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Sediment loads in the lower Jinshajiang of the Yangtze River: current status and potential impacts of the cascade dams

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Abstract Dam construction has changed natural sediment loads in rivers at the global, regional, and local scale. This study investigates the potential impacts of four proposed cascade dams on downstream sediment loads in the lower Jinshajiang in the upper Yangtze basin. The sediment trapping efficiency of the proposed dams was computed, and the amount of trapped sediment estimated. The changing trends in sediment loads since the 1950s in the study section (both main channel and main tributaries) are examined to understand the current status and likely future trends after completion of the dams. A sediment budget is constructed for various time periods in the river section.

Key words sediment load; dam; reservoir; the upper Yangtze River (Changjiang)

INTRODUCTION

Fluvial sediment fluxes can affect various aspects of water quality, fish habitats, and channel morphology, as well as coastal environments. The current land–ocean transfer of sediments has largely been changed by humans; reservoir construction represents the most influential anthropogenic perturbation on recent sediment fluxes (Syvitski *et al.*, 2005; Walling, 2006). Sediment trapping by reservoirs has been extensively examined at global, regional and local scales. Vörösmarty *et al.* (2003) found that globally >50% of the sediment fluxes in regulated basins were likely to be trapped in artificial impoundments. According to Syvitski *et al.* (2005), over 100 Bt of sediment have been sequestered in artificial reservoirs within the past 50 years, which caused a net reduction in global sediment fluxes of about 1.4 Bt year^{-1} over pre-human loads, although some of these losses have been counterbalanced by increased soil erosion.

The lower Jinshajiang is a very important river section in term of sediment supply to the Three Gorges Reservoir (TGR) (Fig. 1). This stretch of the river is also ecologically important as it contains the greatest diversity of fish species found in the upper Yangtze basin. Thus, understanding the sediment input to and output from this section of the river is critical not only for the TGR, but also for the conservation of biodiversity. This is especially true as more dams will be constructed in this river section and its upper stream. Four cascade dams have been proposed for the main stem of the lower Jinshajiang, Wu Dongde (WDD), Bai Hetan (BHT), Xiang Jiaba (XJB), and Xi Luodu (XLD) (Fig. 1). The potential impacts of the four dams on downstream sediment fluxes, especially to the TGR, will be significant. This paper attempts to quantify the changes in sediment loads before and after the cascade dams are constructed in this section of the lower Jinshajiang.

STUDY AREA

This study is focused on the river reach from Xiangjiaba on the lower Jingshajiang to the backwater of the TGR (Fig. 1). The gauging stations located in the mainstem include Pingshan, Zhutuo, and Cuntan. There are five major branches in this section from Pingshan to Chongqing, including Minjiang, Tuojiang, and Jialingjiang on the left bank, and Hengjiang and Chishuihe on the right bank. Long-term averages for water discharge and sediment fluxes in the main channel, and the five tributaries are summarized in Table 1.

