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Impacts of large dams on downstream fluvial sedimentation: An example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River)

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SUMMARY

Under the influence of climate and human activities, fluvial systems have natural ability to make adjustments so that the river hydrology, sediment movement, and channel morphology are in dynamic equilibrium. Taking the Changjiang (Yangtze River) for example. In the early stages after the Three Gorges Dam (TGD) began operational ten years ago, the suspended sediment content (SSC) and fluxes in the middle and lower reaches of the river decreased noticeably. At present, they appear to be in a stable state on the decadal scale. Although the river runoff has not shown any trends, the water level in the river decreased appreciably in time. In the meantime, channel down cutting along the thalweg almost existed throughout the river course. The riverbed has turned from depositional before the dam construction to erosional afterwards. In other words, the riverbed had turned from being sediment sinks to sediment sources. In the main channel of the Changjiang between Yichang and Nanjing, a distance of 1300 km, the riverbed sedimentation mode displays strong, intermediate, and weak erosion depending on the closeness to the TGD.

1. Introduction and background

Fluvial sedimentation is the result of the interactions among river runoff, sediment supply, basin geology and regional structure in the past and present (Young et al., 2001). In response to the forcing, erosion and deposition occurs along the fluvial systems. River dams store water and intercept large amount of sediment and cause changes in the downstream river hydrology and the sediment carrying capability of the river, leading to the alteration of the natural behavior of rivers (Graf, 2006; Milliman and Farnsworth, 2011). This is a worldwide phenomenon.

Downstream from the Aswan High Dam on the Nile severe down cutting occurred on river dikes and the channel (Aleem, 1972; HRI, 1987). The construction of the Iron Gate Dam on the Danube caused permanent erosion and unstable riverbanks and the generation of numerous islands in the river channel (Bondar, 2000; Panin, 2003). Dams in the Ebro River basin seriously reduced the river sediment load from 15×10^6 t/yr in the beginning of the 20th century to the present day 0.2×10^6 t/yr. This reduction not only triggered the recession of the Ebro Delta, but also made the riverbed sediments to become coarser (Batalla, 2003; Batalla et al., 2004). The fluctuation rate of the thalweg of the Mississippi River was 6.6 m/yr before the dam construction and 1.8 m/yr afterwards. The riverbed slopes and stream power in the lower reaches also increased (Shields et al., 2000; Harmar et al., 2005). Williams and Wolman (1984) conclude that after dam constructions, 21 rivers in North America displayed rapid riverbed erosion. Five Italian rivers (the Tagliamento, Piave, Brenta, Trebbia, and Vara) exhibited channel narrowing, decrease of braiding intensity, and incision up to 4–5 m in their lower reaches as the result of human activities especially the construction of dams (Surian and Rinaldi, 2004). On the other hand, after the construction of the Flaming Gorge Dam on the Green River, which is a tributary of the Colorado River, the downstream riverbed showed noticeable armoring instead of incision below the dam at any location (Grams and Schmidt, 2005). Other studies also indicate that under the combined influence of the climate, the change of land use and damming, downstream riverbed might experience deposition/erosion or channel narrowing and deepening (Erskine, 1996; Prosser et al., 2000; Young et al., 2001). Therefore, the impact on river dams on river basins has become a research topic in the general theme in the Anthrpocene (Vegas-Vilarrúbia et al., 2011; James and Marcus, 2006).

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At present there are over 45,000 dams in major rivers in the world. These dams have caused the reduction on the fluvial sediment and the river runoff and induced geomorphologic changes in the lower reaches of the river. Therefore, they have become the common focus in the research of fluvial sedimentation and morphology (Graf, 2006; Milliman and Farnsworth, 2011; Syvitski et al., 2005).

The largest dam in the world, the Tree Gorges Dam (TGD), is built in the upper reaches of Asia's largest river, the Changjiang (Yangtze River) (Fig. 1A and B). Since the impoundment began in 2003, the dam has influenced the environment in the middle and lower reaches of the river. However, the recent research on the TGD's impact is mainly in the changes in the material fluxes in the middle and lower reaches and water exchanges between the river and several large lakes (Xu and Milliman, 2009; Dai et al., 2011a; Yang et al., 2011; Yu et al., 2011; Guo et al., 2012; Sun et al., 2012). Little attention has been given to the sedimentation process in the river channel.

The impoundment of TGD caused the drop in the Changjiang's mean yearly sediment load from 418×10^6 t/yr to be less than 200×10^6 t/yr (Dai et al., 2011b). This reduction might have significant impacts on the 1000 km stretch of the river channel in the middle and lower reaches of the river. Although Chen et al. (2011) has done a preliminary study on the suspended sediment dynamics of the Changjiang based on the records between Yichang and Hankou (a distance about 600 km), they have not considered the erosion/deposition characteristics of channel cross-sections. It is of great typological value to study the river-wide response of such a large fluvial system to the water and sediment storage by the TGD. Therefore, the objectives of this study are (1) to quantify the erosion/deposition of the channel, (2) to identify factors affecting the sedimentation of the channel, and (3) to construct a box model for the sediment budget of the river channel to illustrate the sediment dynamics in the middle to lower reaches of the system. The focused segment of the river is between the TGD and the limit of the tidal influence at Nanjing, a length of 1300 km.

