Spatial and temporal changes of sedimentation in Three Gorges Reservoir of China

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Abstract

This study examined the temporal trend of sedimentation in China's Three Gorges Reservoir (TGR) from compiled sediment data at multiple temporal scales. Based on decade-averaged annual sediment loads, a decreasing trend of sediment supply between 1950s and 2000s was found, with a lower-than-expected mean sedimentation rate. From 2003 to 2013, the annual sediment supply generally decreased, with the annual sediment deposition rate being about 50% less than that predicted with prior numerical models. The reduced annual sedimentation rate was attributed to (relatively) small dam building within the upstream watershed, conservation activities and sand/gravel mining. Morphological changes at two cross sections within the TGR between 2003 and 2013 indicated that sediment deposition caused only limited bed accretion along the main course of the TGR. In the tail area of the TGR, where sediment transport ceases first, the sedimentation occurring between 2004 and 2013 was insufficient to impede navigation. These results indicate that at least as a first approximation sedimentation in the TGR is well controlled, making it a subdued 'river dragon'.

Key words

sediment supply, sedimentation, Three Gorges Reservoir, Upper Yangtze River.

INTRODUCTION

Three Gorges Project, begun in 1993 and completed in 2006, dams China's Upper Yangtze River, forming probably the world's most controversial reservoir, the Three Gorges Reservoir (TGR). The reservoir is bounded by upstream Chongqing City and downstream Yichang City along the main Yangtze River (Fig. 1). It has a water storage capacity of 39.3 km^3 and a filled water surface area of 1084 km^2 (Avakyan & Lakovleva 1998; Pelicice *et al.* 2014). The TGR generates 22 000 MW of power, being the largest hydroelectric power plant in the world. Geomorphologically, the TGR receives water and sediment from the entire Upper Yangtze River Basin (UYRB), which consists of several subwatersheds associated with the main tributaries of the Upper Yangtze River (Fig. 1). The Jinsha (dark pink in Fig. 1) and Jialing (green in Fig. 1) subwatersheds supply the largest quantity of sediment to the TGR. Although the UYRB contains largely hilly terrains, it has been heavily used for intensive agriculture and urbanization to support one-eighth of the country's population. Thus, the TGR is directly affected by these anthropogenic activities, and its construction has raised a series of environmental issues that have been debated both domestically and internationally.

One controversial issue is whether or not sedimentation will quickly fill the reservoir after its completion, similar to what happened with the Sanmenxia Reservoir, which was built on the middle reach of Yellow River in the late-1950s (Jiang & Fu 1998; Mei & Dregne 2001). Long before the TGR was constructed, the perception that the gravel-bedded Upper Yangtze River would supply to the TGR sufficient coarse sediments to cause reservoir dysfunction soon after its completion was pervasive in the public eye (Dai *et al.* 1994). In contrast, physical experiments and sediment modelling predictions concluded that (i) continuous sedimentation would stop about 100 years after the dam was completed; 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 normal reservoir operation (Lin *et al.* 1993; Qian *et al.* 1993; Wang *et al.* 2013).

Nevertheless, doubts still remain about how much sediment will be deposited in the TGR. Barber and Ryder

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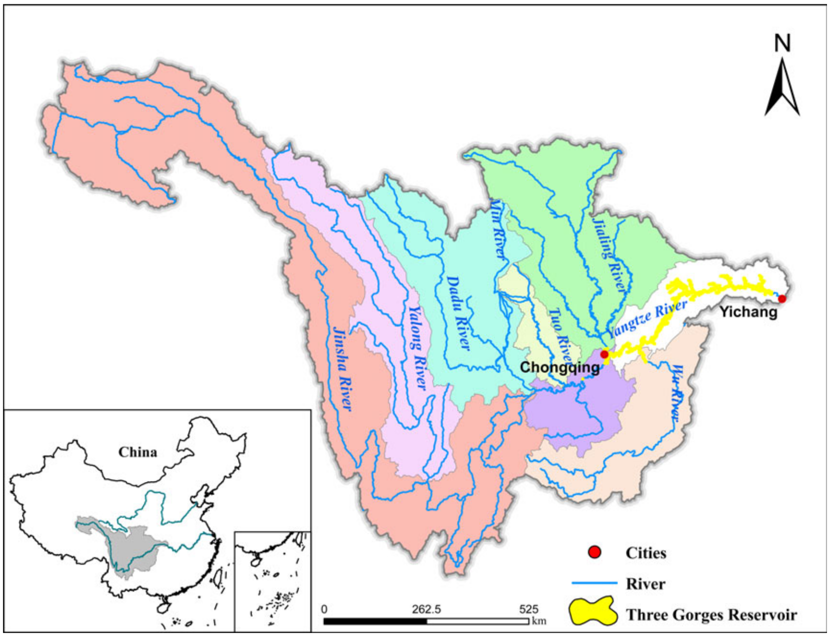

Fig. 1. Upper Yangtze River Basin (UYRB) and location of Three Gorges Reservoir (TGR), Upper Yangtze River and main tributaries (UYRB contains area surrounding TGR and seven other subwatersheds represented in different colours).

