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Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam

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ABSTRACT

Over the past decades, >50,000 dams and reforestation on the Yangtze River (Changjiang) have had little impact on water discharge but have drastically altered annual and particularly seasonal sediment discharge. Before impoundment of the Three Gorges Dam (TGD) in June 2003, annual sediment discharge had decreased by 60%, and the hysteresis of seasonal rating curves in the upper reaches at Yichang station had shifted from clockwise to counterclockwise. In addition, the river channel in middle-lower reaches had changed from depositional to erosional in 2002.

During the four years (2003–2006) after TGD impoundment, ~60% of sediment entering the Three Gorges Reservoir was trapped, primarily during the high-discharge months (June–September). Although periodic sediment deposition continues downstream of the TGD, during most months substantial erosion has occurred, supplying ~70 million tons per year (Mt/y) of channel-derived sediment to the lower reaches of the river. If sand extraction (~40 Mt/y) is taken into consideration, the river channel loses a total of 110 Mt/y. During the extreme drought year 2006, sediment discharge in the upper reaches drastically decreased to 9 Mt (only 2% of its 1950–1960s level) because of decreased water discharge and TGD trapping. In addition, Dongting Lake in the middle reaches, for the first time, changed from trapping net sediment from the mainstem to supplying 14 Mt net sediment to the mainstem. Severe channel erosion and drastic sediment decline have put considerable pressure on the Yangtze coastal areas and East China Sea.

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1. Introduction

Global river systems have been increasingly altered by dam construction and water diversions for water and energy needs (Nilsson et al., 2005). Humans are simultaneously increasing river sediment transport through soil erosion and decreasing it through sediment retention in reservoirs (Syvitski et al., 2005). Fluvial sediment delivered to the oceans has been estimated to be ~20 billion tons per year (Bt/y) (Milliman and Syvitski, 1992), but the world's registered 45,000 large reservoirs can effectively trap as much as 4–5 Bt/y (Vorosmarty et al., 2003). More than 80% of water and sediment discharge from the Indus River, for instance, has been diverted by large reservoirs and flow diversion (Giosan et al., 2006). China has been particularly active in dam construction, building more than half of the world's large dams commissioned since 1950 (Fuggle and Smith, 2000). Over the past 25 years, for example, the Yellow River sediment discharge has decreased by ~90% because of dam construction and increased water consumption (Wang et al., 2006, 2007b). Of concern in this paper is the impact of the world's largest dam, the Three Gorges Dam (TGD), on the Yangtze River (Changjiang) (Fig. 1).

The TGD began to impound water and sediment discharge on 1 June 2003; by 2009 when the TGD is in full operation, the water storage capacity of the Three Gorges Reservoir (TGR) will be 39 km^3, about 4.5% of the Yangtze's annual discharge. Because the Yangtze not only sustains 440 million inhabitants in its drainage basin but also helps nourish rich fishing grounds in the East China Sea, the response of the Yangtze lower reaches and coastal area to upstream damming has raised considerable interest (Shen and Xie, 2004). In the past decade, for example, the Yangtze delta has changed from one of progradation to regression and its wetlands have been disappearing (Yang et al., 2006a); the degree to which primary production in the East China Sea has been affected, however, is a matter of debate (Gong et al., 2006; Yuan et al., 2007).

Land use change, most of which predates the TGD, also has affected the Yangtze drainage basin. Although water discharge has changed little, sediment discharge in the upper (at Yichang station, Fig. 1) and lower (at Datong) reaches of the river had decreased >60% before the impoundment of the TGR in 2003 (Fig. 2). These pre-TGD declines were mainly due to construction of >50,000 tributary dams, reforestations and decreased precipitation in the high-sediment-yield basin of the Jialing River (Xu et al., 2007). Nevertheless, impact after the TGD was

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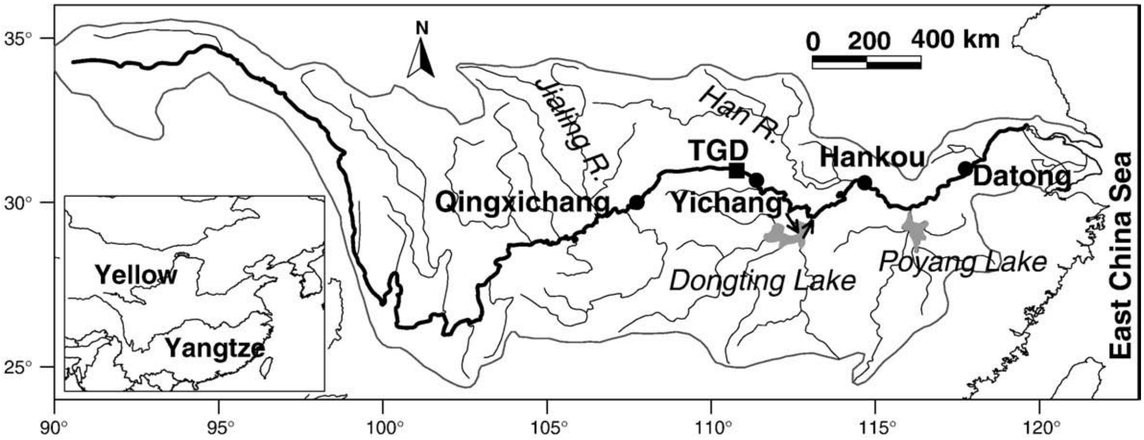