2. Materials and methods

2.1. Data and methods

The middle reach of the Changjiang is defined between Yichang and Hankou, and down-river from Hankou is defined as the lower reach of the river. The landward limit of the tidal river of the Changjiang is located at Datong and Nanjing during the flood and dry seasons, respectively (Fig. 1A and B). In this study, our data is composed of five groups. The first group included the mean yearly river runoff and SSC between 1955 and 2010 at the following eight gauging stations as reference stations: Yichang, Zhicheng, Shashi, Luoshan, Hankou, Jiujiang, Anqing, and Datong. We also collected daily water level of the river between 2000 and 2010 at the same eight stations (Fig. 1B).

The second group included the mean yearly-suspended sediment fluxes since 1982 at the confluences of Dongting Lake (Chenglingji), Poyang Lake (Hukou), and Hangjiang (Huangzhuang). The third group included the thalweg depths between Yichang and

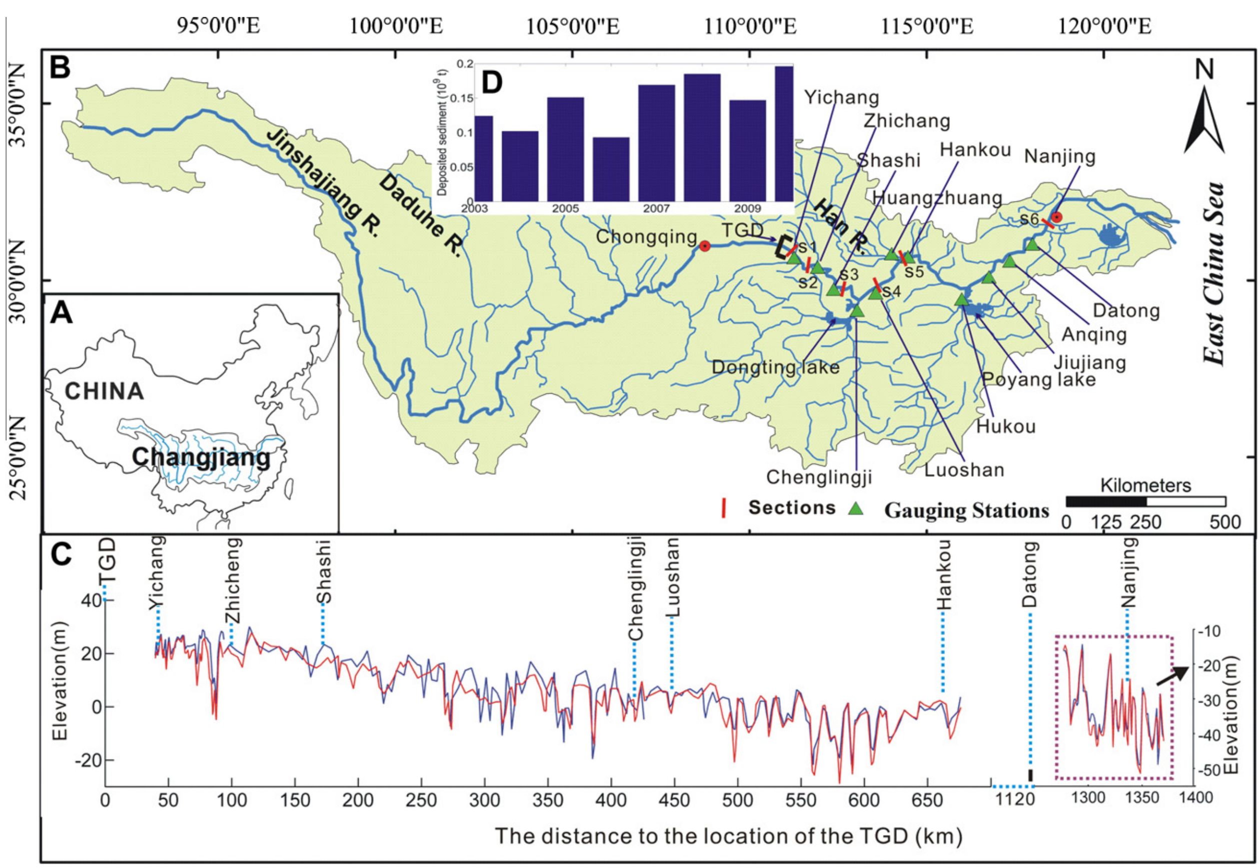

Fig. 1. (A) Map of China shown the area of the Changjiang basin, (B) enlarged map of the Changjiang basin showing the locations of the TGD, and reference gauging stations, and the six cross-sections, (C) depth of the thalweg (in elevation) along the course of the river. The blue curves were earlier surveys (September 2002 for Yichang–Zhicheng; October 1998 for Zhicheng–Chenglingji; October 2001 for Chengliji–Hankou; November 1998 for Nanjing); the red curves were later surveys (October 2010 for Yichang–Zhicheng; October 2009 for Zhicheng–Chengliji; November 2011 for Chengliji–Hankou; May 2006 for Nanjing) and (D) yearly amount of sediment intercepted by the TGD. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Survey data series of River thalweg profiles and cross-section.

River talweg profile heights	Yichang–Zhicheng	Zhicheng–Luoshan	Luoshan–Hankou	Nanjing segment	/	/
Cross-section heights	S1, S2	/	/	S6	S3	S4, S5
Surveyed time	9.2002, 10.2010	10.1998, 10.2009	10.2001, 10.2010	11.1998, 5.2006	1.1998, 9.2009	10.2000, 11.2010

Hankou and at Nanjing and the representative river cross-sections at six locations that were surveyed intermittently between 1998 and 2010 (Fig. 1C, Table 1) (Bulletin of China River Sediment, 2006, 2009, 2010, available on http://www.cjh.com.cn).