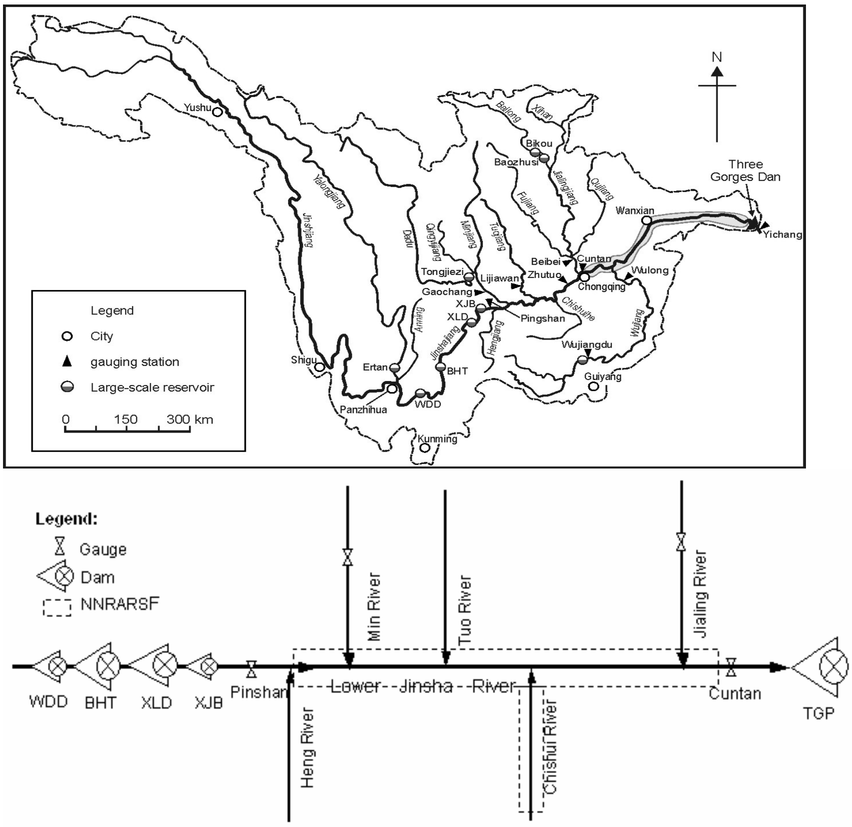

Fig. 1 The upper Yangtze and a sketch map of study area (source: TNC, 2007).

Table 1 The water discharge and sediment load in the main channel and the five tributaries in the study stretch from the 1950s to 2000.

River	Station name	Drainage area (10^4 km^2)	Water discharge (10^8 m^3 year^{-1})	Sediment load (10^8 t year^{-1})
Main channel				
Jinshajing River	Pingshan	48.51	1400	2.6
Jinshajing River	Zhutuo	69.47	2700	3.1
Jinshajing River	Cuntan	86.66	3400	4.2
Main tributaries				
Minjiang River	Gaochang	13.54	870	0.5
Jialingjiang River	Beibei	15.61	660	1.2
Tuojiang River	Lijiawan	2.33	120	0.1
Hengjiang River	Hengjiang	1.48	90	0.1
Chishuihe River	Chishui	1.72	82	0.07

CHANGING TRENDS IN SEDIMENT FLUXES

Figure 2 shows long-term variations in water discharge and sediment fluxes in the lower Jinshajiang, including two stations in the main channel (Pingshan and Cuntan). Sediment fluxes in the lower Jinshajiang have been declining since the end of the 1990s. However, there was no concomitant decline in discharge. Two inflections on the double mass plot for Pingshan indicate an increase in sediment loads during the 1985–1998 period, and a decrease in sediment loads since 1999, although the former change was not very obvious. The increasing trend since the middle of the 1980s probably results from increased soil erosion caused by human activities such as mineral extraction and deforestation in the Jinshajiang basin. Besides the effects of reforestation in the basin carried out since 1998, the abrupt decline in sediment loads after 1999 partly was caused by the completion of the Ertan dam in the lower Yalongjiang, the largest tributary of the Jinshajiang (Fig. 1). The Ertan dam, the largest hydropower station in China before the TGR, with a storage capacity of 5.8 Bm^3, was completed in 1999 after 8 years of construction. It has been reported that the Ertan dam trapped about 95% of the incoming sediment, and the trapped sediment accounted for about one fifth of the total sediment load reduction observed at Pingshan (Feng *et al.*, 2008). The reduction in sediment load after 1999, due to the impact of the Ertan dam, is also shown in the double mass plot for Cuntan (Fig. 2(b)).