Fig. 1. The Yangtze River drainage basin. Two grey areas in the southeastern basin are Dongting and Poyang Lakes. Note that Yangtze mainstem delivers water and sediment into Dongting Lake and flows back to the mainstem (shown in arrows). TGD, Three Gorges Dam.

immediate: during the two years after impoundment (2003–2004), sediment discharge at Yichang and Datong decreased by 164 and 128 million tons (Mt) (Fig. 2), respectively, and intense riverbed scouring led to active channel erosion (Xu et al., 2006). This declining trend in sediment transport was further exacerbated by the extreme drought in 2006 when flood season water level was lowest in the past 50 years (Dai et al., 2008); water discharge decreased by ~30%, and sediment drastically decreased to 9 Mt (only 2% of its 1950–1960s level) in the upper reaches at Yichang (Fig. 2).

During the past decade, numerous studies have been documented water and sediment discharge of the Yangtze River. Long-term sediment flux from the river to the sea since the 1860s was reconstructed using water discharge data collected from the middle reaches (Wang et al., 2008). Statistical analyses of sediment and runoff changes at four mainstem and three tributary stations during the past 55 years were done by Zhang et al. (2006). Sediment flux sensitivity to climate change (e.g., temperature and precipitation) in upper reaches was documented by Zhu et al. (2008). Flood records in a sediment core collected in the middle reaches and its sediment sources were investigated by Yi et al. (2006). Dam impacts on sediment discharge, channel variations, and delta erosion have been further studied by Yang et al. (2006a, 2007) and Yang et al. (2006b). Temporal and spatial variations of basinwide and subbasin discharge of the river were analyzed by incorporating climatic and anthropogenic impacts (Xu et al., 2007). In addition, sediment budget analysis and sand extractions were discussed by Chen et al. (2006, 2008), Walling (2007), and Wang et al. (2007a).

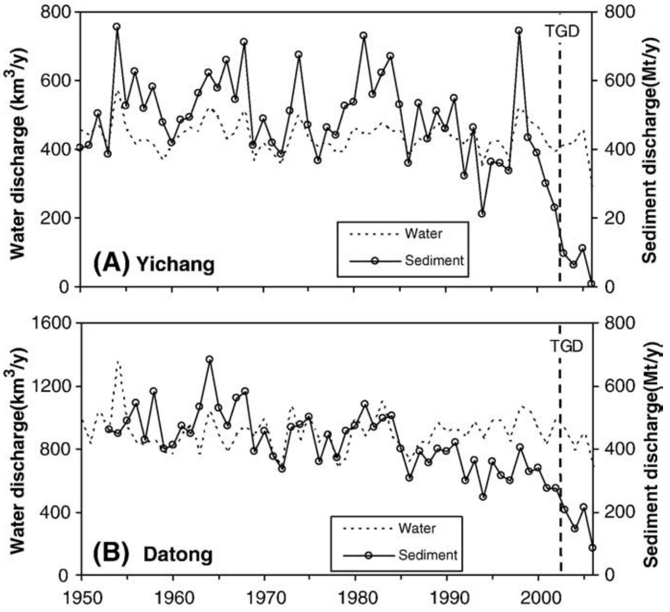

Fig. 2. Temporal variations of annual water and sediment discharge in upper (Yichang station) and lower (Datong station) reaches of the Yangtze River in 1950–2006. Bold vertical dashed lines labeled TGD (Three Gorges Dam) indicate the impoundment in June 2003. Data are from Changjiang Water Resources Commission. Declined sediment discharge before 2003 was mainly caused by tributaries damming and reforestation.

Although many aspects of water and sediment discharge of the Yangtze have been addressed, few have delineated (i) seasonal rating-curve changes before and after the TGR impoundment, (ii) monthly sediment trapping in the TGR, and (iii) seasonal variations of channel erosion/deposition. These rating-curve changes may significantly impact the timing and pattern of hydrological cycle and sediment transport in the Yangtze basin. Reservoir trapping and channel erosion also play key roles in determining how much sediment can be delivered to the Yangtze estuary to maintain the geomorphology of the Yangtze delta. In addition, quantifying seasonal water and sediment variations is critical for better management of watershed water/sediment resources and to ensure a sustainable development for the Yangtze basin.

Our two recent publications (Xu et al., 2006, 2007) mainly focused on annual variations using data up to 2004 or 2005, respectively, but here we report on the most recent (1950 to 2006) *seasonal* water and suspended-sediment discharge measured at both mainstem and tributary stations. Because the Yangtze usually is divided into upper (above Yichang), middle (Yichang to Hankou) and lower (downstream of Hankou) reaches (Chen et al., 2001), we emphasize both upper (Yichang, directly downstream of the TGD) and lower (Datong, the seaward-most station) reaches. In contrast to other studies, here we (i) show dramatic hysteresis shifting of rating curves, from clockwise to counterclockwise upstream before and after the TGD, (ii) analyze annual and particularly monthly sediment budgets for channels and lakes in the middle-lower reaches, and (iii) attempt to quantify the forcings that caused the drastic Yichang sediment decline to 9 Mt in 2006. Because bedload only represents 5% of total sediment discharge (Chen et al., 2001), it is not addressed in our paper except when considering sand extraction from the river channel. Most water and suspended-sediment discharge data are from the Bulletin of Yangtze Sediment (2000, 2001, 2002, 2003, 2004, 2005, 2006, available in http://www.cjh.com.cn/) or Changjiang Water Resources Commission.