The fourth group included data of the maximum spring tidal level and yearly mean tidal range (Fig. 1B) at Nanjing between 1955 and 2008, and the amount of intercepted sediment by the TGD between 2003 and 2010. All the above original data came from the Changjiang Water Resources Commission (CWRC) (available on http://www.cjh.com.cn).

The fifth group contained the amount of riverbed erosion/deposition between Yichang and Hukou (950 km long) surveyed between 1981–2002 and 2002–2010, and the Nanjing segment of the river between 2002 and 2006, which were obtained from published literatures (Xu, 2012; Yang et al., 2009). The scale for the surveyed river-channel charts of 1981, 2002, 2006, and 2010 was 1:10000.

Based on the raw data, yearly mean river discharge, suspended sediment discharge (SSD), river surface elevation, the thalweg-elevation differences at each station for the flood (May–October) and dry (November–April) seasons were estimated. The volume change of the riverbed sediment was converted to weight assuming the bulk density of 1.2 kg/m^3. Subsequently, sediment budget for each river segment was computed. All the observations were integrated into a simple box model for sediment budget for the middle and lower reaches of the river between Yichang and Hanjiang. The model has two tributary inputs (Qingjiang and Hanjiang) and two lake inputs and outputs (Dongting and Poyang Lakes). The riverbed could be source or sink for sediment through entrainment and deposition, respectively. In each segment in the model, the suspended sediment inputs and outputs were computed from the SSD observed nearby. Riverbed sediment fluxes were computed from the depth changes.

Trend analysis of the river runoff and surface elevation changes was conducted based on the Kendall method (1975), Assuming normal distribution at the significant level of $P = 0.05$, a positive Man-Kendal statistics Z larger than 1.96 indicates an significant increasing trend; while a negative Z lower than 1.96 indicates a significant decreasing trend. Critical Z values of ±1.64, ±2.58, ±3.29 were used for the probabilities of $P = 0.1$, 0.01 and 0.001, respectively (Liu et al., 2011).

2.2. Data quality control

All the original raw data and published data from the literature used in this study were obtained from the CWRC (http://www.cjh.com.cn). Before these data were released to the public, they had gone through rigorous verification and uncertainty analysis following government protocols such as those published by the China Ministry of Hydraulics, including 'Specifications for the Observation of River Discharge' (GB-50179-1993JRX, 1993), 'Specifications for the Monitoring Riverine Suspended Matter' (GB 50159-92, 1992), and 'Specifications for the Waterway Survey' (SL257-2000, 2000). Quality control methods such as uncertainty estimates, random errors, system errors and pseudo system errors were all specified in Chapter 7 in the 'Specifications for the Observation of River Discharge' to ensure the system-wide confidence level is above 95%.

Presently data published by CWRC have been widely used by international scholars in hydrology and geomorphology studies. Specific data sets such as the yearly mean river runoff between 1955 and 2010, suspended sediment flux between 1955 and 2010, and mean daily water level between 2000 and 2010, and tide level between 1955 and 2008 have been published by Syvitski et al. (2005), Milliman and Farnsworth (2011), and Yang et al. (2011). Data sets of the river-thalweg elevations, river cross-sectional profiles at fixed locations, and secular erosion/deposition changes have been published yearly by CWRC in the Bulletin of China River Sediment (for example, 2005, 2006, 2009, 2010). River channel survey (including cross-sectional profiles at fixed locations, riverbed elevations) employs the use of GPS-RTK (real time kinematic) and echo sounders. The horizontal errors were within 1 m and the vertical errors were restricted within 0.1 m based on China Huanghai (Yellow Sea) datum. The survey was carried out in seasons when the river flow and course were relative stable. The flow measurements across fixed cross-sections were restricted on the cross-section in the direction perpendicular to the cross-section. If there were wave interference, the measurements needed to be repeated three times and taken the average. If the measurements were off the cross-section, they needed to be repeated (SL257-2000, 2000; GB-50179-1993JRX, 1993). The thalweg data were read off 1:10,000 survey charts. The entire river channel survey was based on 1:5,000 or 1:10,000 scales. For special channel morphology such as piers or bridge pilings the survey scale was increased to 1:200–1:1,000. Large-area channel charts (1:10,000) have been used in studies of different segments of the Changjiang by scholars (e.g. Shi et al., 2002; Wang et al., 2009; Xu, 2012). The quality control imposed by the surveying agencies ensuring the reliability of the data and the published work that used these data all attest to the trustworthiness of the data.

3. Results

3.1. Changes of the river runoff and water level

The results of Mann–Kendall trend analysis show that except for Zhicheng ($Z = -1.16$), all the water level at the 8 reference stations showed statistically significant ($p = -0.001$) decreasing trends for the period between 2000 and 2010 (Table 2). Except for Luoshan, Hankou, and Datong where the runoff showed decreasing trends, the rest of the stations showed trends of increase. The max. spring tide at Nanjing also showed increasing trend (Table 2).

The yearly mean water levels for flood and dry seasons showed significant decrease (Fig. 2), especially at Yichang, Shashi, Hankou, and Anqin. There were higher fluctuations for the yearly mean and flood season water levels. Furthermore, for all the stations the lowest values in the yearly mean and flood season water levels for all the stations appeared in 2006.