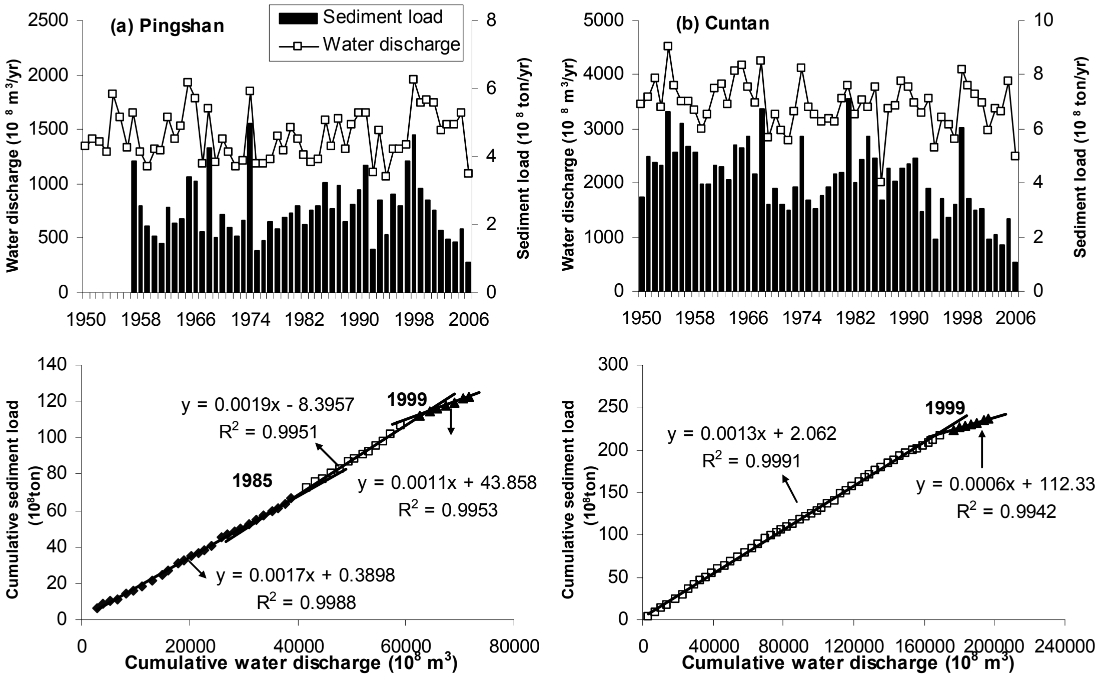

Fig. 2 Temporal variations of water discharge and sediment load in the lower Jinshajiang and double mass plots of cumulative water discharge vs cumulative sediment load at (a) Pingshan and (b) Cuntan.

Table 2 Variations of water discharge (10^8 m^3 $year^{-1}$); and sediment load (10^6 t $year^{-1}$) of the six stations representing five tributaries and the total amount of the five tributaries. The data period is the 1950s–2000s except at stations Lijiawan and Chishui where data are not available after 1987. For the period 1991–2000 and post-2000, total amount of water discharge and sediment load of the major tributaries were calculated by assuming water discharge and sediment load of the Tuojiang at Lijiawan and Chishuihe remained same with the period 1981–1990.

No	Station		before 1960	1961–1970	1971–1980	1981–1990	1991–2000	Post–2000
1	Gaochang	Water	920	890	840	890	830	800
		Sediment	56	58	33	61	35	36
2	Beibei	Water	630	750	610	760	540	540
		Sediment	140	180	110	130	40	22
3	Lijiawan	Water	130	130	110	130	–	–
		Sediment	14	17	8	13	–	–
4	Hengjiang	Water	88	100	87	87	78	69
		Sediment	11	11	14	16	15	6
5	Chishui	Water	57	75	81	85	–	–
		Sediment	5	4	10	7	–	–
	Total	Water	1800	1900	1700	2000	1700	1600
		Sediment	230	270	180	230	110	84

The five tributaries of the Jinshajiang also have shown substantial declines in sediment loads, but only slight declines in water discharge since the 1990s (Table 2). For example, at the Beibei station in the Jialingjiang, sediment loads in the 1990s only accounted for 28%, 22%, 37%, and 30% of the sediment load in the pre-1960, 1960s, 1970s, and 1980s, respectively. Markedly reduced sediment loads were observed post-2000 at most stations. The total sediment load for the five major tributaries in the post-2000 period decreased to 84×10^6 t $year^{-1}$, which is only 36%, 31%, 48%, 37%, and 76% of the sediment loads in the periods pre-1960, 1960s, 1970s, 1980s, and 1990s, respectively.