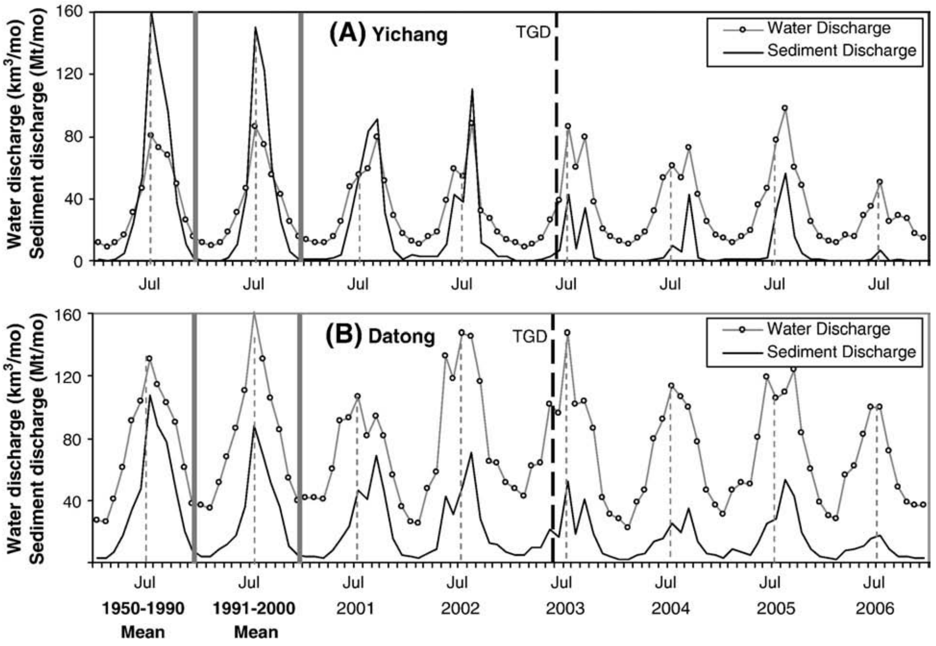

Fig. 3. Monthly water and sediment discharge measured in upper (Yichang) and lower (Datong) reaches from 1950 to 2006. Note that 1950–1990 and 1991–2000 are long-term monthly means, followed by monthly discharge from 2001 to 2006. For ease of comparison, thin vertical dashed lines represent July for each year; bold vertical dashed lines labeled TGD (Three Gorges Dam) indicate the impoundment in June 2003.

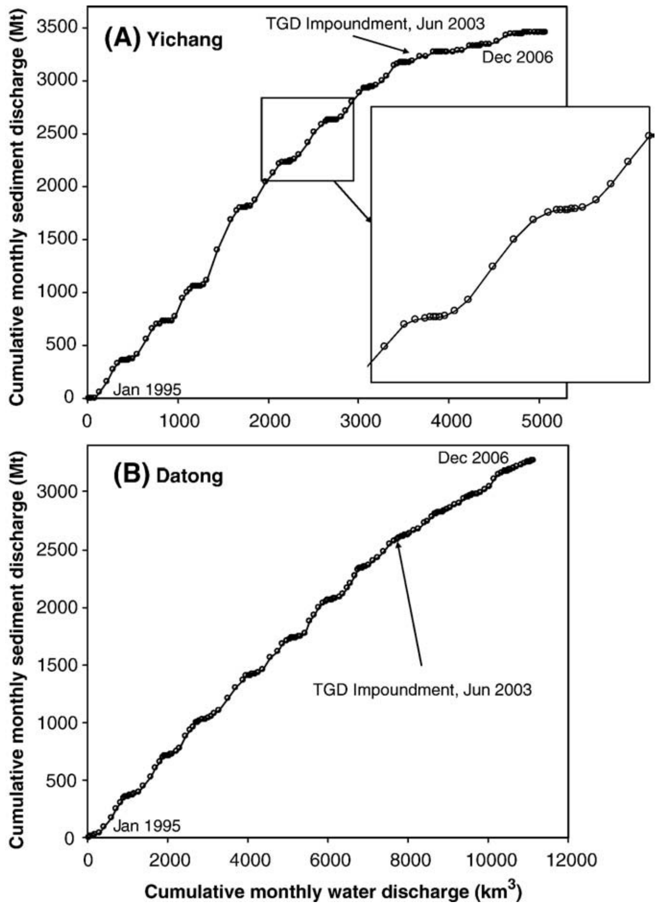

Fig. 4. Cumulative monthly water and sediment discharge at upper (Yichang) and lower (Datong) reaches of the Yangtze River in 1995–2006. The inset shows gentle and steep curves in winter and summer, respectively. TGD (Three Gorges Dam) impoundment in June 2003 is highlighted for the comparisons before and after the impoundment.