(1994), for example, contended that because the models for predicting reservoir sedimentation were one-dimensional, they failed to characterize the complex three-dimensional processes of sediment transport. Luna Leopold, a renowned American fluvial geomorphologist, raised a concern on the basis of uncertainties of future sediment prediction over 50 years of reservoir operation (Leopold 1998). Concerns about how deposited coarse sediment might handicap navigation and lead to flooding in the tail section of the reservoir (e.g. Chongqing City and its neighbouring area in Fig. 1) also have been discussed in public debates for decades (Dai *et al.* 1994). Since the reservoir was impounded in 2003, however, the TGR has in fact not encountered severe sedimentation problems. Furthermore, relevant studies have indicated that there exists a decreasing trend of sediment supply to the TGR (Wang *et al.* 2007; Xiong *et al.* 2009; Lu *et al.* 2011; Xu *et al.* 2013), suggesting the sedimentation rate would be reduced.

Nonetheless, since the full impoundment of the reservoir in 2010, doubts regarding sedimentation in the TGR still persist in public media, examples being Probe International (Dai 2010), Facts and Details (Hays 2011), News China (Wang *et al.* 2010) and China National Geographic (Fan 2014). Although predicting exactly what will happen 100 years from now in the TGR is impossible because no theory that can precisely predict sediment load under a given water discharge and sediment component currently exists (Simons & Senturk 1992), assessing the quantities of available sediment data before, during and after the dam building does provide a means of piecing the temporal trend of sediment changes that may serve as accurate evidence to address, and perhaps close, the debates. Studies on sediment transport in the Upper Yangtze River and its main tributaries are not new (Lu & Higgitt 2001; Yang *et al.* 2002; Zhang *et al.* 2006; Dai *et al.* 2008; Xiong *et al.* 2009; Xu & Milliman 2009; Lu *et al.* 2011). In these studies, however, sediment data were obtained at different sets of hydrological sites within the river system under varying times. Thus, the results are not comparable.

This study compiles sediment transport and associated data at multiple temporal and spatial scales to highlight the dynamic patterns of sediment movement above and within the TGR, as follows: (i) decadal-averaged sediment loads from 1950s to 2000s; (ii) annually averaged sediment loads between 2003 and 2013; (iii) monthly sediment loads in 2005, 2007 and 2013; (iv) temporal changes of net sedimentation rates in three segments of the reservoir tail; and (v) channel morphological changes along channel cross sections within the reservoir. From these measured (not modelled) data, this study illustrates the temporal trend of average reservoir sedimentation, its spatial and temporal variations, and the tendency of sedimentation in the backwater zone.

METHODOLOGY

Four types of field-measured data were compiled at different spatial and temporal scales from China's River Sediment Gazette published between 2002 and 2013, and a recently published summary report on sediment issues in the TGR (Sediment-Panel 2014). The first type of data consists of decade-averaged annual run-off and sediment loads from the 1950s to 2000s entering and leaving the TGR. The data for the 1950s were calculated using the data obtained from 1955 to 1960, whereas the 2000s data were the data collected between 2001 and 2007 (Table 1). As similar decadal data were not available from the Qingxichang and Huanglingmiao hydrological stations (Fig. 2), the input sediment load for each decade was calculated as the sum of those reported at the Cuntan and Wulong stations, and included the sediment load from higher-elevation areas around the TGR. Data from the Yichang station were used to represent the decadal output sediment load (Fig. 2).

The second type of data consists of calculated annual total sediment load supplied to and transported out of the TGR between 2001 and 2013. The input data for different time periods were calculated using data from different sets of the hydrological stations to achieve a high accuracy. Before 2003, when the reservoir impoundment first began, the tail of the reservoir was far downstream of the tributary (Wu River). Thus, input data on sediment inputs to the TGR were best represented by those obtained from the Qingxichang station, located furthest upstream (Fig. 2). From 2003 to 2007, as the reservoir filled and its water level increased to 156 m above sea level, the sediment transport to the then-upstream expansion of the reservoir tail was best reflected by the sum of the sediment data from both the Cuntan and Wulong stations (Fig. 2). Since 2008, sediment input to the further-upstream extended reservoir tail was most appropriately reflected by the sum of sediment data from the Zhutuo, Beibei and Wulong stations (Fig. 2).

