INVESTIGATION OF SEDIMENTATION IN THE THREE GORGES RESERVOIR, CHINA

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ABSTRACT

The Three Gorges Reservoir (TGR) is the largest built hydropower reservoir in the world, having comprehensive functions of flood control, power generation, navigation and irrigation. The construction of the TGR has greatly changed the upstream flow field and generated a complex sediment transport. Sedimentation in the TGR is a major factor affecting reservoir function and reservoir life and is also a controversial issue. In this study, long-term series field measured hydrological and terrain data before and after the TGR's impoundment are used to investigate the trend of runoff and sediment load transport into the TGR. The effect of sedimentation on the TGR is discussed. The result shows that the total amount of sediment load transported into the TGR has a significant reducing trend after the impoundment of the TGR. Analysis of the field data shows that the average sediment delivery ratio of the TGR is 24% during 2003-2016 and the annual loss in storage capacity is about 0.3%. Sediment mainly deposits in river reaches with wide cross sections, especially in the permanent backwater area, where the flow velocity is relatively small. It is expected that this study will help optimizing the TGR operations and improving its comprehensive function.

Keywords *: Three Gorges Reservoir, Sedimentation, sediment transport, delivery ratio*

1. INTRODUCTION

Reservoirs play a very important role in the development of human civilization. Globally, water from reservoirs supplies an estimated 30-40% of irrigated areas (World Commission on Dams, 2000), contributes 20% of the global electricity generation in the form of hydropower (Demirbas, 2009), and serves a number of other beneficial purposes including flood control, recreation, and navigation. However, sedimentation is a major factor affecting reservoir function and reservoir life (Fan & Morris, 1992), leading to an increase in the flooding magnitude, which could make the downstream areas more vulnerable and less secure (Serban, 2011). Therefore, it is very important to study reservoir sedimentation, especially in the mega reservoirs, such as the Three Gorges Reservoir (TGR) in order to optimize the reservoir operation and comprehensive function.

The Three Gorges Dam (TGD) is the largest built hydroelectric project in the world and the most important water control project along the Yangtze River (Nilsson et al. 2005, Shi, 2011, Xu et al. 2011, Bao et al. 2015). The TGD provides multiple social services such as the flood control, navigation and electricity generation. Meanwhile, the TGR is also probably the most controversial reservoir in the world (Gao et al. 2015). One of the controversial issues is whether or not sedimentation will quickly fill the reservoir after its impoundment. Sedimentation at the TGR might be similar to what happened with the Sanmenxia Reservoir, which was built in the middle reaches of the Yellow River in the late 1950s (Jiang & Fu 1998, Mei & Dregne 2001). Some researchers pointed out that coarse sediment moving into the reservoir could cause serious deposition along the river bed. These views had caused great public concern during the reservoir design and construction period (Dai, 1989, Huang, 1993, Zhou, 2005). In contrast, some physical experiments and sediment modelling predictions concluded that (i) continuous sedimentation would stop about 100 years after its impoundment; and (ii) the new channel bed elevation would remain sufficiently below the designed base level of 145 m above sea level to maintain its water storage capacity and assure the normal reservoir operation (Lin et al. 1993, Qian et al. 1993, Wang et al. 2013). However, doubts still remain about how much sediment will be deposited in the TGR (Barber & Ryder, 1994, Leopold, 1998). Even since the full impoundment of the reservoir in 2010, doubts regarding sedimentation in the TGR still persist in public media, such as Probe International (Dai, 2010), News China (Wang et al. 2010) , Facts and Details (Hays, 2011) and China National Geographic (Fan, 2014).

In fact, since the construction of the TGD, the conditions in the upper reaches of the Yangtze River Basin and the sediment load from the upstream flowing into the TGR have been significantly changed. Firstly, many new dams are being built in the Yangtze River and its tributaries upstream of the TGR (Changjiang Water Resources Commission, 2012). This greatly changes the flow process (Duan et al. 2016) and intercepts considerable sediment (Huang et al. 2013). Secondly, a series of soil erosion protection project (together named the Changzhi Project) have been carried out in the upper catchment of the Yangtze River and the TGR region since 1989. These projects aim to reduce the soil erosion within the Yangtze River catchment upstream the TGR and thereby reducing the amount of sediment flowing into the TGR (Liao et al. 2012). Thirdly, a large amount of building materials such as sand and gravel has been extracted from the river bed over the past three decades due to the rapid development of the Chinese economy (Changjiang Water Resources Commission, 2014). Some studies suggest that sand extraction may have a significant impact on the sediment balance of the Yangtze River and could reduce the river sediment discharge (Chen et al. 2006, Yang et al. 2007, Zhang et al. 2009). As a result of the above combined effects, sediment transport in the upper reach of the Yangtze River is decreasing year by year since the TGR's impoundment. Relevant studies have also indicated that there is a decreasing trend of sediment supply to the TGR, which may reduce the sedimentation rate (Wang et al. 2007, Xiong et al. 2009, Lu et al. 2011, Xu et al. 2013). So far, majority of studies mainly focused on investigating the trend of sediment transport to the TGR. However, the important sedimentation in the TGR has not been paid sufficient research attention and few studies have been carried out to investigate the relationship between reservoir deposition and sediment transport. The controversial issue of sedimentation in the TGR, therefore, remains.