2. Mainstem variations at Yichang and Datong

2.1. Temporal variation

Under the control of summer Asian monsoons, water and sediment discharge from Yangtze upper (Yichang) and lower (Datong) reaches both show seasonal patterns. In 1950–1990, more than 70% of water discharge at Yichang and Datong occurred during summer (May–October), with an average peak in July (Fig. 3). Water discharge at two stations has shown little change during the past 56 years (Fig. 2), with peak discharge averaging 80 and 130 km^3/month (mo), respectively (Fig. 3). In June 2003, about 10 km^3 of water impoundment in the TGR had relatively small impacts on water discharge at two stations. Interestingly, a decrease in water discharge was obvious at Yichang in August 2003 (Fig. 3); this decline is probably related to decreased precipitation, as no impoundment took place at this time.

Sediment discharge at both stations, however, has decreased dramatically since 1950 (Fig. 2). Peak monthly sediment discharge at Yichang decreased from 160 Mt/mo in 1950–1990 to only 7 Mt/mo in 2006; Datong peak discharge also declined from 110 to 17 Mt/mo over the same period (Fig. 3). Sediment decrease is more drastic in Yichang than that in Datong (Figs. 2 and 3), mainly because of the compensation from channel erosion downstream of the TGD (discussed later). The timing of peak sediment discharge at both stations, however, shifted from July before 2000 to August or September in 2001, 2002, 2004, and 2005 (July is marked by thin dashed lines in Fig. 3 for comparison).

2.2. Cumulative discharge variation

The plots of cumulative sediment discharge versus water discharge (1995–2006) at Yichang and Datong both show stepwise curves, which were fairly steep in summer but gentle in winter (Fig. 4). The curve of Yichang began to bend slightly in 2001–2002 and became very flat after the impoundment in June 2003. In contrast, the curve at Datong changed more gradually, showing a much smaller impact by the TGD impoundment (Fig. 4). Because the slope of the curve indicates sediment

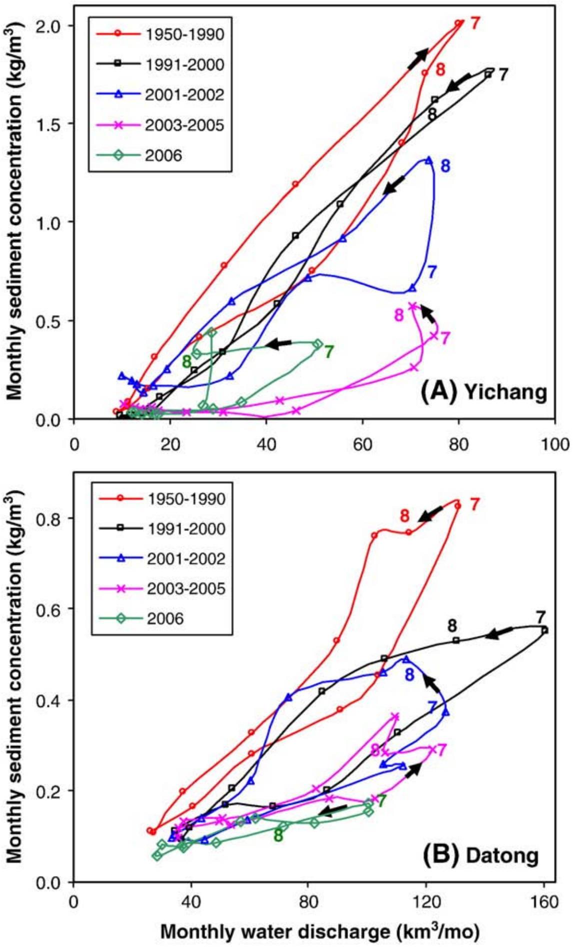

Fig. 5. The rating curves of monthly water discharge versus sediment concentration for 1950–1990, 1991–2000, 2001–2002, 2003–2005, and 2006 at Yichang and Datong, respectively. Numbers on the curves represent the sequential months (7 for July 477 and 8 for August) of the years, and arrows show the clockwise or counterclockwise hysteresis loops. The curves at Yichang shifted from clockwise in 1950–1990 to counterclockwise after 2001.

concentration, sediment concentrations at Yichang in summer were much higher than in winter, with concentrations decreasing rapidly after June 2003.

2.3. Rating-curve variation

Yangtze water mainly comes from the SE owing to higher precipitation, but Yangtze sediment is from the NW because of more erodible soils and steep mountains (Xu et al., 2007). Each year Asian monsoons move northward from the low-sediment-yield SE (in April and May) to the high-yield NW (June–August) (Shi et al., 1985). In upper reaches at Yichang during 1950–1990, sediment concentration in the rising stage (June) on the rating curve was greater than that in the falling stage (October) presumably because there was more easily-erodible sediment available in June (Fig. 5). In contrast, lower-reach variations at Datong reflect the combination of spatial source difference and temporal monsoon moving. In 1950–1990 Datong's sediment concentration in the rising stage of water discharge (June, sediment-poor) was lower than that in the falling stage (August–September, sediment-rich) during which turbid sediment was supplied by upper reaches (Fig. 5). These temporal and spatial settings led to a unique downstream transition on the hysteresis of rating curves from clockwise at Yichang to counterclockwise at Datong in 1950–1990 (Fig. 5).

