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Is the Three Gorges Dam the cause behind the extremely low suspended sediment discharge into the Yangtze (Changjiang) Estuary of 2006?

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Abstract In 2006, the suspended sediment discharge (SSD) into the Yangtze (Changjiang) Estuary, China, reached the historical low value of 85×10^6 t. One hypothesis is that this was caused by the second impoundment, i.e. the second stage of the water-level increase behind the Three Gorges Dam (TGD). However, coincidentally, a significant drought occurred in the same year. From our analysis of long-term data on discharge and SSD, we conclude that the SSD decrease in the upstream catchment area resulting from the extreme drought is primarily responsible for the historical low SSD into the Yangtze Estuary. We quantified the contributions of the extreme drought and the second impoundment to the reduction of SSD into the Yangtze Estuary in 2006 as 82% and 18%, respectively. Even though the TGD is the largest dam in the world, the results indicate that the extreme drought conditions had a greater impact than such a manmade river regulation.

Key words suspended sediment discharge (SSD); Yangtze (Changjiang) Estuary; China; Three Gorges Dam (TGD); extreme drought

Le barrage des Trois Gorges est-il la cause du débit des sédiments en suspension extrêmement bas de 2006 au niveau de l'Estuaire du Yangtze (Changjiang)?

Résumé En 2006, le débit des sédiments en suspension (DSS) dans l'estuaire du Yangtze (Changjiang), en Chine, a atteint la valeur historiquement basse de 85 × 106 t. Une hypothèse est que cela est causé par la seconde mise en eau, i.e. la seconde étape de l'élévation du niveau de l'eau derrière le Barrage des Trois Gorges (BTG). Toutefois, une sécheresse importante s'est produite en coïncidence la même année. D'après notre analyse des données à long terme de débit et de DSS, nous concluons que la diminution du DSS dans le bassin versant amont résultant de l'extrême sécheresse est la cause principale du niveau historiquement bas du DSS dans l'estuaire du Yangtze. Nous avons quantifié les contributions des effets de la sécheresse extrême et de la seconde mise en eau sur la diminution de 2006 du DSS au niveau de l'estuaire du Yangtze respectivement à 82 et 18%. Même si le BTG est le plus grand barrage du monde, les résultats indiquent que les conditions de sécheresse extrême ont eu une influence plus grande que cette infrastructure anthropique de régulation fluviale.

Mots clefs débit des sédiments en suspension (DSS); estuaire du Yangtze (Changjiang); Chine; Barrage des Trois Gorges (BTG); sécheresse extrême

INTRODUCTION

Presently, there is considerable concern about the decrease in suspended sediment discharge (SSD) in the large estuaries of the world as a result of extensive human activities in their catchment areas (Milliman 1997, Syvitski *et al*. 2005, Zhang *et al*. 2008). Most studies indicate that dam constructions have led to a significant impact on the decrease of SSD in rivers (Vörösmarty *et al*. 2003, Walling and Fang 2003, Dai *et al*. 2010b, Yang *et al*. 2010). As a consequence of the upstream obstruction due to dams, notable reductions of SSD into the estuaries of large rivers, such as the Nile, Mississippi, Colorado, Ebro and Yellow rivers have been reported (Sánchez *et al.* 1998, Carriquiry *et al.* 2001, Frihy *et al*. 2003, Yang *et al.* 2004, Syvitski *et al.* 2005). However, a decrease in SSD to an estuary may also be due to soil and

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water conservation and sediment control programmes in the upper reaches, and may be aggravated by climate change (Walling and Fang 2003). For example, decrease in precipitation is responsible for 30% of the decrease in sediment load at Huayuankou station in the Yellow River; soil conservation practices contribute 40% to the total decrease (Wang *et al.* 2007). However, the remaining 30% of the decrease in sediment load is a result of the operation of reservoirs upstream at Huayuankou station in the Yellow River (Wang *et al.* 2007). It is difficult to separate the impact of climate change from that due to human activities on the decreasing levels of SSD (Walling and Fang 2003).

Since the Three Gorges Dam (TGD), the largest dam in the world, was constructed in the Hubei Province of China, the decrease of SSD into the Yangtze Estuary has been investigated (Syvitski *et al.* 2005). Previous studies have addressed the impacts of human activities on the SSD changes (Yang *et al*. 2002, Gao and Wang 2008), the impacts of the first impoundment in 2003 (Chu and Zhai, 2006, Yang *et al.* 2007) and an assessment of SSD into the estuary (Yang *et al.* 2007). In general, insufficient data are available to distinguish between the impact of climate change and that due to the TGD on SSD. However, our collection of a long data series allows this distinction to be made. As described by the Changjiang River Water Resource Commission (CRWRC), the drought situation in the catchment area in 2006 was the worst in the previous 50 years (CRWRC, 2007). The precipitation in the Yangtze River basin in 2006 was very low compared to normal years: e.g. it was 15–25% lower than that in the years 2000–2005. The precipitation measured in 2006 at some stations (e.g. Cuntan, Beibei) was as much as 30% lower than that in normal years (CRWRC, 2007, Dai *et al*. 2010b). The flood season in the Yangtze River lasts from May to October and the dry season from November to April (Liu *et al*. 2010). However, between 20 September and 27 October 2006, water was stored behind the TGD, increasing the water level from 135 m to 156 m, and this has been suggested as one of the reasons for the low discharge in the Yangtze River (Dai *et al*. 2008). The total SSD at Datong, the tidal limit of the Yangtze River, reached a historical low value of 85×10^6 t in 2006, which might be due to the sediment trapping efficiency of the TGD, but also to other factors. Therefore, the purposes of this study are: (a) to analyse the characteristics of SSD into the Yangtze Estuary in 2006; (b) to assess the SSD changes before and after the water-level increase from 135 to 156 m behind the TGD; (c) to assess the factors contributing to the lowest value of SSD into the Yangtze Estuary in 2006; and (d) to quantify the contribution of the extreme drought conditions and the second TGD impoundment on the SSD decrease in 2006.