In this study, the trends of sediment deposition into the TGR and the sedimentation models for the reservoir will be investigated by using the long-term field observed hydrology and topographic survey data at pre-fixed sections. It is expected that this study will provide a reference for maximizing the benefit of the TGR comprehensive functions and the related research.

2. DESCRIPTION OF STUDY AREA

The TGR locates in the Yichang Reach of the Yangtze River, as a control reservoir for the middle and lower Yangtze River. It is a strategically important reservoir to the Southwest China which improve the shipping mileage by 660km (Fig. 1). The total installed capacity is 22.4 million KW. At the normal pool level of 175m, the total storage is 39.3 billion m^3 with the flood control storage of 22.15 billion m^3 and the total surface water area of the reservoir is 1,084km^2. The river reach upstream of the TGR is about 4,540 km long and has a catchment area of 1 million km^2. Upstream of the TGR, there are two main tributaries flowing into the TGR. They are Jialing river and Wujiang river with catchment areas of 156,142 km^2 and 83,053 km^2 respectively.

The TGR region locates between the Chongqing municipality and Hubei province, covering the total area of 59,900 km^2 with 16 million residents. The TGR region stretches along the Yangtze River from Jiangjin District of Chongqing to Yichang City of Hubei. The region is 74% mountainous area; 4.3% plains area and 21.7% hilly area. The TGR is a river channel type reservoir with both banks are constituted of exposed rocks. The river channel has a complicated geography with great variation of width. Typical example is that the width of the river valley in the gorge section is only about 200-300m. While in the broad sections, the river width can reach about 600-800m, even 1,000-2,000m during the flood season. The cross section of the narrow gorges is generally "V" shaped while the cross section in the broad sections is generally "U" shaped. The river bed is usually covered with rocks and pebbles. In the evolution process of river channels, the boundary conditions and water level played dominant roles before the TGR impoundment.

The TGD started construction at the end of 1994 and was completed by the end of 2008. It entered the cofferdam and storage period in June 2003 for four years. The water level at the dam was 135m in flood season and 139m in dry season. After the flood season in 2006, the reservoir entered the initial impoundment period with the water level at the dam being 144m in flood season and 156m in dry season. At the end of the flood season in 2008, the reservoir started entering a testable storage period with the normal water level being set at 175m. On October 26, 2010, the water level at the TGD reached 175m for the first time. Since then the reservoir entered the 175m testable storage period, as shown in Figure 2.

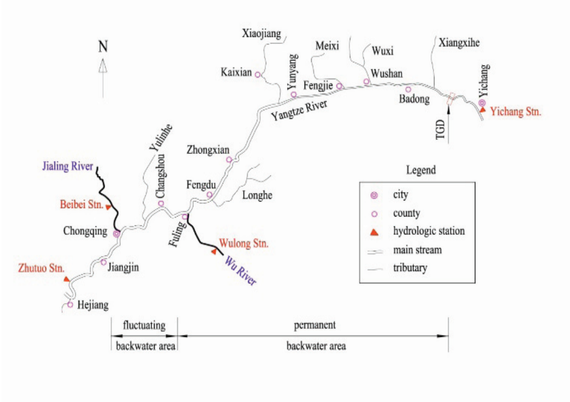


Figure 1 : Sketch of the TGR

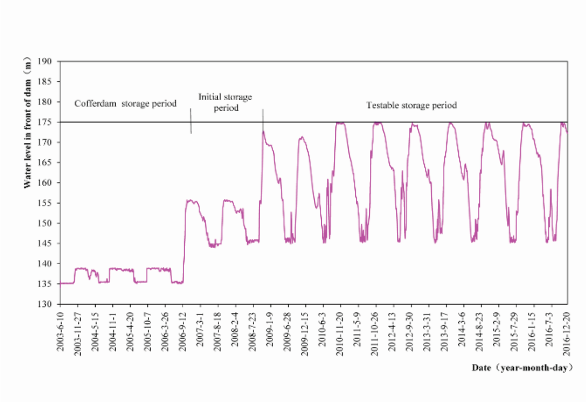


Figure 2 . Water level at the dam wall

3. FIELD MEASUREMENT

As well as the upper Yangtze River, there are two tributaries, namely the Jialing river and the Wujiang river, that flow into the TGR. There are three control hydrological stations of the upper Yangtze River, Jialing river and Wujiang river, namely the Zhutuo station, the Beibei station and the Wulong station, while there is one control hydrological station, the Yichang station, downstream of the TGR.