The input sediment data for all 13 years did not include the quantity of sediment supplied from higher-elevation areas around the TGR. Data from these upland areas, however, were incorporated into the decade-averaged annual loads (Sediment-Panel 2014). Examination of the temporal trend of the per cent ratio of these loads to the total input sediment loads (Fig. 3) indicated that the upland percentage began to decrease since the 1980s and, by the 2000s, it was only about 6% of the total. Thus, the annual input sediment load was increased by 6% to account for this component of the annual sediment supply.

Table 1. Decadal-averaged annual Three Gorges Reservoir run-off and sediment input and output

	Run-off ($\times 10^{11}$ m^3 year^{-1})	Sediment input ($\times 10^8$ t year^{-1})	Sediment output ($\times 10^8$ t year^{-1})
1950s	4.14	5.25	5.25
1960s	4.55	5.56	5.56
1970s	4.19	4.8	4.8
1980s	4.43	5.54	5.41
1990s	4.34	4.17	4.17
2000s	4.00	2.33	1.23

Although the annual sediment output data from the TGR were available for both the Yichang and Huanglingmiao stations, those from the latter station were more accurate because it is located closer to the dam (Fig. 2). Comparing the loads from both stations, however, indicated (Fig. 4) that the difference was negligible. Thus, data from the Yichang station were selected for this study to be consistent with the decadal sediment loads (Table 2). Furthermore, monthly sediment load deposited in the TGR for 3 years was compiled (i.e. 2005, 2007 and 2013) to indicate seasonal sediment dynamics after three reservoir expansions occurring in 2003, 2006 and 2010.

The third type of data consists of channel morphological data measured at two cross sections in the main channel of the TGR. Two sets of cross section profiles between 2003 and 2013 were compiled for stations located 5.6 and 160.1 km upstream of the dam (cross sections 1 and 2, Fig. 5). These data illustrated spatially varied sediment deposition within the TGR main section.

The fourth type of data shows the spatial and temporal variations of sediment movement in the tail of the backwater zone, the 25-km upper-confluence and 15-km lower-confluence segments along the Yangtze River, as well as a 20-km segment at the end of the Jialing River that merges into the Yangtze River (Fig. 5). These data include the following: (i) two sets of cross section profiles between 2004 and 2013, being located 605 and 617 km upstream of the dam (cross sections 3 and 4; Fig. 5), respectively; (ii) longitudinal profiles along the main channel of the reservoir tail over the same time period; and (iii) the annual net sediment changes of the three segments in the tail section of the backwater zone over the same time period (Table 2).

RESULTS AND ANALYSIS

Temporal pattern of sediment input and output at the decadal scale

The sediment load entering the TGR reach between the 1950s and 1980s balanced the load leaving the TGR, varying slightly around the multidecade mean of 5.27×10^8 t year^{-1} (Table 1). From the early-1990s when dam construction commenced to the late-2000s, the sediment load to the TGR decreased dramatically, while the decadal-averaged annual run-off remained close to the

Fig. 2. Locations of hydrological stations used for decadal and annual run-off and sediment data collection and calculations (not to scale; the two cities link these locations to the Three Gorges Reservoir shown in Fig. 1).

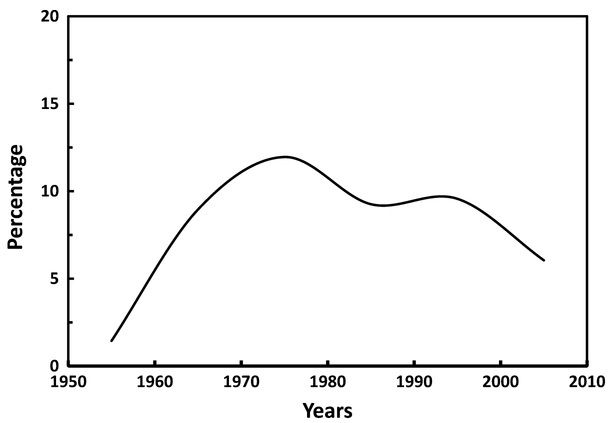

Fig. 3. Ratio (in percentage) of decade-averaged annual sediment load supplied from higher-elevation area around the Three Gorges Reservoir (TGR) to that from the TGR upstream area.