3.2. Along-river thalweg changes

Depths changes along the thalweg between Yichang and Hankou (about 600 km) and at Nanjing (about 100 km) (Figs. 1C, 4A) showed gradually deepening between Yichang and Chenglingji. The riverbed slope remained leveled between Chenglingji and Han-

Table 2
Mann–Kendall trend analysis of the runoff and water level during different periods.

Periods	Yichang	Zhicheng	Shashi	Luoshan	Hankou	Jiujiang	Anqing	Datong	Nanjing
Daily runoff (2000–2010)	2.89	9.24	4.01	−5.63	−4.49	3.00	/	−3.99	/
Daily water level (2000–2010)	−11.16	−1.16	−13.21	−9.78	−13.06	−12.89	−11.27	−10.34	5.51[a]
Yearly runoff (1955–2010)	0.55	/	/	/	0.86	/	/	0.96	/

[a] Water level data at Nanjing is the yearly maximum tide level from 1955 to 2008.

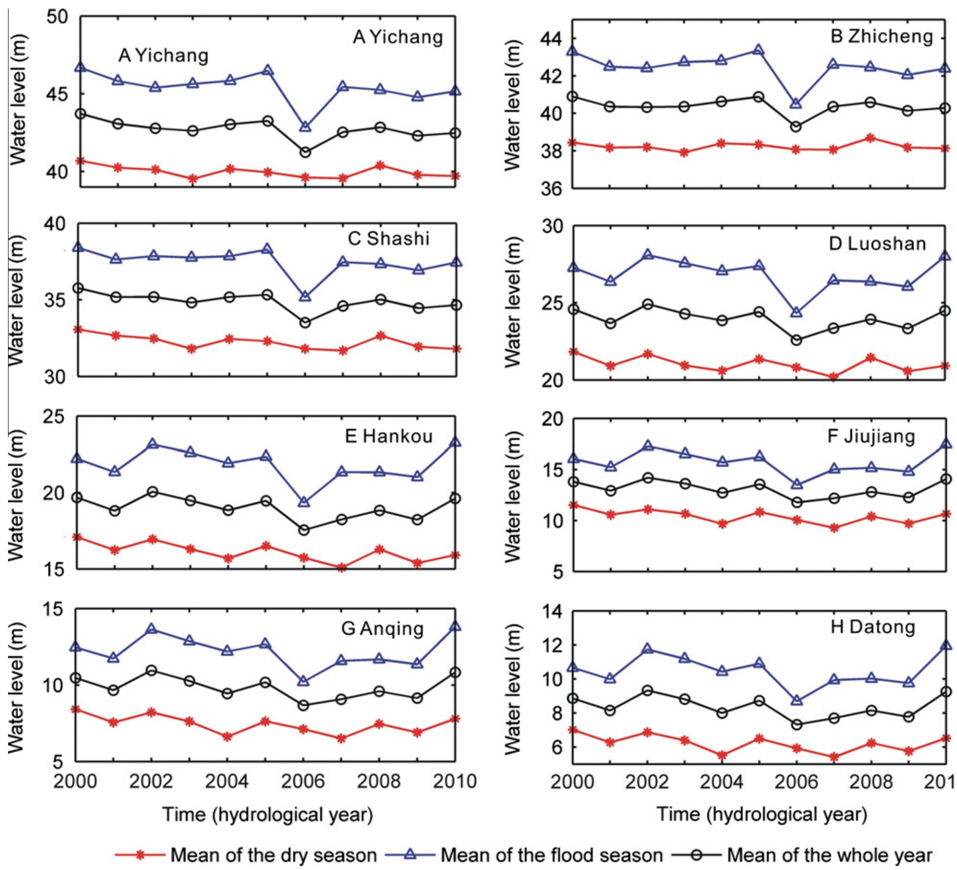

Fig. 2. The Yearly mean water level for the dry, wet seasons and for the entire year at the eight reference gauging stations between 2000 and 2010.

kou. After the initial impoundment of TGD in 2003, the thalweg depths between Yichang and Shashi lowered significantly. The deepest depth could reach −12 m. The average down cutting was −2.5 m. Between Shashi and Luoshan, the thalweg elevation changes alternate between positive and negative values, but mostly negative, whose average down cutting was −1.5 m. In this segment of the river, accretion appeared at Chenglingji where the Dongting Lake meets the Changjiang. Except for localized accretion the 250 km segment between Luoshan and Hankou also showed general down cutting having the average of −1.0 m. In the tidal river around Nanjing, the thalweg also showed down cutting having the range of −1.0 m.

3.3. Cross-sectional changes in the middle reaches

The changes on six selected cross-sections (s1–s6) near the reference gauging stations show that the riverbanks are basically stable, but the there was enlargement of the cross-sectional area between different time periods (Fig. 3B). Serious down cutting appeared at Shanshi (Fig. 3B, s2) and Zhicheng (Fig. 3B, s3). Minor down cutting occurred at Yichang (Fig. 3B, s1) in the trough and Nanjing (Fig. 3B, s6) on the mid-channel shoal. Furthermore, at Luoshan alternate accretion and erosion occurred (Fig. 3B, s4) on the mid-channel shoal and in the trough, respectively. Converce pattern occurred at Hankou where down cutting occurred on the mid-channel shoal and accretion occurred in the trough (Fig. 3B, s5).