In this study, the hydrologic data from the above four hydrological stations are used to analyse the flow discharge and the sediment transport. The hydrological data used in this study consist of monthly and annual flow discharge and the sediment load at the four hydrological stations since the 1950s. The hydrological data are collected from the Yangtze Water Conservancy Committee (YWCC) and the Bulletins of Changjiang Sediment from 2000 to 2016 (BCS, 2000-2016). The length of reservoir reach along the Yangtze River is about 600 km in which 340 cross-sections with the interval distance from one to three kilometres are arranged according to the terrain situation to monitor the river morphodynamic. After the TGR impounding, the river bed topography is measured annually at each cross-section. These measured field terrain data are used to analyse the sediment transport and river bed morphodynamic in the TGR.

At each hydrological station, the flow discharge is measured by using the ADCP method. The water level is monitored by using a bubble type automatic water level gauge. The suspended sediment transport is measured by the AYX2-1 type suspended sediment samplers. The sediment particle size is nalysed by using the instrument "LISST100 laser sediment concentration meter". The bed load is measured by using the improved sampler Y90. The water depth is measured by using the single-beam digital sounding system HY1601. At 340 cross sections, river bed topography is measured by using Trimble GNSS R8, R7 and R10 instruments. The distance between each sampling point is about 8m.

4. RESULTS AND DISCUSSION

4.1 Runoff and sediment inflow

The annual runoff and suspended sediment volume data are collected at the three hydrological stations within the TGR during the period from 1956 to 2016. The total annual runoff and suspended sediment observed at the three hydrological stations represents the amount of suspended sediment transported into the TGR. The results show that there is no obvious change in the annual runoff at the three hydrological stations. It can be seen from Figure 3, the average annual runoff was 380km^3 during 1956-2002. After the TGR's impoundment during 2003-2016, the average annual runoff was 360km^3; which is 94.7% of that from 1956 to 2002, indicating that the average annual runoff has insignificant change during the last six decades. However, the suspended sediment discharge has been decreasing over the past 20 years. In particular, the decreasing trend is more obvious since the TGR was put into operation in 2003.The total average annual suspended sediment was 451.9Mt during 1956-2002; while the total average annual suspended sediment is only about 164.3Mt after the TGR's impoundment. It's only about 36% of that during the 1956-2002 period. In particular, in the past five years, the total average annual suspended sediment has further reduced to 98.5Mt. As some new mega dams are put into impoundment in the upper Yangtze River (Changjiang Water Resources Commission, 2012), more sediment would be intercepted within these mega reservoirs upstream of the TGR, leading to the continuous reduction of the annual suspended sediment transported into the TGR. This is a positive indication for the TGR's function and life.

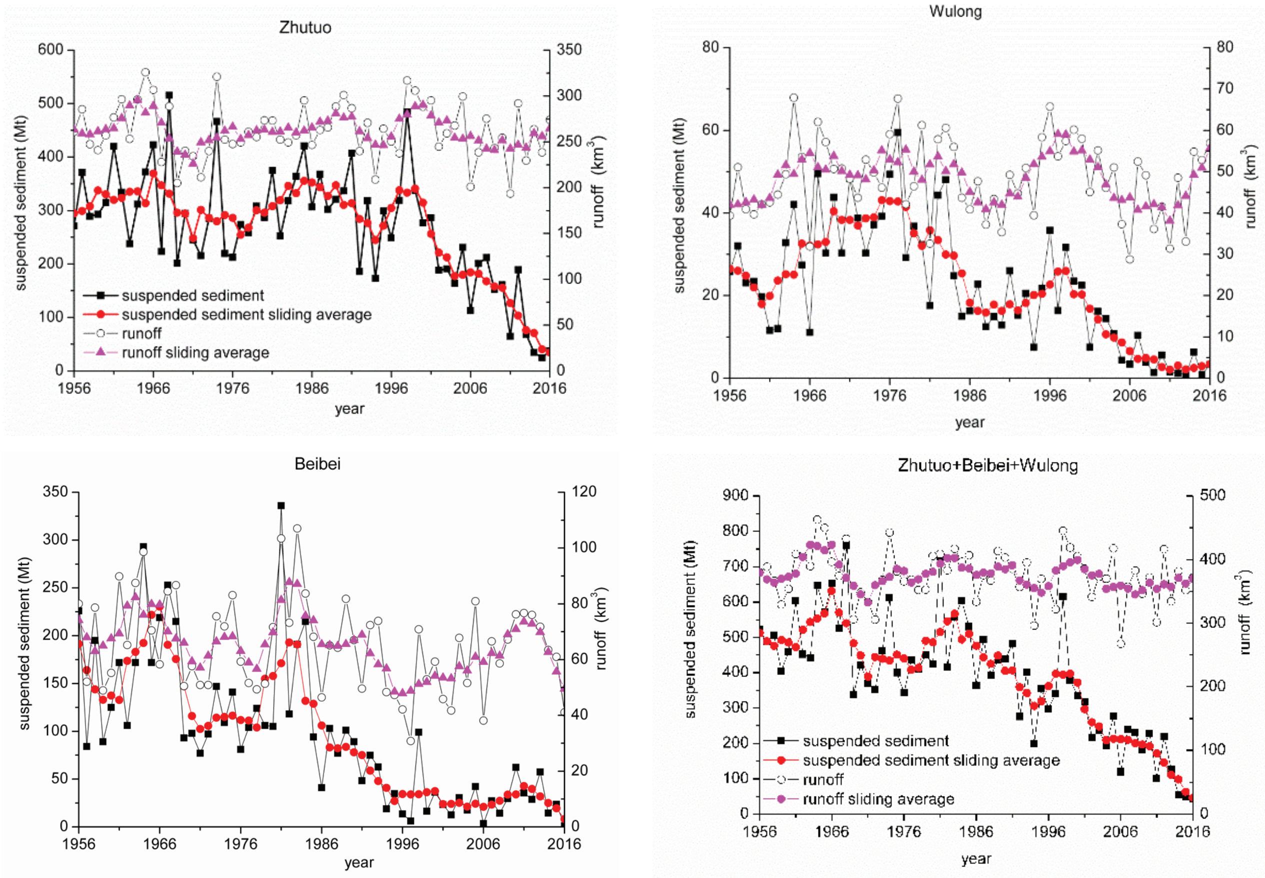
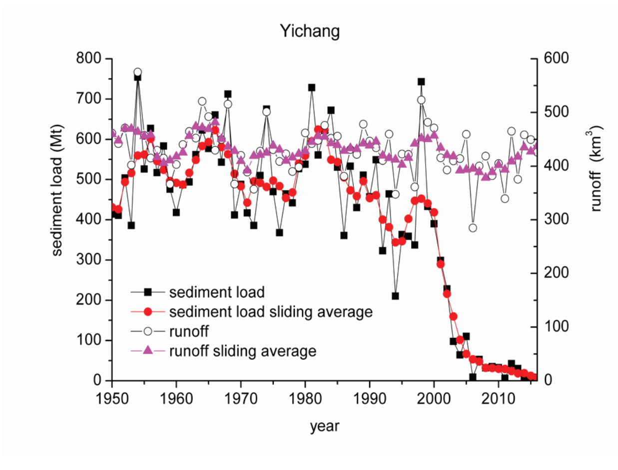