This downstream transition, however, has changed gradually since the 1990s. The curves at Yichang switched to being counterclockwise in 1992 and 1995–1997 but remained clockwise in the other years of the 1990s, leading its 1991–2000 curve to shift to a semi-counterclockwise hysteresis (Fig. 5). It then fell and became counterclockwise in 2001–2002, after which it maintained counterclockwise and dropped further in 2003–2005 and 2006. Of these decreases in sediment concentrations at Yichang, the most dramatic is July of 2001–2002 when concentration decreased by 60% compared with 1991–2000; in contrast, sediment concentration in August declined by only 20% over the same periods (Fig. 5). Downstream at Datong, all the curves since 1991 fell below the 1950–1990 line but remained counterclockwise (Fig. 5).

3. Spatial and temporal variations

Variations at Yichang and Datong actually reflect changes on both mainstem and tributaries in the Yangtze basin. As such, our discussion of changes on water and sediment discharge will focus on the transition from the upper to the lower reaches: upstream, inside and downstream of the TGR, respectively.

3.1. Upstream of the TGR

In 2006, the upper reaches of the Yangtze experienced an extreme drought, during which water level in flood season was the lowest in the last 50 years, a situation called "no flood in the flood season" (Dai et al., 2008). Annual water discharge at Qingxichang (upstream of the TGR, Fig. 1) also reached its lowest level (278 km^3/y) in the past half century, ~30% less than its long-term (1956–2005) mean (390 km^3/y) (Fig. 6). Since the year 1986 was the beginning of the Yangtze Upstream Water and Soil Conservation Project and 2003 is the first TGR impoundment, the plots of water versus sediment discharge at Qingxichang can be divided into three periods: 1956–1985, 1986–2002, and 2003–2006. Sediment discharge began declining in 1986, and reached its lowest level in 2006 (Fig. 6). Based on the rating curve for 2003–2006, decreased water discharge in 2006 led to a drop of 110 Mt in sediment discharge (dashed lines in Fig. 6).

3.2. Sediment trapping inside the TGR

The 600-km-long TGR is located in the upper stream of the Yangtze, and sediment trapping inside the reservoir has been substantial since the impoundment in 2003. Located immediately

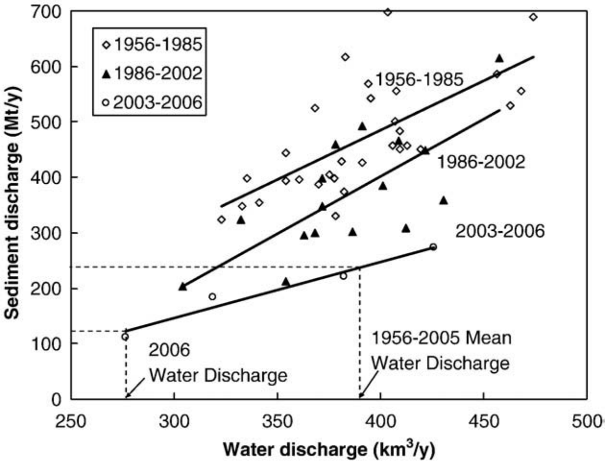

Fig. 6. The rating curves of annual water discharge versus sediment discharge at Qingxichang station in 1956–1985, 1986–2002, and 2003–2006. 2006 was an extremely dry year during which decreased water discharge led to a 110-Mt decline in sediment discharge. Discharge of Qingxichang was calculated by adding discharge from a nearby upstream station (Zhutuo) to that of two tributaries (at Beibei and Wulong stations) between Zhutuo and the TGR.

