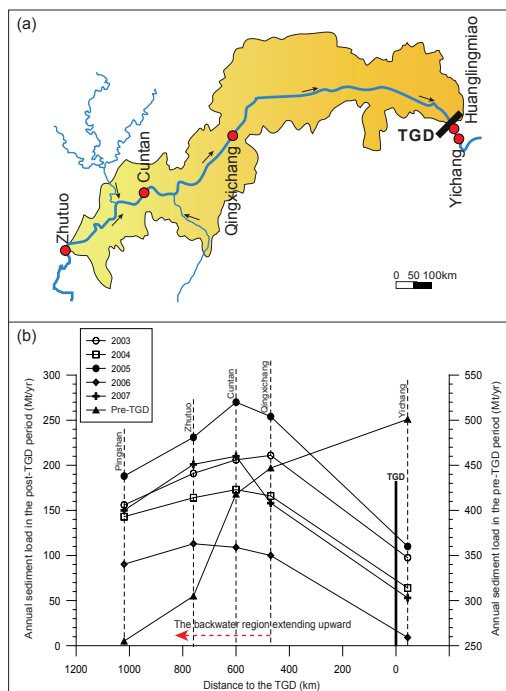


Fig. 3. (a) The sketch map of the Three Gorges Dam and (b) The annual sediment load after the impoundment of the TGD in comparison with the long-term (Pre-TGD) average values at the major stations along the upper Changjiang. The average values for the pre-TGD period is 1950s–2000. It is suggested that the backwater region of TGD has extended upstream direction to Zhutuo station in 2006 (760 km upstream of the TGD site).

5203

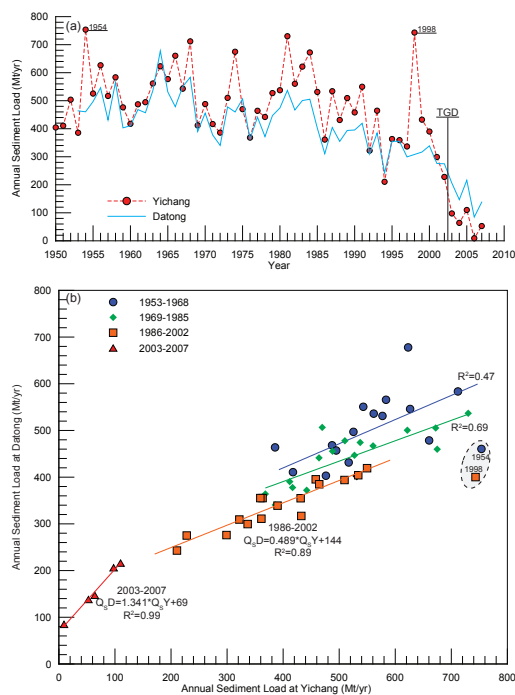


Fig. 4. (a) Time series of annual sediment load at Yichang and Datong stations from 1950s to 2007 and (b) Correlations between annual sediment load at Yichang and that at Datong in the pre-TGD period (after Yang et al., 2006b, the extreme flood year of 1954, 1998 was excluded) and the post-TGD period.

5204