Figure 3 : The runoff and suspended sediment flowing into the TGR

According to the field data of the three hydrological stations from 1991 to 2016, the total annual gravel load (bedload) also shows a decreasing trend. As shown in Figure 4, the total average annual bed load is 40.75×104t from 1991 to 2002; while the value is reduced to 5.9×104t during 2003 to 2016 (about 14.5% of that of 1991-2002) and is declined to 4.1×104t (about 10% of that of 1991-2002) over the past five years. This reduction of the gravel load sediment transported into the TGR could be ascribed to the facts (1) the new mega dams upstream of the TGR have intercepted large amount of the bedload sediment as the flow velocity there is reduced due to the construction of these dams; and (2) significant sand is extracted in the upper Yangtze River (Chen et al. 2006, Yang et al. 2007, Zhang et al. 2009). It is expected that the amount of bedload sediment deposited into the TGR will continue to decline in the future. This study shows that the previous prediction that more coarse sediment would be transported into the TGR (Dai, 1989, Huang, 1993, Zhou, 2005) will not happen.



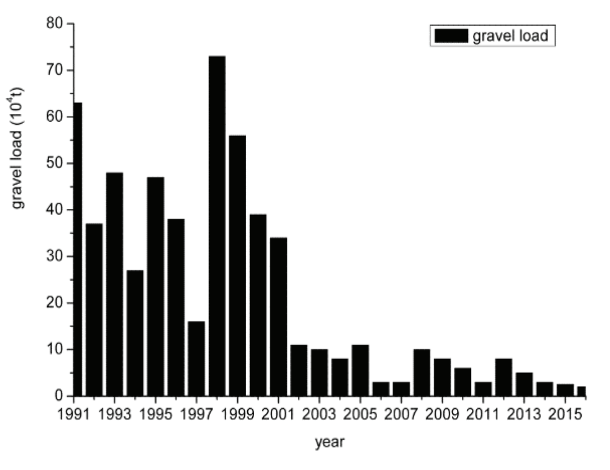


Figure 4 : The change of gravel load into the TGR

Figure 5 : The change of sediment load in the Yichang station

4.2 *Runoff and sediment outflow*

Yichang hydrological station locates 44 km downstream of the TGD. The runoff and sediment load data of the station can represent the runoff and sediment load that flows from the TGR. The observation data at this station have been collected from 1950 to 2016, which is plotted in Figure 5. As showed in Figure 5, the average annual runoff was 436.9km^3 during 1950-2002; after the TGR's impoundment, it declined to 406km^3, which is about 93% of that from 1950-2002. This shows that the average annual runoff decreases slightly after the construction and impoundment of the TGR. However, the sediment load has significantly changed after the construction of the TGR. Figure 5 reveals that the average annual suspended sediment was 492Mt during 1950-2002, while after the TGR's impoundment, it declined to 38Mt, which is only about 7.7% of the value at 1950-2002. Particularly, in the past five years, the average annual suspended sediment has declined to 18.9Mt, which is 3.8% of the average value during the years 1950-2002. The suspended sediment grain size observed downstream of the TGR also decreases. The measurement demonstrates that the median diameter (d50) of the suspended sediment transported into the TGR is 0.011mm, while that measured at the Yichang station is 0.006mm. This indicates that the coarse suspended sediment deposits in the reservoir and only the fine sediments discharge into the river downstream. Moreover, the bedload was too low to be measured at the Yichang station after the impoundment of the TGR, indicating that the bedload is all deposited in the TGR. This result demonstrates that the TGR has a strong effect on the downstream sediment budgets (Lauer et al. 2016).

4.3 Deposition and sediment delivery ratio of the TGR

Based on the measured data of the upstream and downstream hydrological stations of the TGR, the amount of sediment deposited in the reservoir can be calculated by deducting the amount of sediment downstream(Yichang)from the amount of sediment upstream (Zhutuo+Beibei+Wulong). As showed in Figure 6, during 2003-2016 the cumulative sediment load inflow was 2157Mt; the total cumulative deposition was 1637Mt; the average amount of annual deposition was 116.9Mt respectively. The sediment delivery ratio is defined as the ability of a reservoir to deliver sediment to the downstream. The sediment delivery ratio of the TGR is calculated by dividing the amount of sediment load outflow to the amount of sediment load