3.4. Sediment budget of the middle reaches of the Changjiang

To demonstrate the initial impact of TGD on the fluvial sedimentation in the middle reaches of the Changjaing above the tidal river, sediment budget was estimated for periods (1981–2002) before and after (2003–2010) the TGD. Furthermore, previous studies have not taken into account of the credit and debt effect due to entrainment and deposition on the riverbed in the river budget calculation (e.g. Chen et al., 2011). In this study, the amount of erosion/accretion on the riverbed before (1981–2002) and after (October 2002–October 2010) was used to estimate the sediment budget.

Before the TGD, the sediment budget shows that there was accretion between Yichang and Zhicheng in the upper reaches (Fig. 4A). This was probably due to the input form the tributary called Qingjiang. Also the riverbed slope in the upstream side is

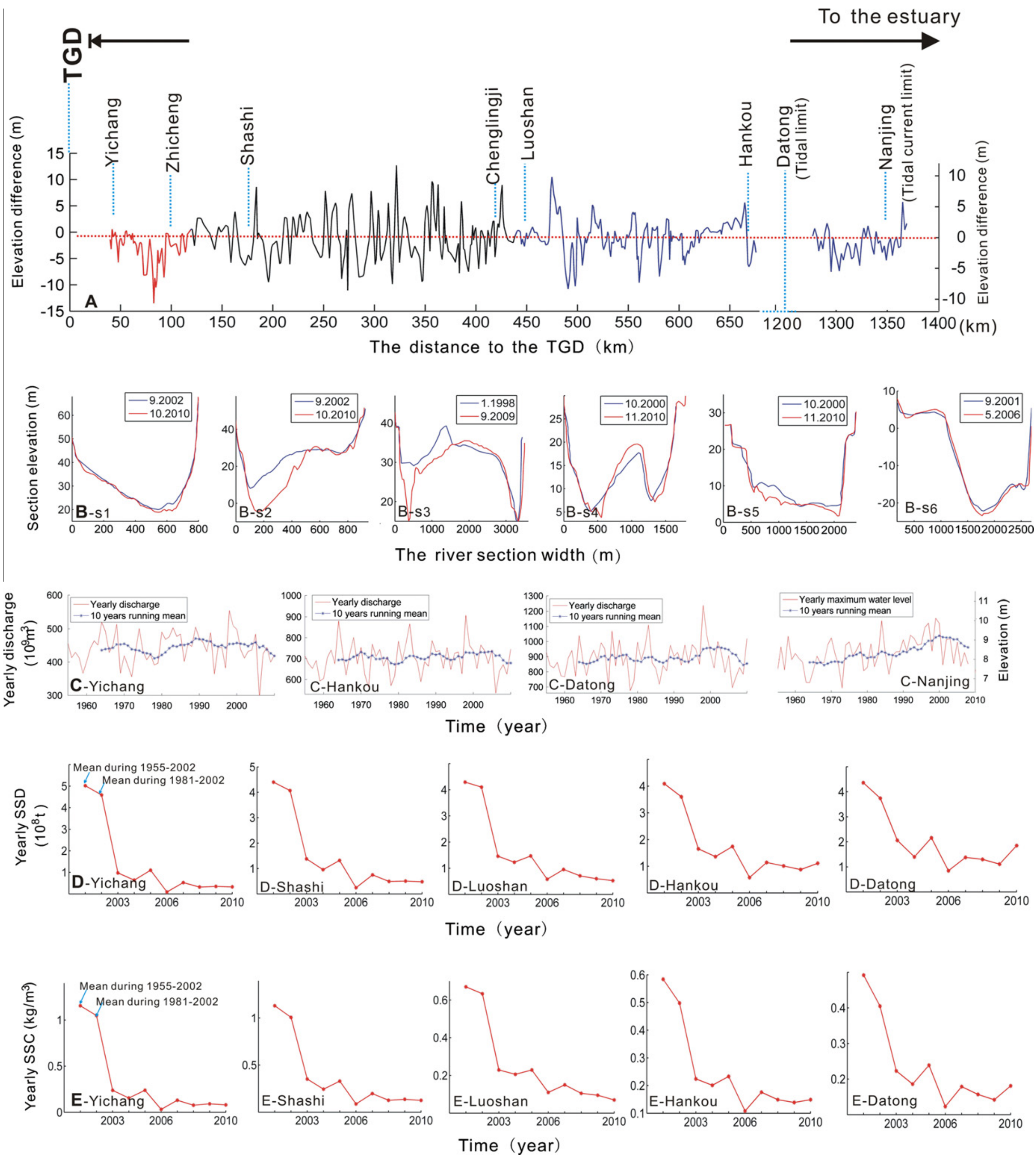

Fig. 3. Spatial and temporal variability along the river course of the Changjiang including: (A) changes in the thalweg depth along the river course (based on Fig. 1C), (B) changes on the cross-section at 6 locations; (C) The yearly river runoff at Yichang, Hankou, and Datong and the max. high water level at Nanjing; Composites of SSC (D) and SSD (E) at five reference stations, in which the first data point is the mean value between 1955 and 2002, the second point is the mean value between 1981 and 2002, and the rest points are mean yearly values.