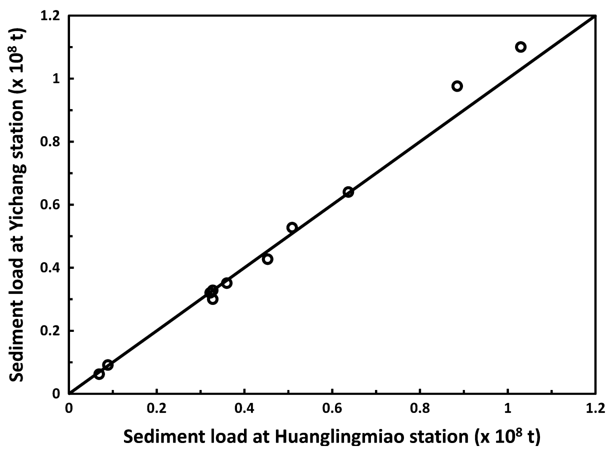

Fig. 4. Comparison of sediment loads between two hydrological stations downstream of Three Gorges Reservoir (solid line represents 1:1 line).

multidecade mean of 4.27×10^{11} m^3 year^{-1} (Fig. 6). The decadal mean annual sediment load during the 2000s was 2.33×10^8 t year^{-1}, less than half of the previous multidecade mean value. The cause of this obvious reduced sediment load was likely attributable to the decadal implementation of rigorous water and soil conservation policies in the UYRB uplands, and construction of more than 60 small dams along the main upstream Yangtze River and its tributaries (Yang *et al.* 2006; Wang *et al.* 2007; Wei *et al.* 2011; Xu *et al.* 2013).

During the same two decades, the sediment output from the TGR decreased even faster, with only a lower decadal mean annual sediment load of 1.23×10^8 t year^{-1} in the 2000s. The additional sediment reduction was attributed to sedimentation in the TGR since its initial impoundment in 2003. The decade-averaged annual sediment deposition rate was 1.10×10^8 t year^{-1}, three times smaller than the 3.55×10^8 t year^{-1} predicted with numerical models under the extreme weather condition (Yang *et al.* 2009). In other words, the numerical models significantly overpredicted the mean annual sedimentation rate in the reservoir. Assuming the same quantity of annual sediment deposition occurs in the following years, the models predicted the bed of the TGR will be raised to a level close to 145 m above the sea level 100 years after the dam was built (Wang *et al.* 2013). Thus, the actually much lower decadal-averaged annual sedimentation rate suggests that reservoir sedimentation will not affect the water storage capacity of the TGR over the long term, even with severe weather.

Annual changes in sediment inputs and outputs during and after the building of the TGR

The sediment input ostensibly decreased from 2001 to 2003 (Fig. 7). The sediment input varied from year to year between 2003 and 2013, but exhibited a decreasing trend with an average annual decreasing rate of 8.38×10^6 t year^{-1} (Fig. 7). This decrease is again likely attributable to the continuous influence of water and soil conservation policies and dam building activities within the UYRB.

The annual sediment deposition in 2003 was significantly larger than for 2001 and 2002, probably being related to the first reservoir impoundment, which raised the water level and caused a slower water flow velocity

Table 2. Annual total sediment and annual net sedimentation of Three Gorges Reservoir

	Annual total sediment ($\times 10^8$ t)		Annual net sedimentation ($\times 10^4$ m^3)		
	Input	Output	Upper main segment	Lower main segment	Jialing tributary segment
2001	3.14	2.99	-	-	-
2002	2.43	2.28	-	-	-
2003	2.10	0.98	-	-	-
2004	1.66	0.64	−77	−332	−100
2005	2.54	1.10	−332	89	−62
2006	1.12	0.09	60.4	−34.8	−15
2007	2.20	0.53	−122.2	71.1	−58.4
2008	2.18	0.32	121.9	224.5	14.9
2009	1.83	0.35	−78.2	−52	−33.4
2010	2.29	0.33	135.4	130.8	79.3
2011	1.02	0.06	−1.3	−130	−29.7
2012	2.19	0.43	−252.9	94.1	38.1
2013	1.27	0.30	−438.9	−104.7	−102.7