inflow. The average sediment delivery ratio of TGR was 24% during 2003-2016(Table1). For the first three years from 2003-2006, the average sediment delivery ratio was about 36%. The average sediment delivery ratio reduced to around 18% from 2007 to 2016, which was only about half of the estimated value of the original results of early literatures (The Science and Technology Department of Ministry of Water Conservancy and Electric Power, 1988, State Council Three Gorges Project Construction Committee Executive Office Sediment Experts Group China Three Gorges Project Corporation Sediment Experts Group, 2002, State Council Three Gorges Project Construction Committee Executive Office Sediment Experts Group China Three Gorges Project Corporation Sediment Experts Group, 2008). Perhaps the reason for this problem is that, during the TGR demonstration stage, fine grain sediment below 0.01mm is considered as the wash load flowing out of the TGR. Therefore the study did not include this part of the sediment deposition (Lin, 1989). In fact, a large amount of sediment with diameter less than 0.01 mm is deposited in the TGR (see 4.4).

Table 1 : Annual sediment inflow, sediment outflow, deposition and trap efficiency

Years	Sediment inflow (Mt/yr)	Sediment outflow (Mt/yr)	Deposition (Mt/yr)	Trap efficiency (%)	Sediment delivery rate (%)
2003	208	84	124	60	40
2004	166	64	102	62	38
2005	254	103	151	59	41
2006	102	9	93	91	9
2007	220	51	170	77	23
2008	218	32	186	85	15
2009	183	36	147	80	20
2010	229	33	196	86	14
2011	102	7	95	93	7
2012	219	45	174	79	21
2013	127	33	94	74	26
2014	55	11	45	81	19
2015	32	4	28	87	13
2016	42	9	34	80	20
2013-2016	2157	520	1637	76	24

The total deposition volume in the TGR was 1.66 billion m3 during 2003-2016; the average annual deposition volume in the TGR was 0.19 billion m3; then the annual loss in storage capacity was 0.3%, which is considered to be very low compare to the world average (White, 2001, Basson, 2009). The annual trap efficiency (TE) in the TGR ranged from 59% to 93%, and averaged 76%, increasing from 64% during 2003-2006 to 82% during 2007-2016. The highest TE occurred in 2006 and 2011(Table1), which were the two extreme drought years in post-TGD period. The observed TE is higher than the 69-70% predicted for the first decade of operation by the TGD designers (IWHR and YCRI, 1990, Xiong, 1996). Annual TE against C/I from the TGR shows close scatter on both sides of the classic three curves (Fig.6), Brune(1953), USDA-SCS(1983) and Harbor(1997), which are suit for fine and clay-silt sediment like in TGR. The TE-C/I plot predicted by the designers is far below that observed in this study, and also below the three curves. The underestimation of TE in previous studies may be partly attributed to changes in hydrological conditions. For example, the prediction in previous studies was based on water inflow in the 1960s, but water inflow to the TGR in 2003-2016 was 11% lower than in the 1960s, the result of climatic changes and human activities (Yang et al. 2010). And the upstream sediment supply has decreased from 545Mt/yr in the 1960s to 216Mt/yr in 2003-2016, which may also have influenced the TE.

Statistics show that (Fig.7), the amount of annual sediment deposition is proportional to the amount of annual sediment flowing into the reservoir. This correlation is very good. The water level at dam wall was 135m in flood season during 2003-2006 and 145 m during 2007-2016. The correlation coefficients R2 during above two periods were 0.9124 and 0.9867, respectively. This shows that, the annual deposition in the TGR is a linear correlation with annual sediment load influx and also a positive correlation with water level at dam wall in the flood season. The upstream sediment load is mainly concentrated in the flood season (Huang, 2013).