At most stations, significant declines in sediment loads, due to human impacts, were observed during the 1990s, although the changes varied in different rivers (Fig. 3). For the Minjiang at Gaochang, large declines in sediment load occurred from 1971 to 1980 and after 1994. This decline mainly appears due to dam and reservoir construction in the river basin. For example, the inflection points in 1971 and 1994 in the double mass curve at Gaochang are close to the dates when the Gongzui and Tongjiezi reservoirs in the Minjiang were operated for electrical generation. The inflection point in 1981 corresponds to the date when the Gongzui Reservoir silted up. More significant sediment declines in the Minjiang can be expected due to the large-scale hydropower projects planned for the river basin.

For the Jialingjiang at Beibei, continuous declines in sediment loads were observed at two stations. There are three inflection points in the double mass curve at Beibei station (1969, 1985, and 1995). As in the Minjiang, dam and reservoir construction is a major factor for sediment declines in the Jialingjiang. In addition, soil and water conservation practices carried out since the end of the 1980s probably play an important role in reducing surface erosion and consequently, sediment input to the Jialingjiang. Hence, the sediment decline in the latter period (1995–2006) is the joint result of dam construction and soil and water conservation. The sediment decline in the Hengjiang was observed in the latter 1990s, for similar reasons.

Our results are consistent with previous studies (Xiong *et al.*, 2008; Xu, 2008). Xiong *et al.* (2008) reported a total sediment decline of 147 Mt $year^{-1}$ to the TGR, roughly 73% from the Jialingjiang, and 17% from the Minjiang and Toujiang. They also estimated reductions of about 88 Mt $year^{-1}$ due to the construction of large and medium sized reservoirs, about 24–29 Mt $year^{-1}$ from water and soil conservation measures, and about 65–70 Mt $year^{-1}$ from sand excavation and sediment deposition. The reduction in precipitation contributed to only a 22 Mt $year^{-1}$ decline, while anthropogenic activities such as road construction and mining resulted in sediment increases of around 45 Mt $year^{-1}$ (Xiong *et al.*, 2008).

SEDIMENT TRAPPING BY THE CASCADE DAMS

The empirical relationship developed by Brune (1953) was used for estimating the theoretical trapping efficiency (TE) for the cascade dams. The calculated TEs for the four individual dams, and a cascade of the four reservoirs are listed in Table 3. For individual dams, the TE was calculated using the adjustable storage capacity and inflow for each dam. For a cascade of the four dams, the TE was calculated using the sum of the adjustable total storage capacity of the four dams and the inflow at the most downstream dam.

Based on the trapping efficiency of the cascade of the four dams, the sediment load, post-dam in the lower Jinshajiang was estimated as follows:

$$S_{post\text{-}dam} = S_{pre\text{-}dam} - S_{settled} = S_{pre\text{-}dam} \times (1 - TE)$$

where $S_{post\text{-}dam}$ is the sediment load after dam construction, $S_{pre\text{-}dam}$ is the sediment load before dam construction, and $S_{settled}$ is the sediment deposited within the reservoirs.

Based on the average annual sediment load before dam construction, for the most downstream dam (247 Mt for the period 1965–1987), and the TE of the cascade of the four dams (87%), the annual sediment load after construction of the four dams is 32 Mt. Based on the most recent data (168 Mt at Pingshan for the period 2001–2006), the annual sediment load at Pingshan after dam construction will be 22 Mt.