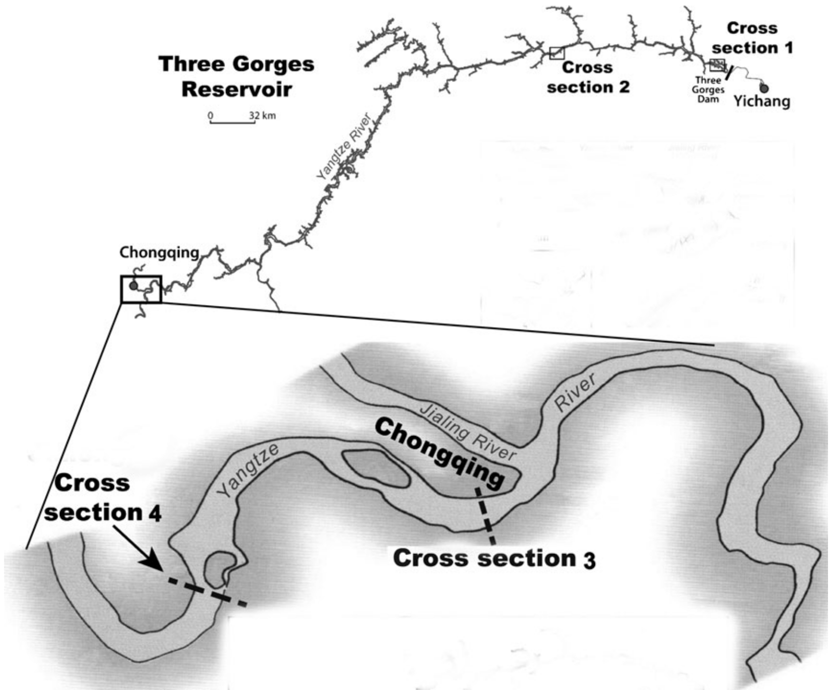

Fig. 5. Tail section of Three Gorges Reservoir backwater zone and its three (upper-confluence, lower-confluence and Jialing tributary) segments (time series of profiles along four marked cross sections between 2003 and 2013 are shown in Figs 8, 10, respectively).

and resultant sediment deposition. Similarly, between the second and final reservoir impoundment in 2006 and 2010, the raised water levels also relate to an increased sedimentation trend, with a mean of 1.47×10^8 t, which is only 41% of the predicted value (i.e. 3.55×10^8 t). After 2010, the sediment input followed a decreasing trend with a mean of 1.20×10^8 t, suggesting the reservoir sediment deposition continuously decreased even during the 4 years when the TGR was regularly operated. Overall, the annual quantity of reservoir sediment deposition was much less than the predicted value (Fig. 7).

Although increased landslides and rock falls caused by up to 30-m water level oscillations every year (Xu *et al.* 2013) and provided additional sediment to the TGR,

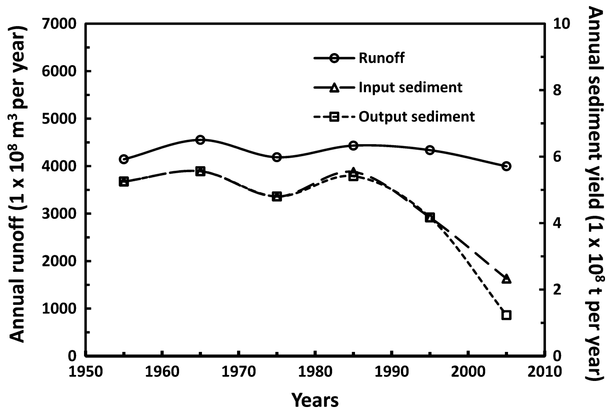

Fig. 6. Decade-averaged annual run-off and sediment input and output of Three Gorges Reservoir.

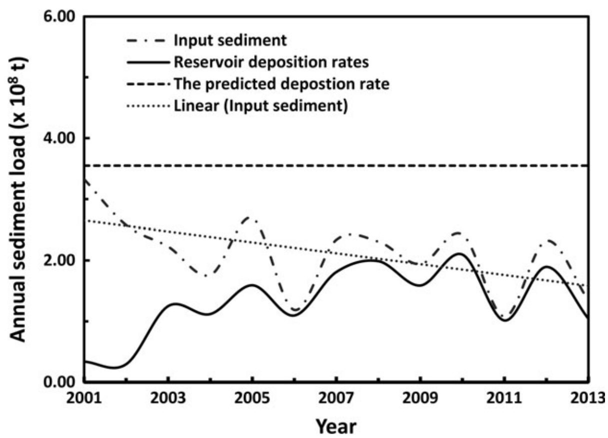

Fig. 7. Annual quantity of sediment input to and deposition within Three Gorges Reservoir (TGR) (horizontal dashed line represents predicted quantity of sedimentation used to design TGR).

the quantity of the additional sediment from these sources was so small that it was insufficient to affect the decreasing annual sedimentation rate trend. These additional mass movements will gradually subside, as the reservoir banks adapt to the new hydrological condition (Zhang 2009).