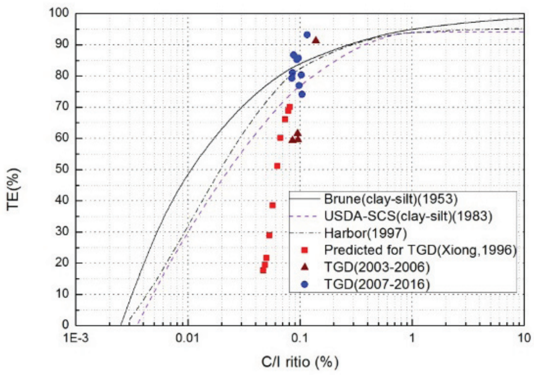


Figure 6 : Relation between annual trap efficiency

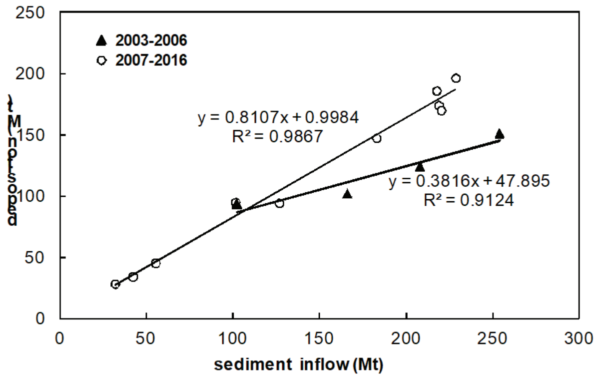


Figure 7 : The relationship between deposition and sediment inflow (TE) and the ratio of capacity to annual water inflow (C/I) for the TGD's operation (2003-2016) compared to the results of other studies. The TE predicted for the TGD before its construction (Xiong, 1996) is based on decadal data, and it decreases from the first decade to the tenth decade after the TGD operation.

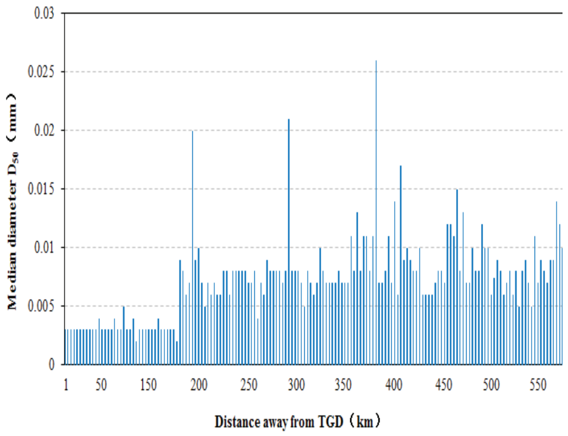
4.4 Deposition Distribution in the TGR

4.4.1 *Deposition distribution along the TGR reach*

Based on the annual field observed terrain at 340 sections, the deposition distribution can be analyzed and estimated. Assuming that the sediment is uniformly deposited along the river reach between two adjacent observing sections; the deposition volume and its spatial distribution can then be estimated.

As showed in Figure 7, the deposition in the TGR shows a positive correlation with sediment load inflow in the flood season. According to statistics, the average flow discharge in the flood season (from June to September) is about 20,000m^3/s since the TGR's impoundment. On the condition that the upstream discharge is 20,000m^3/s and the dam wall water level is 145m, the river width of each section is counted along the TGR reach (Fig. 8). The terrain was measured in 2002, which acted as a basis for comparison and analysis. The deposition thickness in each section is calculated from 2002 to 2015, to display the deposition thickness along the TGR reach (Fig. 8).

As shown in Figure 8, the width of the sections changes dramatically along the TGR reach, the smallest section width is 220m, but the biggest section width is more than 2000m. The different widths produce different section areas which produce different flow rates. The vast majority of sections along the TGR reach showed cumulative deposition, especially in the broad sections. In very small proportion of sections, which were usually in the narrow canyons with small river width, the river bed was scoured. Sediment is mainly deposited in the permanent backwater area, little deposition occurs in the fluctuating backwater areas. It is noticeable that there is no deposition in the tail of the backwaters. The length of the reach in which sediment is deposited is 277 km, accounting for about 1/3 of the total length of the reservoir backwater reach, and accounting for 85% of the total sediment deposition. Unlike the lake-shape reservoirs such as Lake Nasser on the Nile (El-Manadely et al. 2002) and the Danjiangkou Reservoir on the Hanjiang River(Tao, 2002), where deposition occurs mainly at the entrance to the reservoir and forms a delta, less deposition has been found at the entrance of the TGR.