steeper than that in the downstream part of the upper reaches, which caused a greater sediment input into the upper reaches than the output (Ali et al., 2012). The erosion and accretion were balanced in the middle reaches between Hankou and Datong. The sediment load reduced by 4% in the segment between Zhicheng and Luoshan. This was due to (1) the slope of the riverbed turned gentler so that there was higher sediment accretion (the mean rate was 0.8×10^6 t/yr), (2) although the Dongting Lake received and supplied sediment from and to the Changjiang, it retained 60×10^6 t/yr more sediment between 1981 and 2002 so that the mean sediment flux at Luoshan was smaller than that at Zhicheng. Although in the next segment between Luoshan and Hankou the SSC dropped by 16% but because of the input from another tributary Hanjiang and fast settling rate, the accretion was the highest

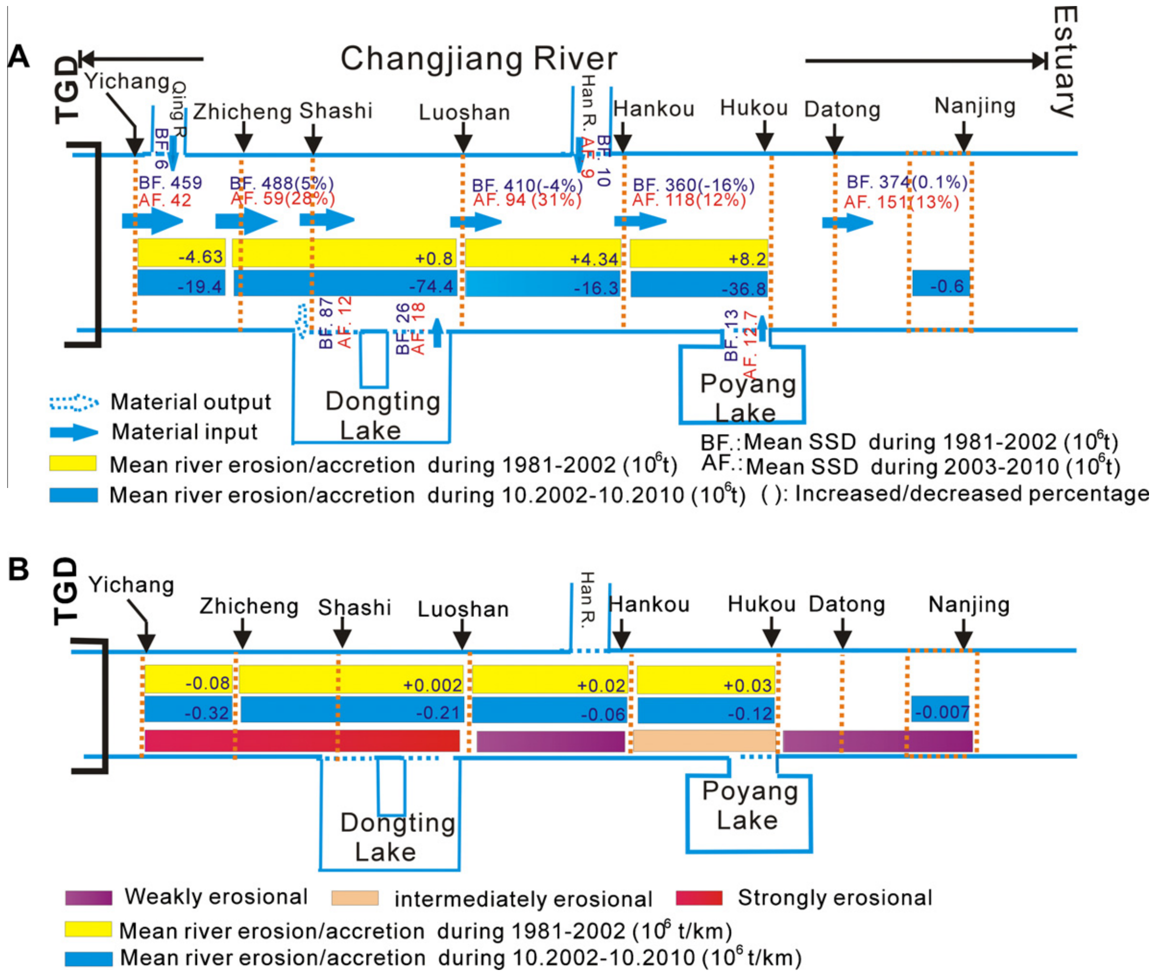

Fig. 4. The box model for the sediment budget of the middle and lower reaches of the Changjiang. (A) Comparison between the pre-TGD (BF, 1982–2002) and post-TGD (AF, 2003–2010) suspended sediment budget and the amount of riverbed erosion/accretion. Values for the Nanjing segment are the mean between September 2001–May 2006. Numbers in the parentheses are the percentage of change within the segment as compared to the adjacent segments and (B) riverbed erosion/accretion per unit length of the river.

(Fig. 4A). After Luoshan, the Changjiang's course passes Plains of Donting, Hanjiang, and Poyang, where the riverbed was gentle, leading to slower river flow, and thus, reduced sediment carrying capacity. Except for Poyang Lake, there was no other tributary input between Hankou and Datong. The erosion/accretion and suspended sediment budget were roughly balanced. Before the TGD operation the overall fluvial characteristics of the Changjiang showed progressively decreasing SSD, leading to accretion on the riverbed.