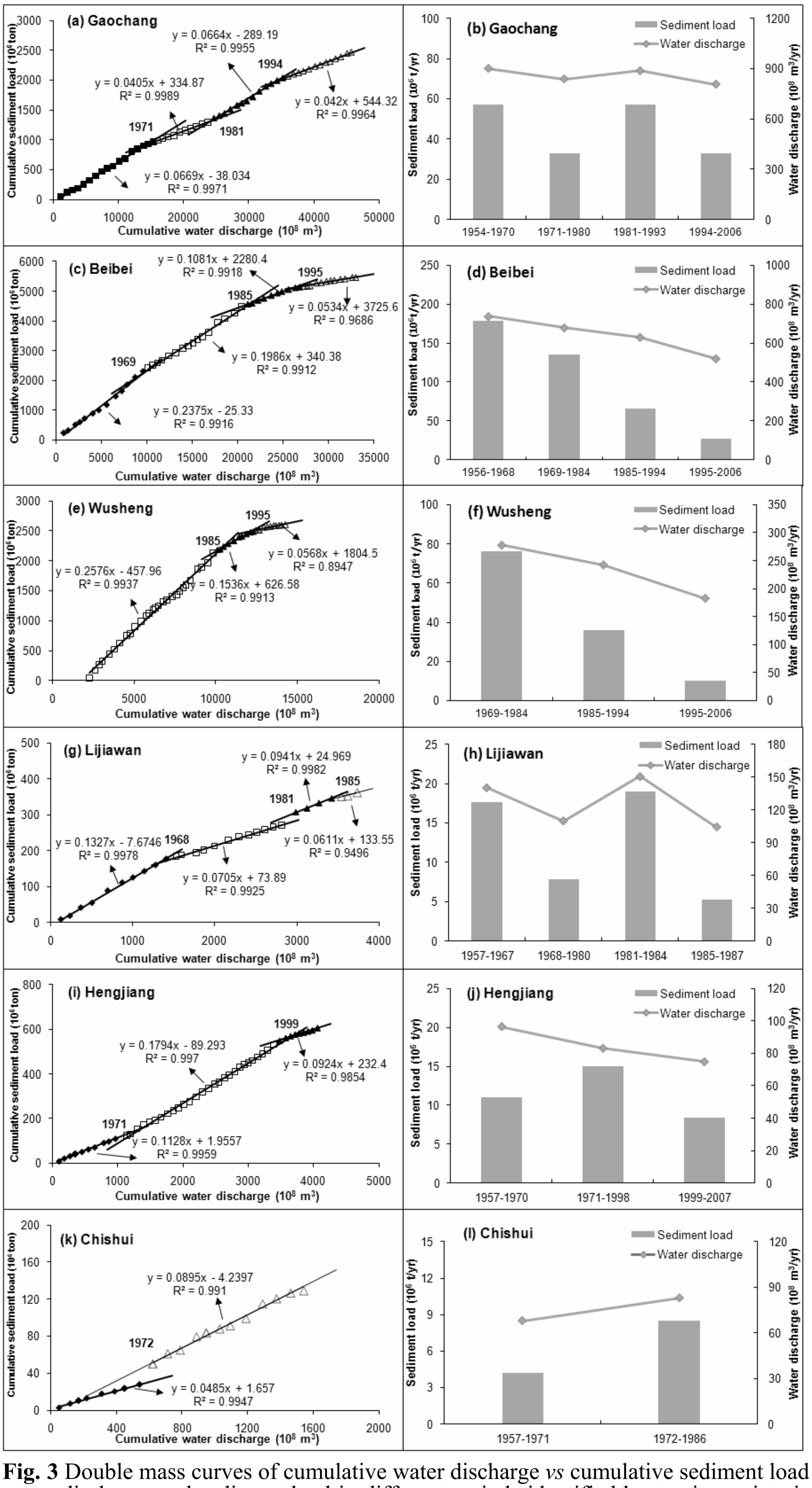

Fig. 3 Double mass curves of cumulative water discharge *vs* cumulative sediment load and variations of water discharge and sediment load in different periods identified by turning points in the double mass curves at stations Gaochang ((a) and (b)), Beibei ((c) and (d)), Wusheng ((e) and (f)), Lijiawan ((g) and (h)), Hengjiang ((i) and (j)) and Chishui ((k) and (l)).

Table 3 Theoretical trapping efficiency for individual dams and the cascade.

Dams	Inflow ($I, 10^8\ m^3$)	Total capacity ($10^8\ m^3$)	Adjustable capacity ($C, 10^8\ m^3$)	C/I	TE (Brune's)
Wudongde (WDD)	1164	58.6	26.2	0.023	0.67
Baihetan (BHT)	1312	205.1	104.4	0.080	0.82
Xiluodu (XLD)	1440	115.7	64.6	0.045	0.76
Xiangjiaba (XJB)	1440	51.63	9.0	0.006	0.37
Cascade of 4 dams	1440	431.0	204.2	0.142	0.87

I is the annual inflow expressed in m^3. C is the reservoir adjustable storage capacity expressed in m^3. TE (Brune's) is the TE calculated using the Brune's equation.