As the TGR has an elongate shape, sediment deposition must vary spatially and might locally comprise the reservoir water storage capacity. One year after the first impoundment of the TGR in 2003, the channel bed raised significantly, with a maximum elevation increase of 40 and 20 m at cross sections 1 and 2, respectively (Figs 5, 8). Between 2004 and 2010, when the reservoir was not full, the increased bed elevation along both cross sections was limited. During normal reservoir operation at full capacity (2011–2013), both cross sections changed very little (Fig. 8). These temporal cross section changes also

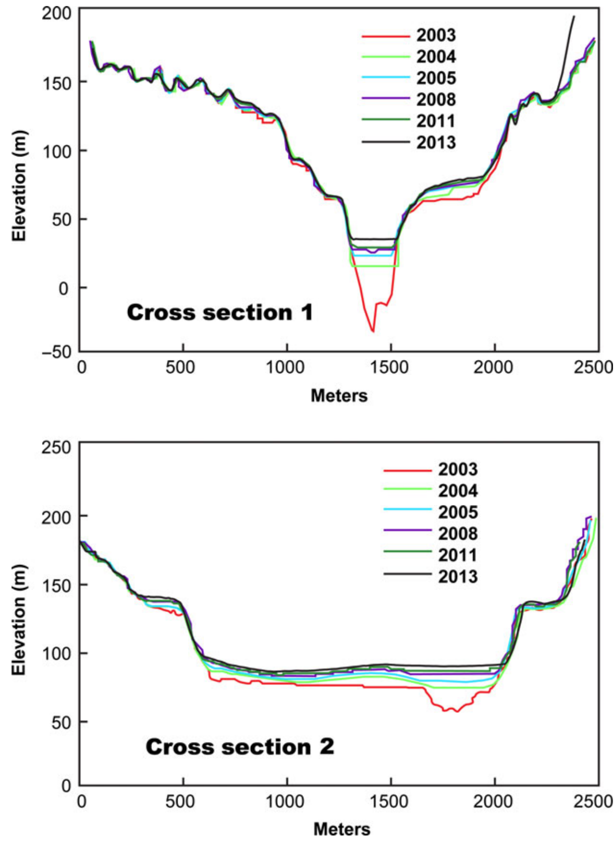

Fig. 8. Time series of cross section profiles between 2003 and 2013 within main Three Gorges Reservoir as shown in Figure 5.

indicated that spatially varied sediment deposition could not threaten the life expectancy of the TGR.

Changes of sediment deposition in the tail of the backwater zone

Erosion occurred at the three segments located near the reservoir tail (Fig. 5) with the calculated average annual net sedimentation from 2004 to 2005 being -204.5, -121.5 and -81×10^4 m^3, respectively. During this period, the highest reservoir water level (135 m) after the first impoundment in 2003 did not extend to these tail segments. Consequently, sediment transport in these segments was mainly controlled by natural fluvial processes. Between 2006 and 2009, when the water level increased to 156 m, the rising backwater of the TGR covered part of this tail section, increasing the sediment deposition, as evidenced by a smaller mean annual erosion in the upper and tributary segments of -4.5 and -23.0×10^4 m^3, respectively, and deposition in the lower segment of 52.2×10^4 m^3. In 2010, the full impoundment (175 m) covered the entire tail section, leading to sediment deposition in all three segments of 135.4, 130.8 and 79.3×10^4 m^3 for the upper, lower and tributary

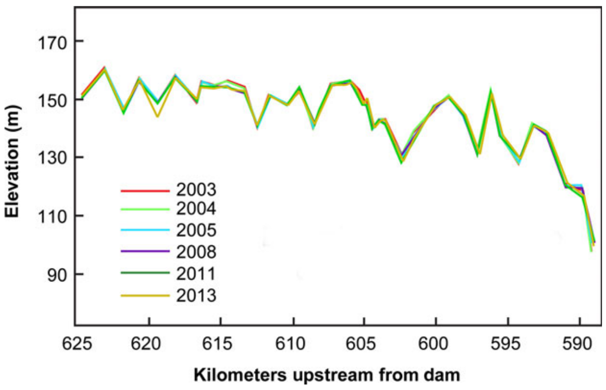

Fig. 9. Time series of longitudinal profile representing elevation changes of tail section within Three Gorges Reservoir backwater zone.