After the TGD's operation the mean SSD in different segments noticeably increased. The SSD increased by about 30% in segments between Luoshan–Zhicheng and Zhicheng–Hankou. The SSD increased by about 12% in segments between Luoshan–Hankou and Hankou–Datong. The suspended sediment budget generally matched the erosion/accretion on the riverbed in different segments (Fig. 4A). The riverbed has changed from stable to erosional after the TGD's operation. The eroded sediment in the segment between Shashi and Luoshan amounted to 74.4×10^6 t/yr. It is clear that the high SSD in the Changjiang was caused by the entrainment of the riverbed sediment as the result of erosion. This suggests that the role of the riverbed has changed from being sediment 'sinks' to sediment 'sources'.

It is also noted that between 2001 and 2006 the segment around Nanjing showed slightly erosional. Although no data was available between Hukou and Nanjing, but SSD supply from Poyang lake and significant erosion took place between Hankou and Hukou at the rate of 36.8×10^6 t/yr, which could make up the sediment deficit between Hankou and Datong (Fig. 4A). Therefore, we deduced that the segment between Hukou and Nanjing also went though slight erosion, similar to the observation around Nanjing (Fig. 3C).

For further comparison, the rate of erosion/accretion was converted to the amount of erosion/accretion per unit length of the river (Fig. 4B). Following previous arguments that the riverbed behavior has changed from accretionary before the TGD's operation to erosional afterwards. An arbitrary scheme that classifies erosion into the following categories: strong (greater than 0.2×10^6 t/km), intermediate ($0.1–0.2 \times 10^6$ t/km), and weak (smaller than 0.1×10^6 t/km) was devised. According to this scheme, the riverbed of the Changjiang from Yichang downstream to the river mouth could be divided into segments of strongly erosional (Yichang–Loushan), weakly erosional (Luoshan–Hankou), intermediately erosional (Hankou–Hukou), and weakly erosional (Hukou–Nanjing).

4. Discussion

4.1. Changes in the river hydrology and suspended sediment characteristics in the lower reaches

Depositional fluvial systems have higher ability to make self-adjustments. In the case of the Changjiang, one decade after the

TGD began operational, the river seems to be basically stable, for which the impact of the dam on the middle and lower reaches could be assessed. First of all, the runoff at three major reference stations at Yichang, Hankou, and Datong does not show apparent changes between 1955 and 2010 (Table 2). The long-term trend of sediment carrying capacity of the river flow does not seem to have changed. Between 2000 and 2010 the runoff records at Luoshan, Hankou, and Datong show decreasing trends and at all other stations the trends are increasing (Table 2). This suggests localized variability in the sediment carrying capacity within the overall stable trend. The SSD records show that slight decrease between 1981 and 2002 when compared to that during 1955–2002. However, when using year 2003 as the reference when the TGD impoundment began, the SSC sharply decreased down the river until the minimum value appeared in 2006 (Fig. 3E). Between 2007 and 2010, the yearly mean SSC remained unchanged (Fig. 3E). The SSD follows the same trend (Fig. 2D). However, the yearly mean runoff remained almost unchanged between 1955 and 2002 (Fig. 3C).

In addition, in the recent 10 years the runoff in discrete segments around Luoshan, Hankou and Datong decreased (Table 2). However, decreases in water level around Luoshan, Hankou and Datong could be more obvious than runoff in those stations (Table 2), which indicated riverbed erosions in areas near Luoshan and Hankou (Fig. 3A). Moreover, near the Datong station, the medium grain-size of the riverbed sediment increased from 0.18 mm before the TGD's operation to 0.19 mm afterwards (Fig. 5). The coarsening trend suggests erosion.

The sediment carrying capacity of a river is related to the river flow, initial SSC, and the slope of the riverbed (Young et al., 2001; Ali et al., 2012). The overall river flow in the main stream of the Changjiang remained unchanged but the SSC noticeably decreased. This should cause erosion of the riverbed so that the carrying capacity could be kept constant. Consequently, the thalweg between Yichang and Hankou became deeper. In the lower reaches the deepening thalweg and river cross-section at Nanjing, the grain size coarsening at Datong, and the mean tidal range increased from 0.50 m to 0.55 m (Fig. 6) after the TGD all point to the increased riverbed erosion, suggesting the strengthening of tidal hydrodynamics in the tidal river part of the Changjiang.

4.2. Impact of the TGD

Changjiang's runoff and sediment load have distinct seasonal and secular variability as a result of the climate (Xu et al., 2008; Dai et al., 2011a; Chen et al., 2011). However, in the mean time, 2006 was a year of extreme drought in the Changjiang basin, which coincided with the second stage of the TGD impoundment to raise the water level to 156 m above sea level behind the dam. The combined influence caused the SSD and mean SSC to be the lowest during the last 50 years (Dai et al., 2008). But the decrease in sediment load to be 206×10^6 t at Datong in 2003 was the direct result of the intercept of 124×10^6 t of sediment behind the TGD dam, which is about 50% of the regular SSD of the Changjiang (Dai et al., 2011b). Because of the sediment retention by the TGD sediment delivered by the Changjiang to the sea continued to decrease (Fig. 3D) (Bulletin of China River Sediment, 2010), channel erosion occurred in the segment (Yichang–Zhicheng) immediately downstream of the TGD by 81.4×10^6 m^3 between September 2002–October 2006, by 23.3×10^6 m^3 between October 2006–October 2008, and by 25.3×10^6 m^3 between October 2008–October 2010. In this segment, the river flows through mountains and the riverbanks have high resistance to erosion causing the channel to be eroded that resulted in the down cutting as large as 12 m.