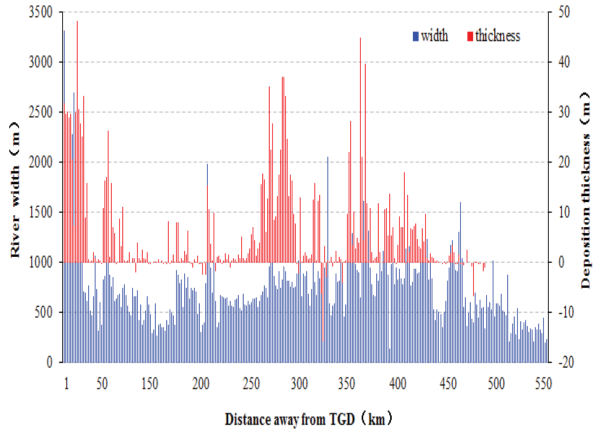


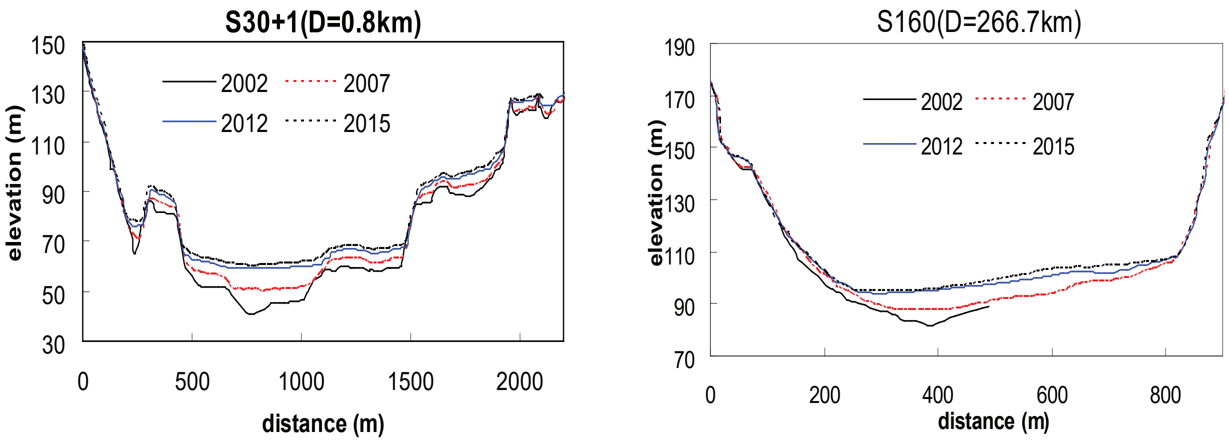
Figure 8 : The river width and deposition thickness along the TGR reach

Figure 9 : The D50 along the TGR reach

According to the data of the riverbed sampling in 2015, the median particle size (d50) distribution of the sediment along the TGR reach was figured out (Fig.9). Except in the most fluctuating backwater reaches, the silt sediment median-particle size (d50) is less than 0.01mm in almost all of the 400km long reach. This means that, plenty of fine sediment (the particle size is less than 0.01mm) is deposited in the TGR, especially in the permanent backwater reaches. This can also explain the reasons why the practical sediment delivery ratio is less than the earlier research indicated (Lin, 1989).

4.4.2 *The deposition distribution across the cross-sections*

The bottom profile of each section was counted, to measure the river bed topography changes along the TGR reach in the different impounding periods. For the sake of clarification, only the data of 2002, 2005, 2007, 2012 and 2015 are used. The deposition across the reservoir is shown in some typical sections (Fig. 10). Sediment is mainly deposited in the wide sections, and little is deposited in the narrow sections. Usually there is widespread deposition across the wide sections in the permanent backwater reaches. The measurements show that, in those wide sections of the meandering river channel, the sediment deposition depth at one side was more than at the other side, for example section S206, S232 and S253. It is also easy to understand: when the water level is high in the meandering river channel, the water flow axis tends to go straight, causing the flow to be near the concave bank, so the sediment is deposited near the convex bank(Ali et al. 2015). As shown in sections S206 and S232, the sediment is mainly deposited at the left side of the channel, which changes the cross-section of the channel to produce a new deep channel and a new river bank. This will cause some new problems, for shipping security, ecogeomorphology, riverside planning and protection. This phenomenon should be considered further (Andrea et al. 2016). It also shown that there was little deposition in the fluctuating backwater reaches, particularly there is no deposition in the tail of the fluctuating backwater reaches.