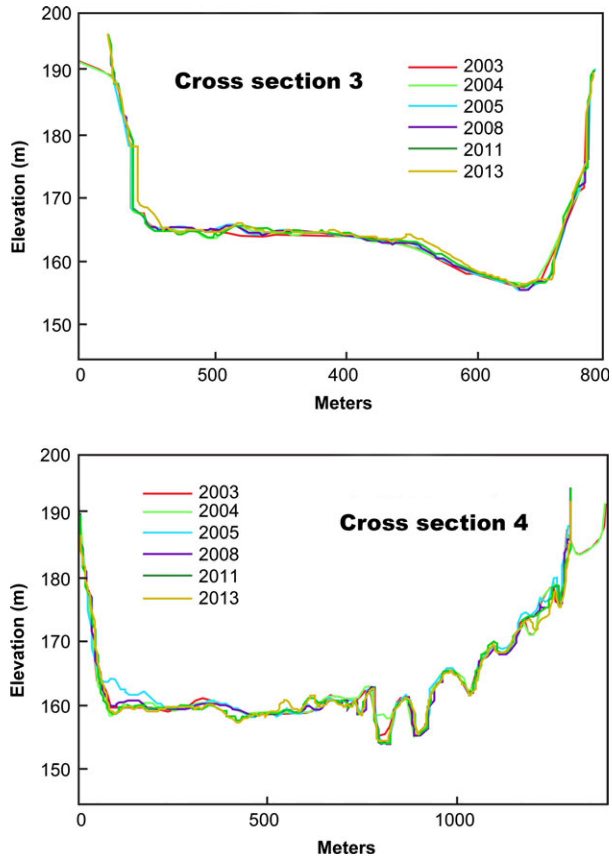

Fig. 10. Time series of cross section profiles between 2003 and 2013 within Three Gorges Reservoir tail section as shown in Figure 5.

segments, respectively (Table 2). During subsequent normal reservoir operation between 2011 and 2013, erosion again dominated over deposition, with the annual net sedimentation being negative at −231.0, −46.9 and -31.4×10^4 m^3, respectively (Table 2).

Comparison of the longitudinal profile along the main Yangtze River within the tail section (Fig. 9) indicated that the channel bed profile essentially remained the same between 2003 and 2013, except for minor local degradation and aggradation. Temporal profile changes at cross sections 3 and 4 (Figs 5, 10) also exhibited no significant elevation changes. The tail section of the TGR was not altered significantly by sedimentation after the dam was constructed.

DISCUSSION

Sediment transport obviously controls a reservoir's lifespan (Tarela & Menéndez 1999; Morris *et al.* 2006; Zeleke *et al.* 2013; Arunbabu *et al.* 2014). Analysis of measured sediment data in and out of the TGR indicated that sedimentation within the TGR is far less than that projected by numerical models utilized prior to when the dam was built. The actually reduced reservoir sedimentation, compared to the projected value, is likely attributable to the decreased sediment supply from UYRB. Studies on vegetation-erosion dynamics indicated that soil erosion on the hilly areas of UYRB may be most efficiently controlled by reforestation and construction of check dams in streams (Wang *et al.* 2013). The Chinese government initiated a series of environmental programmes in the late-1980s to reduce and improve the increased soil erosion in UYRB resulting from increased population and deforestation attributable to the earlier so-called household responsibility system (Yang *et al.* 2009). Examples of these programmes include planting trees and fruit orchards on steep bare lands, using conservative (contouring) tillage, terracing farm lands on hill slopes and protecting forest by designating non-grazing conservation lands (Xiong *et al.* 2009; Wei *et al.* 2011). Furthermore, additional programmes were begun after 1998, examples being the green-to-grain programme and natural forest conservation (Fu *et al.*, 2010). These programmes have effectively reduced soil erosion from hill slopes within UYRB over the past decades. A number of reservoirs of variable sizes also have been constructed within all the UYRB subwatersheds, trapping a significant proportion of the sediment transported through the main tributaries draining to the TGR.

The results of these activities may be further illustrated with sediment data from the Jingsha Jiang and Jialing Jiang subwatersheds, which cover 64% of UYRB and contribute 77% of the total sediment load supplied from UYRB to the TGR (Wei *et al.* 2011). Between 1990 and 2004, about 40% of the lands suffering soil erosion in Jialing Jiang subwatershed was treated, while about 8% of these lands in the Jinsha Jiang subwatershed received various management practices (Xiong *et al.* 2009). From the 1980s to 2005, about 59 medium and large reservoirs also were constructed on rivers within the Jinsha Jiang subwatershed, leading to 84.32×10^8 m^3 of reservoir storage capacity (Wei *et al.* 2011). During the same time period, 74 reservoirs were constructed within the Jialing Jiang subwatershed, providing another 81.24×10^8 m^3 of reservoir storage capacity. The less intensive watershed management practices, and the smaller number of dams built in the Jinsha subwatershed, are consistent with its smaller degree of sediment reduction from the 1980s (Fig. 11). As these two subwatersheds originally exhibited the highest degrees of soil erosion (Xu *et al.* 2004), their reduced sediment loads suggest the general reduction of the decadely averaged annual sediment load now occurs from the entire UYRB, a finding consistent with the decreasing trend of sediment supply to the TGR during the same time period (Fig. 6).