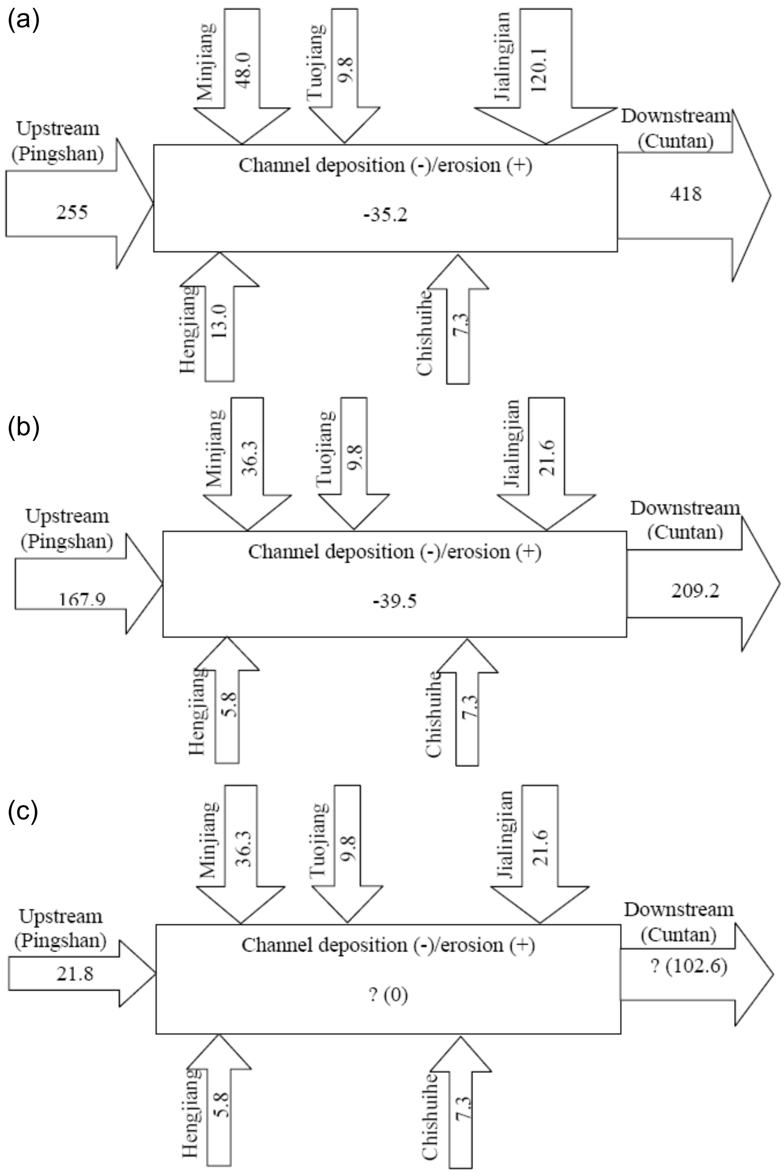

Fig. 4 Sediment budget for the stretch from Pingshan to Cuntan in the lower Jinshajiang (unit: Mt year^{-1}) (a) 1950s–2000, (b) post-2000 and (c) post-dam. For the calculation of sediment budget for the period post-2000, the sediment load from the Tuojiang and Chishuihe were assumed to remain the same level as in the period 1950s–2000. For the calculation of sediment budget for the period post-dam, the sediment load from the main tributaries were assumed to remain at the same level as in the period post-2000. If an equilibrium between channel deposition and erosion was assumed for the period post-dam, sediment load at Cuntan would be 10^3 Mt year^{-1}.

SEDIMENT BUDGET

Based on a sediment budget analysis (Fig. 4), about 35 Mt of sediment was deposited annually in the channel from Pingshan to Cuntan between the 1950s and 2000. For the post-2000 period, sediment deposits within the channel were similar to the earlier period, although decreased sediment loads were observed in both the main channel and main tributaries, particularly in the Jialingjiang during the post-2000 period. In this study, sediment loads during the post-2000 period for the Tuojiang and Chishuihe tributaries of the lower Jinshajiang were assumed to be same as that during the 1950s–2000 period. However, the actual sediment loads for these two tributaries should decline post-2000, as in the other tributaries. Hence, the actual amount of sediment deposited in this section in the post-2000 period should be smaller than the figure estimated here, even though the conventional assumption would assume less deposition or even erosion, with decreasing sediment supply from both the upper stream and the tributaries. This could be due to backwater pooling from the TGR (Hu *et al.*, 2009).