The riverbed in the segment between Yichang-Nanjing experience general erosion between 2002 and 2010. Although the thalweg down cutting could be as large as 10 m (Fig. 4), it is difficult to ascertain that it was contributed by migrating sand dunes on the riverbed. A recent study by Chen et al. (2012) reveal that large sand waves have wave length about 90–300 m and height around 3-8 m. They appear in the middle and lower reaches where the riverbed gradient is about $0.2–2.0 \times 10^{-5}$ and the wetted surface area is between 10,000 and 35,000 m^2. The riverbed gradient between Yichang and Chenglingji is steeper and therefore, unlikely to have large sand waves/dunes. Furthermore, the down cutting between Yichang and Nanjign is basically on the scale of 100 s of kilometers. The infilling of the thalweg is usually restricted to localized areas on the scale of tens of kilometers. The infilling can be as much as 10 m whereas the max. sand-wave height is only 8 m. Any occurrence of infilling or down cutting that exceeds 10 m cannot be attributed to migrating sand waves. Therefore micromorphological

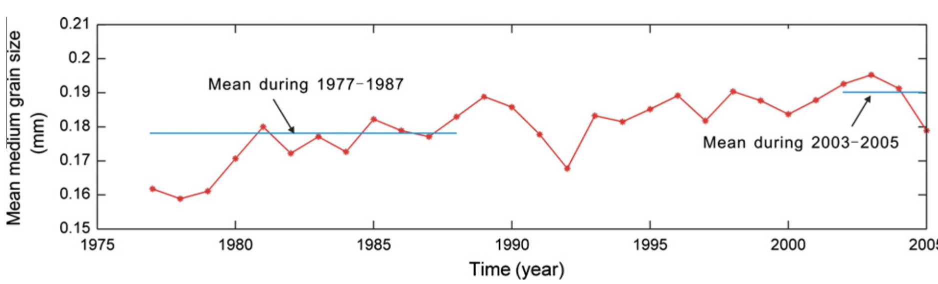

Fig. 5. The medium grain-size in riverbed sediments at Datong station.

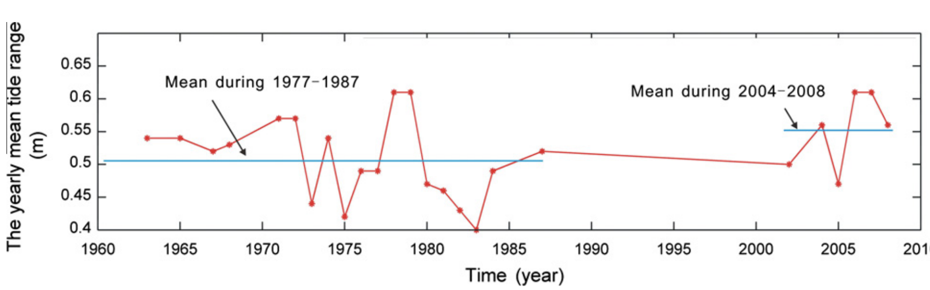

Fig. 6. The yearly mean tide range at Nanjing station.

changes caused by moving sand waves are less likely to affect riverbed infilling and down cutting on a much larger scale.

The sediment stored in the TGD in the following years between 2007 and 2010 was basically 140×10^6 t annually. This explains the stability in the SSD and SSC in the middle and lower reaches since 2007. It seems that although the TGD influenced the river hydrology and sediment characteristics in the middle and lower reaches of the Changjiang, the erosion and deposition along the river has gradually reached a state of stability in the recent years.

4.3. Influence of aggregate extraction

As the economy grew, aggregate extraction along the middle and lower reaches increased. Large scale aggregate extraction began in the 1990s. The operations mainly occurred in the middle and lower reaches. Before 2002, the annual amount of aggregate removal was 53×10^6 t. and the mean grain-size of the removed sediment was 0.1 mm (Xu and Xu, 2012). Since 2004, aggregate removal was regulated. To avoid causing navigational hazards, only restricted areas were allowed for aggregate removal, which limited the yearly amount to be less than 15×10^6 t (Bulletin of China River Sediment, 2005, 2006). Along the stretch between Yichang and Nanjiang, the total amount of aggregate extraction was less than 5% of the total amount of channel erosion. Therefore, aggregate removal had little effect on the natural erosion/deposition patterns in the Changjiang.

5. Conclusions

The impact of damming on the fluvial hydrology and sedimentology of rivers has been the focus of research. However, due to the lack of systematic and long-term data on the river flow and water level, SSC, and the cross-sectional morphology of the river channel, and sediment characteristics of the riverbed, little study have been done on the fluvial response to damming for large rivers in the world. In the case study of the Changjiang, through integrated analysis of the river hydrology, sedimentation, and channel morphology, our findings show that 10 years after the TGD became operational, the SSC and SSD shows noticeable decrease, but has reached a stable state. The water level along the river also decreased with the corresponding down cutting of the thalweg in the middle and lower reaches. The riverbed has turned from accretionary before the TGD to erosional afterwards. In the tidal river part of the Changjiang, the mean high tide level increased due to the increase of the tidal range. Therefore, the impact of TDG on the Changjiang is not only limited to the river hydrology and sedimentology in the middle and lower reaches, but also the estuarine and deltaic regions near the river mouth. The immediate and future environmental impacts also need to be assessed.

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