DATA COLLECTION AND METHODS

Daily discharge and suspended sediment concentration (SSC) data for the gauging stations shown in Fig. 1 were obtained for the years 2000–2007 from the CRWRC, Ministry of Water Conservancy of China (*Bulletin of Yangtze River Sediment*, 2000–2007). Monthly accretion amounts behind the TGD from 2003 to 2007 were also obtained from the CRWRC (*Bulletin of Yangtze River Sediment*, 2000–2007). Monthly discharge and SSC data from 1955 to 1999 at gauging stations were provided by the CRWRC. The gauging stations Cuntan, Yichang, Hankou and Datong, are on the Yangtze River; Beibei, Wulong and Huangzhuan are on the tributaries of the Yangze, Jialingjiang, Wujiang and Hanjiang, respectively (see Fig. 1). The sediment load contribution from Dongting and Poyang lakes into the Yangtze River is gauged at Chenglingji and Hukou stations, respectively. These are two main sediment supplies in the middle of the Yangtze River, besides the river Hanjiang (Yang *et al*. 2007, Xu and Milliman 2009). Observations of discharge and SSC at these hydrological stations are based on the national standards issued by the Ministry of Water Conservancy and Electric Power (e.g. 1962, 1975), and the procedures followed for hydrological surveys, sampling and laboratory SSC analyses at hydrological stations in China are based on international standards (Xu 2007). In addition, the homogeneity and the reliability of the data have been checked by CRWRC before the data were released (Zhang *et al.* 2006). Therefore, hydrological data in this study should be considered reliable. Here, based on the characteristics of sediment supply to the Yangtze River, the total SSD (being the product of river discharge and SSC) at Cuntan, Beibei and Wulong stations (collectively referred to as CBW) represents the suspended sediment discharge upstream of the TGD. The total SSD at Chenglingji, Hukou and Huangzhuan stations (CHH) represents the SSD in the middle reach of the Yangtze River, where the sediment supply from Dongting Lake is the difference between that at Chenglingji and the three distributaries into Dongting Lake from the Yangtze River (Yang *et al*. 2007). The data at Datong represent the SSD into the Yangtze

Fig. 1 Hydrological station distribution.

Estuary. Our analysis also includes SSC, since it is more sensitive to the discharge than SSD.

Statistical analysis of the hydrological data for 2006 was applied to study the characteristics of discharge and SSD delivered into the estuary. The results are compared to data of: normal years (e.g. the mean over the years 1955–2002); the extreme drought year of 1978 (Dai *et al.* 2008); the impoundment start year (2003); the mean over the years 2004–2005 after the first impoundment phase of the TGD; and the subsequent year 2007 with the impoundment water-level increase from 145 to 156 m during 25 September–23 October. The mean (M), standard deviation (SD) and coefficient of variation (C_V) of discharge, SSD and SSC were calculated by the most common statistical methods.

RESULTS

Change in SSD

The yearly variations of discharge and SSD at Datong since 1954 are presented in Fig. 2(a) and (b) and the monthly values are given in Fig. 2(c) and (d). Note that, while in the discharge no trend appears, a slightly decreasing trend in the SSD starts in the 1970s and, from the mid-1980s, it steepens, which may be due to the change in land use from disordered human activities to practices that showed more concern for water and soil conservation in the catchment area (Yang *et al.* 2002). In addition, annual discharge changes in the Yangtze River basin might be influenced by climate change, especially changes in precipitation (Zhang *et al.* 2006). Our interest, though, is in the characterization of the monthly variation of discharge and SSD in 2006 compared to other years and/or multi-year periods, and, to quantify this, the statistical analysis was carried out. From the results of the analysis shown in Table 1, and the corresponding Fig. 2(c) and (d), we observe that the ratio, R, between the maximum and minimum SSD and SSC at Datong in 2006 is the smallest compared to other years. The SD and C_V further indicate that the standard deviation of SSD is rather small in 2006 compared to that in the other years, even when compared to that with the similar impoundment effect in 2007. As a result, the monthly changes of SSD in 2006 are clearly different from the other years (Fig. 2(c)). This can be characterized as "low SSD in the flood season and even lower SSD in the dry season" (LSFS-LSDS).