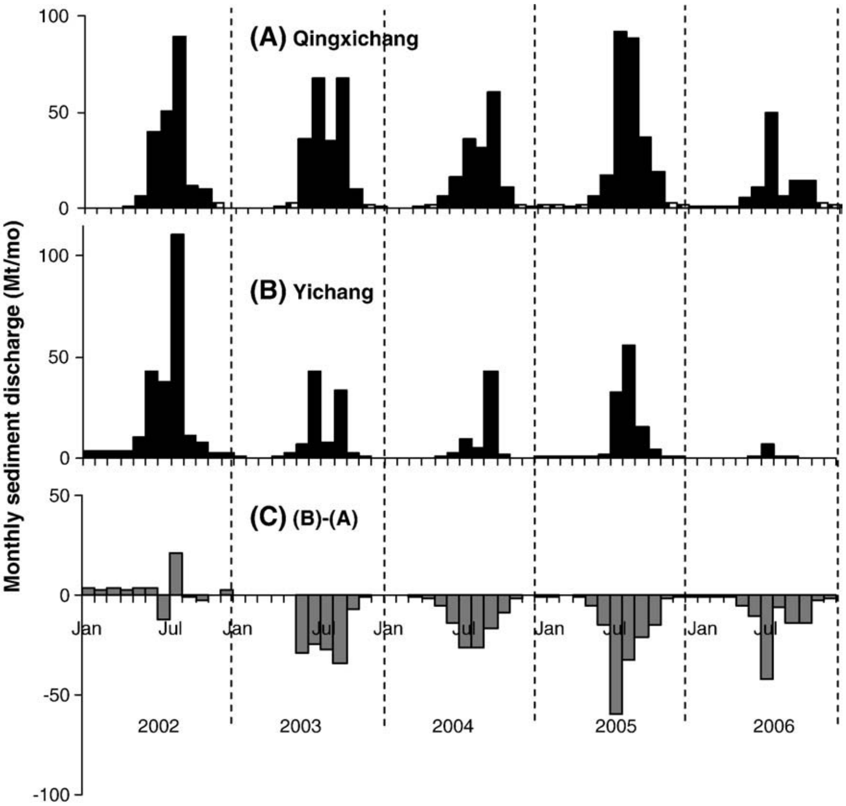

Fig. 7. Monthly sediment discharge at Qingxichang (A) and Yichang (B), and trapped sediment in the TGR (C). The tributary upstream of Qingxichang is Jinsha River. Discharge of Qingxichang was calculated by adding discharge from a nearby upstream station (Zhutuo) to that of two tributaries (at Beibei and Wulong stations) between Zhutuo and the TGR.

upstream and downstream of the TGR, Qingxichang and Yichang stations have been used to monitor the sediment entering and exiting the reservoir, respectively (Fig. 1). The contribution from nearby small rivers to the TGR has been regarded as small, although it may reach as high as ~25 Mt/y (Yang et al., 2007). During 2002 and before TGD impoundment, sediment discharge passing two stations was similar, indicating little net erosion or deposition along the channel between Qingxichang and Yichang (Fig. 7). After impoundment, however, 124, 102, 151, and 93 Mt of sediment were trapped in 2003, 2004, 2005, and 2006, respectively, an average of 118 Mt/y (Fig. 7).

During 2003–2006, sediment retention occurred mainly from June to September, a pattern similar to the sediment discharge at Qingxichang (Fig. 7). The more supply from upstream of the TGR, the more trapping of sediment inside the reservoir. Monthly sediment discharge entering the TGR correlated with trapped sediment in the TGR (Fig. 8); approximately 50% of the sediment entering the TGR was trapped based on the slop of the line in Fig. 8. The highest trapping (60 Mt) in July 2005 corresponded to the highest sediment discharge (90 Mt) passing Qingxichang.

Inside the TGR, sediment was mainly accumulated near the thalweg and became thicker nearer to the TGD; maximum accumulation thickness (53 m) occurred 6 km upstream of the TGD (Bulletin of Yangtze Sediment, 2005, 2006). In August 2003, however, sediment discharge at both Qingxichang and Yichang was unusually lower than in the preceding and following months (Fig. 7). Because impoundment in the TGR at that time was not significant, this is likely related to decreased water discharge (Fig. 3) and reduced precipitation upstream of the TGR, which propagated downstream to Yichang.

3.3. Channel erosion downstream of the TGR

Another dramatic change in response to TGR impoundment has been channel erosion downstream of the TGD, which plays a key role in sediment transfer in the middle and lower reaches. Along the 1140-km stretch between Yichang and Datong, the Yangtze has lost some sediment (due to siltation and reclamation) through several passages (small arrows in Fig. 1) connecting Dongting Lake, but has received considerable sediment from tributaries merging at Poyang Lake and the Han River. Prior to 2000, sediment transport in this section displayed extreme seasonal variations, sediment being deposited during high-discharge months (June–September) but subsequently eroded in low-discharge months (Fig. 9); net deposition between Yichang and Datong averaged 48 Mt/y (Table 1). Deposition downstream of Yichang declined quickly to 15 Mt in 2001, and then reversed to net erosion (−46 Mt/y) in 2002 (Table 1), erosion occurring

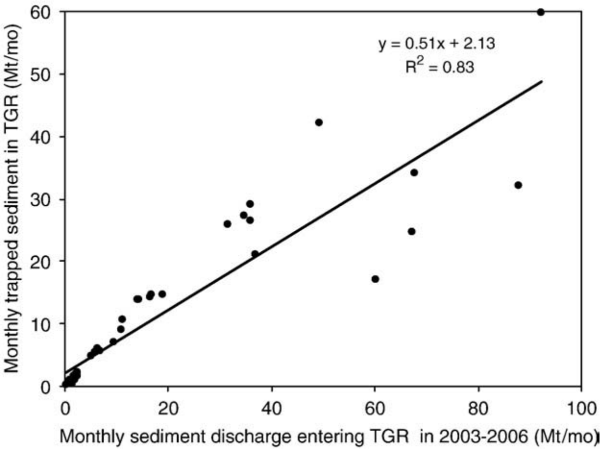

Fig. 8. Suspended sediment discharge entering the Three Gorges Reservoir (TGR) in 2003–2006 correlates with monthly trapped sediment in the TGR. The gauging stations measuring discharge entering the TGR is Qingxichang.