Specifically, the annual sediment concentration in the Jinsha Jiang subwatershed from 2002 to 2013 exhibited a general decreasing trend, with a means value of 0.936 kg m^{-3}. The total sediment input to the TGR during the same period exhibited a similar decreasing trend, although its values were relatively high in some years (Fig. 7). The Jialing subwatershed exhibited an increasing trend, although its mean value of 0.438 kg m^{-3} is still much less than that exhibited before 1990 (Fig. 11). With plans to construct more dams within UYRB (Xu *et al.* 2013), even more sediment transported through UYRB will be trapped, resulting in a continuous decrease in the sediment supply to the TGR in the future. Thus, it follows that sediment deposition in the TGR will still significantly less than that predicted for the foreseeable future.

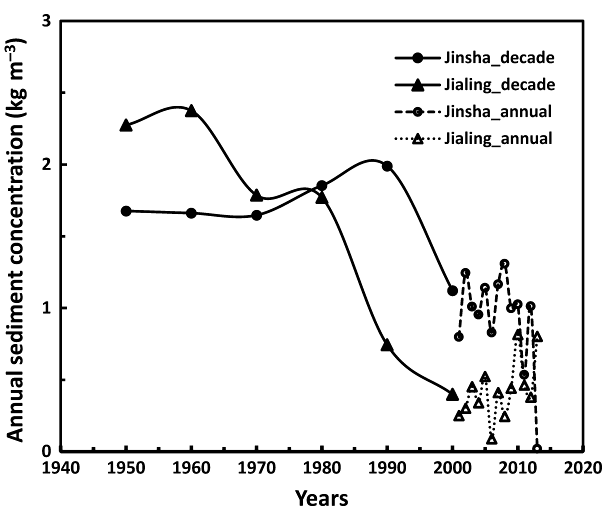

Fig. 11. Temporal changes of annual sediment concentration both over decades and between 2001 and 2013 in two most severely eroded Three Gorges Reservoir subwatersheds.

It is noted that increased road construction and unprecedented expansion of towns and cities in central China also have greatly increased demands for sand and gravels to make concrete. The channel banks and bed of the Upper Yangtze River and its tributaries have become cost-effective sources for such materials. The average annual sediment excavation from the Upper Yangtze River in the 1990s was about 30×10^6 t year^{-1} (Wang *et al.* 2007). In the 2000s, the average annual sediment excavation from even a short reach near the junction between the Upper Yangtze and Jialing River (Fig. 1) totalled about 2×10^6 t year^{-1} (Xiong *et al.* 2009). This direct removal of sediment from the channels obviously also reduced sediment transport and deposition to the TGR, particularly in the tail section.

As a final observation, climate models have predicted a trend of increasing global average temperature (IPCC 2007). If this trend continues, more extreme floods will likely occur in the future (Jena *et al.* 2014), which may induce more sediment supply to the TGR and to reservoir sedimentation. Nevertheless, the TGR was designed to accommodate continual sedimentation rates measured during a historical 1954 flood event with a recurrence interval of 40 years (Wang *et al.* 2013). It is anticipated that the overengineering of the dam with respect to sedimentation will accommodate possibly more extreme floods in the future, along with management of the upland areas by the Chinese government, suggesting climate change should not seriously impact the TGR storage capacity.

CONCLUSIONS

This synthesis of sedimentation history in the TGR reveals two major findings. The first is that the sediment supply to the TGR has decreased since the 1990s and continues to decrease even after completion of the TGR in 2010. This decreased sediment supply is attributable to the following: (i) continuing dam construction in the Upper Yangtze River and its tributaries; and (ii) implementation of soil and water conservation practices in the UYRB. The second is that the annual quantities of sediment deposition in the TGR from 2003 to 2013 were significantly less than the expected quantity, thereby positing no threats to river navigation in the tail of the reservoir. The present study clearly suggests the TGR will not be filled with sediment in the foreseeable future. Although the Three Gorges Reservoir still faces such environmental challenges as degraded water quality and fragmentation of ecosystems, the issue of sedimentation appears to be well controlled.

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