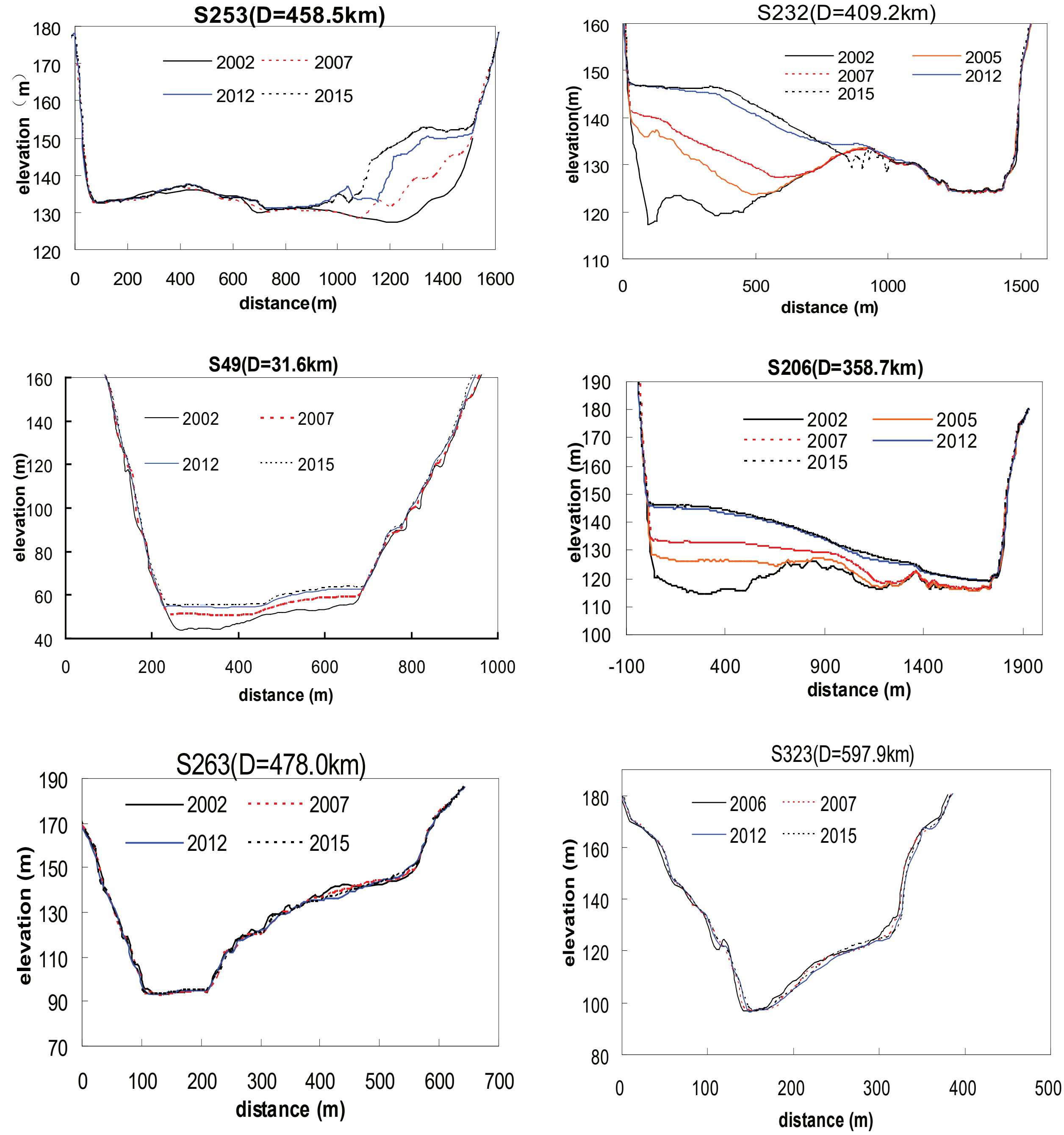


Figure 10 : The deposition in some typical sections, D is the distance to the TGD

5. CONCLUSION

As the biggest hydropower reservoir in the world, sedimentation in the TGR is still a controversial issue. Sedimentation is very important for storage capacity, reservoir function and reservoir life. Using measured hydrological and terrain data before and after the TGR's impoundment, this study has investigated the variation of the runoff and sediment load transported into the TGR. The study has discussed some hot issues concerning the TGR sedimentation raised previously by other researchers.

(1) The analysis of the field observed data from three hydrological stations during the years 1956-2016 shows that there is no obvious change in the annual runoff, however, there is a significant decrease in the suspended sediment and bedload sediment transport in the years after the TGR was impounded. This decreasing trend is mainly due to the changes in the conditions upstream of the TGR and will continue in the future. This is a good indication for the TGR in terms of the performance of its comprehensive function and extension of reservoir life.

(2) In the years 2003-2016 the total deposition volume in the TGR is 1.66 billion m^3, the average sediment delivery ratio of TGR was 24%. The annual loss in storage capacity was 0.3%, which compared to other large scale dams around the world is very low.

(3) Sediment is mainly deposited in the wide sections of the permanent backwater areas, small amounts are deposited in the narrow sections, and it is unusual for sedimentation to be deposited in the tail of the fluctuating backwater reaches. The silt sediment median particle size (d50) was less than 0.01mm in almost the whole of the 400km long reach, which was not expected when the TGD was designed.

(4) Downstream of wide meandering river channels in the permanent backwater area, heavy deposition at one side of the cross-section may cause some new problems. To minimize the adverse effects, further research should be carried out.

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