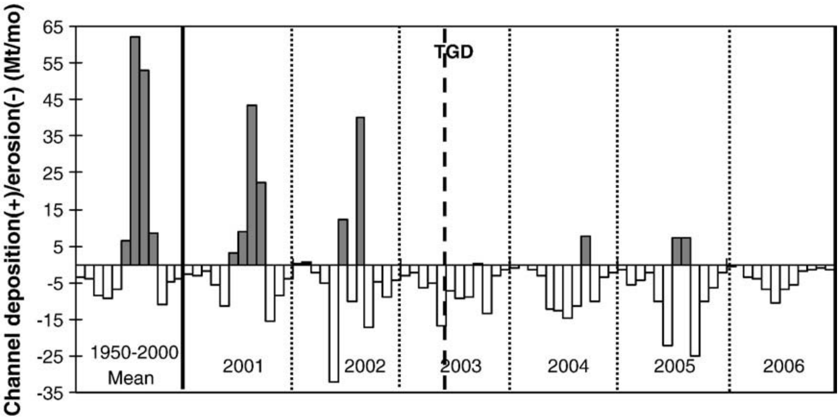

Fig. 9. Monthly channel deposition (+)/erosion(−) between Yichang and Datong stations, calculated by subtracting Datong from the sum of Yichang, Dongting Lake, Poyang Lake, and Han River. The net depositional pattern in 1950–2000 gradually shifted to erosional in 2002, and more significantly in 2003–2006. Note that monthly data of Dongting, Poyang, and Han before 2002 are not available; the pre-2002 plot represents the difference between the discharge at Yichang and that at Datong. Annual variations are shown in Table 1.

in 10 of 12 months (Fig. 9). In 2002, for the first time, sediment discharge at Datong exceeded that at Yichang (Table 1). As these changes occurred before TGD impoundment, clearly human activities (e.g., damming and reforestation) on the Yangtze tributaries had collectively played a key role in this deposition-to-erosion transition.

After the 2003 impoundment, channel erosion occurred in every month in 2003 and 2006 and most months in 2004–2005 (Fig. 4) in response to the release of water from the TGR with sharply reduced sediment concentrations. In 2003–2006, an average of ~70 Mt/y of sediment was eroded between Yichang and Datong, mostly reflecting the abrupt summertime change from deposition to erosion (Fig. 9). Channel erosion mainly took place 630 km directly downstream from the TGD (Yichang to Hankou) but diminished farther downstream from Hankou to Datong (Figs. 1 and 9; Table 1). Because channel-eroded sediment was generally coarser than suspended sediment, median grain size increased from 5 μm at Yichang to 11 μm downstream at Hankou in 2005 (Bulletin of Yangtze Sediment, 2005).

4. Discussion

During the past half century, human activities have increased in the Yangtze basin. Since 1986, the Yangtze Upstream Water and Soil Conservation Project has constructed nearly one million ponds, reservoirs, and levees, and has increased vegetation cover by 23%; these land conservation activities alone are believed to be responsible for the trapping of ~60 Mt of sediment in the upper reaches (Bulletin of Yangtze Sediment, 2003). By 2000, more than 50,000 dams had been constructed throughout the Yangtze basin. The Danjiangkou Dam in the north, for example, has decreased >95% of sediment discharge from the Han River (Fig. 1) since 1968 (Yang et al., 2006b).

4.1. Shifting of rating curves

These human activities have greatly influenced hydrological seasonality and hysteresis of the rating curve in the Yangtze River. Upstream of Yichang, sediment concentration experienced the most dramatic decrease in July of 2001–2002 (Fig. 5), and peak sediment discharge shifted from July before 2000 to August–September in 2001–2002 and 2004–2005 (Fig. 3). The July decline played a major role in the shift of the rating curve from clockwise to counter-clockwise. These drastic sediment drops at Yichang are explained by the effect of numerous reservoirs in tributaries of the river as follows. When precipitation is low in January–May, water levels in most reservoirs fall to meet domestic and agricultural needs. With the re-initiation of monsoonal summer rains in the upper reaches (usually in late June and July), reservoirs begin filling, thereby trapping both sediment and water. Once filled in August–September, water and sediment again are discharged from reservoirs. One result of reservoir trapping has been the significant temporal decrease in median grain size of suspended sediment at Yichang, from 22 μm in 1950–2000 to only 5 μm in 2005 (Bulletin of Yangtze Sediment, 2005).

4.2. Sediment budget and complications

Sediment budget provides a way to understand the distribution of sediment in different parts of a river basin (Wang et al., 2007a).