For the post-dam period, sediment loads at Pingshan could dramatically decline to 22 Mt year^{-1} based on the trapping efficiency of the four cascade dams (87%) (Table 3). Channel erosion can be expected in the reach from Pingshan to Cuntan in response to the "hungry water" from the cascading dams upstream from Pingshan. However, erosion is likely to be limited in this reach because of the gravel-lined riverbed, as well as backwater impacts from the TGR. If we assume equilibrium between channel deposition and erosion, the post-dam sediment load at Cuntan station was estimated at 103 Mt year^{-1}.

CONCLUSIONS

The total amount of sediment supply from the five tributaries to the lower Jinshajiang has decreased from 198 Mt in pre-2000 to 84 Mt in post-2000 (or even less if the actual sediment load could be used for the Tuojiang and Chushuihe), and from 260 Mt to 170 Mt from Pingshan (upstream of the studied section of the lower Jinshajiang), from pre-2000 to post-2000. Such declining trends in sediment load were observed in both the main channel and main tributaries of the lower Jinshajiang during the 1990s. The Jialingjiang supplied most of the sediment pre-2000, but has been replaced by the Minjiang post-2000. The Minjiang will become the major tributary, in terms of sediment supply, after the installation of the cascade dams. The dramatic reduction in sediment supply can potentially cause many problems for aquatic ecosystems (e.g. fish habitats, in the stretch of the river that has abundant rare fish species). The construction of the four cascade dams would likely alter both the flow and sediment regime in different reservoir operation models. The "hungry waters" from the lowermost dam should cause downcutting in the downstream river reach; however, this is unlikely to be severe due to the gravel bed nature of the river. On the other hand, the end result may be complicated by pooling from the TGR.

The reduction in sediment supply resulting from the four cascade dams would likely lead to further sediment declines downstream of the TGR, which already has been severe since the TGR started to store water in 2003 (though the TGR will not reach maximum pool until 2009). Further work is required to investigate how far the backwater from the TGR may extend into the lower Jinshajiang, and to determine why there has been no apparent decline in sediment deposition or erosion, despite recent declines in sediment supply.

REFERENCES

Brune, G. M. (1953) Trap efficiency of reservoirs. *Trans. Am. Geophys. U.* **34**(3), 407–418.

Feng, X. F., Yang, Q. Y., Zhang, O. Y. & Wang, X. K. (2008) Sediment trap of Ertan Reservoir and its effect on sediment budget of Jinsha River. *J. Sichuan University* (Engineering Science Edition) **40**(6), 37–42 (in Chinese with English abstract).

Hu, B. Q., Yang, Z. S., Wang, H. J., Sun, X. X. Bi, N. S. & Li, G. G. (2009) Sedimentation in the Three Gorges Dam and the future trend of Changjiang (Yangtze River) sediment flux to the sea. *Hydrol. Earth System Sci*. **13**, 2253–2264.

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J. & Green, P. (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* **308**, 376–380.

TNC (The Nature Conservancy) (2007) Summary Report Supporting the Development of Ecosystem Flow Recommendations for the lower Jinsha River from Yibin to Chongqin (below XJB dam).

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P. & Syvitski, J. P. M. (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. *Global Planetary Change* **39**(1–2), 169–190.

Walling, D. (2006) Human impact on land–ocean sediment transfer by the world's rivers. *Geomorphology* **79**(3–4), 192–216.

Xiong, M., Xu, Q. X. & Yuan, J. (2008) Analysis of multi-factors affecting sediment load in the Three Gorges Reservoir. *Quatern. Int.* **208**, 76–84.

Xu, J. X. (2008) Plausible causes of temporal variation in suspended sediment concentration in the upper Changjiang River and major tributaries during the second half of the 20th century. *Quatern. Int.* **208**, 85–92.