Table 1
Sediment budget in the middle-lower reaches of the Yangtze River (unit: Mt/y)

Year	Yichang	*Dongting Lake*	*Han River*	Hankou	*Poyang Lake*	Datong	Channel deposition(+)/erosion(−)		
							Yichang to Hankou (630 km)	Hankou to Datong (510 km)	Yichang to Datong (1140 km)
1950–2000	501	*−86*	*56*	404	*10*	433	**67**	**−19**	**48**
2001	299	*−23*	*3*	285	*12*	276	**−6**	**21**	**15**
2002	228	*−16*	*3*	239	*14*	275	**−24**	**−22**	**−46**
2003	98	*−3*	*14*	165	*18*	206	**−56**	**−23**	**−79**
2004	64	*0*	*5*	136	*14*	147	**−67**	**3**	**−64**
2005	110	*−8*	*17*	174	*16*	216	**−55**	**−26**	**−81**
2006	9	*14*	*3*	58	*14*	85	**−32**	**−13**	**−45**

Yichang, Hankou and Datong are three mainstem stations from upper to lower streams, and Dongting Lake, Han River and Poyang Lake (all italicized) deliver tributary discharges into the mainstem (Fig. 1). The Yangtze generally loses sediment into Dongting Lake and receives sediment from Poyang Lake and Han River. Channel deposition(+)/erosion(−) from Yichang to Datong was calculated by subtracting Datong from the sum of Yichang, Dongting, Poyang and Han. The budgets for Yichang–Hankou (630 km channel length) and Hankou–Datong (510 km) were calculated in a similar way. All channel budgets are shown in bold. Dongting sediment itself was calculated by subtracting four passages flowing into Dongting Lake from one passage going back to the mainstem (Fig. 1; Xu et al., 2007). See Fig. 9 for monthly variations.

Sediment discharge delivered to the lower reaches at Datong is dependent on (i) sediment discharge at Yichang, (ii) net sediment flux between Dongting Lake and mainstem, (iii) discharge from un-gauged small rivers, (iv) contributions from the Han River and Poyang Lake, as well as (v) sand extraction along channels in the middle-lower reaches (Fig. 1; Chen et al., 2008). Based on our sediment-budget analysis, about 70 Mt/y of channel-derived sediment was eroded and delivered to the lower reaches in 2003–2006 (Table 1). This budget analysis, however, does not take into account small ungauged rivers in Yichang–Datong and sand extraction. Considering the low-sediment yield in the middle-lower reaches, however, contribution from small ungauged rivers should be fairly small.

Sand extraction in the middle and lower Yangtze basin began as early as the 1950s. In the 1980s, sand extraction rapidly increased to 40 Mt/y and reached ~80 Mt/y in the late 1990s (Wang et al., 2007a). In 2003 the Yangtze River Conservation Commission issued a regulation that total sand extraction/mining should be <34 Mt/y, but the ban on illegal sand extractions has become a challenge to Chinese government (Chen et al., 2006). Actual sand extraction in 2003–2006 may have between 34 and ~80 Mt/y. One complicated issue for the budget analysis here is that extracted sand (>64 μm) is much coarser than the suspended sediment (5–11 μm in median size). When sands are extracted from river bed or banks, there may be more space for suspended fine sediment to deposit on the bed. If we assume 40 Mt/y of sand extraction combined with 70 Mt/y channel erosion (Table 1), the river channel could have lost as much as 110 Mt/y in 2003–2006. The resulting channel erosion could result in river bank landslides and levee failures, endangering the flood control and navigation in the middle-lower reaches.

Dongting Lake is the major lake located in the middle Yangtze reaches, receiving discharge from the mainstem and southern tributaries, which then flows back into the mainstem (arrows in Fig. 1). Net escape of sediment from mainstem to lake has decreased from 86 Mt/y in 1950–2000 to 16 Mt in 2002 (Table 1). Because of active channel erosion downstream of the TGR after June 2003, bed level on the mainstem channel was lowered and sediment escape from the mainstem to lake essentially stopped in 2004 (0 Mt). During the extreme drought year 2006, sharply dropped water discharge and TGR trapping decreased by 110 and 93 Mt sediment (Figs. 6 and 7) in upper stream, respectively, leading only 9 Mt sediment passing Yichang. Because of sediment starvation in the mainstem, sediment transport changed from escaping from the mainstem before 2005 to supplying net sediment (14 Mt) back to the mainstem in 2006 (Table 1).

The area of Dongting Lake has decreased from 4350 km^2 in 1949 to 2623 km^2 in 1995 because of extensive reclamation and severe siltation (Bulletin of Yangtze Sediment, 2000). Dongting Lake has been the major freshwater source for millions of people in the middle reaches of the Yangtze. How to maximize the longevity of Dongting Lake has long been a serious question. This new lake-to-mainstem transport pattern, however, might alleviate the shrinking of the lake and facilitate the management of freshwater resources in the middle reaches.

5. Conclusions

Before the impoundment of the Three Gorges Reservoir (TGR) in 2003, the seasonality of hydrological processes in the Yangtze upper reaches had been altered by tributary dams and reforestation such that the hysteresis of the rating curve in the upper reaches shifted from clockwise to counterclockwise. After the impoundment, 60% of the sediment entering the TGR was trapped in flood seasons. Downstream of the TGR, substantial channel erosion happened most of the time in 2003–2006. In the extreme drought year 2006, sediment discharge in the upper reaches drastically decreased to only 2% of 1950–1960s level owing to both reduced water discharge and TGR trapping. As downstream channel erosion (70 Mt/y) has not yet counteracted TGR trapping (118 Mt/y), sediment delivered to the Yangtze estuary will probably continue to decrease, putting pressure on the Yangtze lower reaches and adjacent coastal areas.

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