Change in SSD during the second impoundment phase of the TGD

The second impoundment phase of the TGD took effect between 20 September and 27 October 2006. It takes about 14 days for the water and associated SSD flowing from the TGD to reach Datong station (Chu

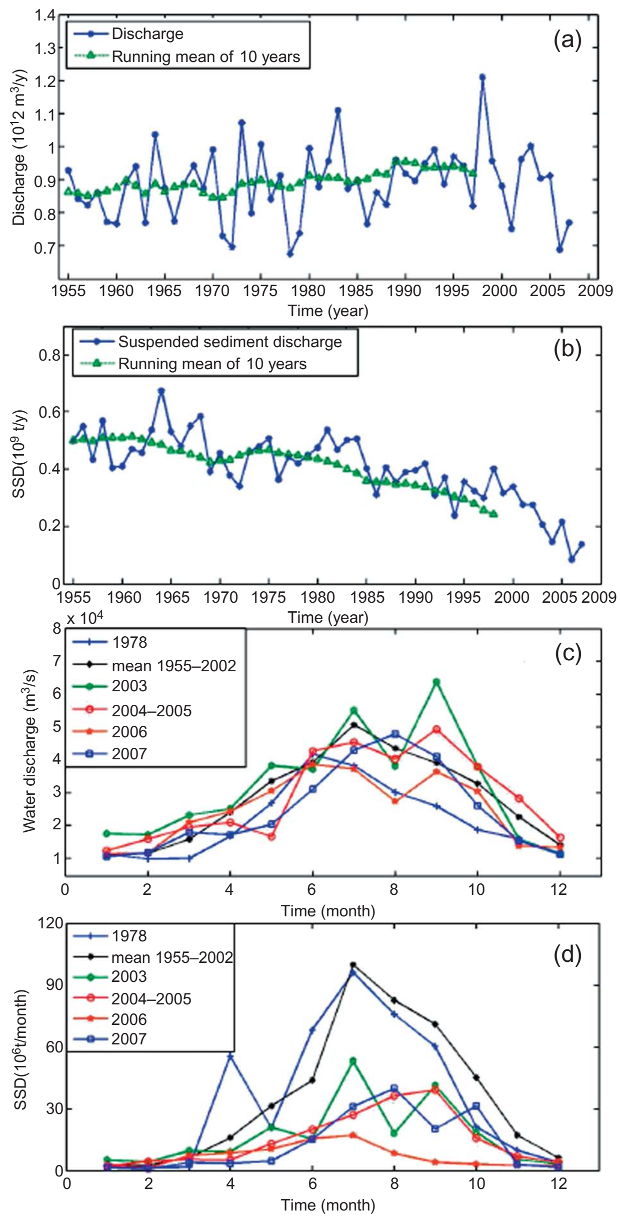

Fig. 2 Discharge and SSD at Datong station.

and Zhai 2006). Hence, we concentrated our analysis of the daily SSD change at Datong on the period 14 days later, i.e. from 4 October to 11 November.

From Fig. 3, obvious changes in discharge, SSC and SSD may be observed at Datong from the end of the flood season, September, to the dry season in 2001, 2002 and after the first impoundment phase, i.e. during 2004 and 2005, and in 2007 after the impoundment phase with water level from 145 to 156 m. A minor decrease in discharge and sediment load can also be seen around 8 November 2003, which is exactly the starting date of the first impoundment when the water level was raised from 135 to 139 m. During and after the first impoundment phase, in 2003, slight changes in discharge and sediment can be noticed.

However, in 2006, around the second impoundment phase of the TGD, small changes in SSC and SSD at Datong station are observed, and only a slight change in discharge (Fig. 3). The characteristics of the SSD in 2006 are almost the same as those in the other years (Fig. 3). Therefore, the SSD in the Yangtze Estuary during the second impoundment phase in 2006 is evidently different, not only from that in the "normal years", but also from those during the first impoundment phase in 2003 and the subsequent similar impoundment situation in 2007.

DISCUSSION

SSD change along the Yangtze River

Generally, the supply of SSD upstream of the TGD is an important contribution to the estuary sediment load budget (Xu *et al.* 2007, Yang *et al.* 2010). Table 2 reveals that the SSD upstream of the TGD is

Table 1 Statistics of the hydrological parameters at the Datong station.

	Year	1978	1955–2002	2003	2004–2005	2006	2007
SSD (kg/s)	M	11671	13413	6511	5744	2693	4987
	SD	12966	12620	5855	4911	2012	5283
	C_V	1.11	0.94	0.9	0.86	0.75	1.06
	R	51.3	34.6	15.9	17.1	10.7	36.3
SSC (kg/m^3)	M	0.41	0.40	0.22	0.21	0.12	0.17
	SD	0.35	0.24	0.07	0.09	0.05	0.09
	C_V	0.93	0.64	0.57	0.55	0.43	0.73
	R	46.7	7.5	9.7	15.2	7.32	28

SSD and SSC are averages over the indicated period; M: mean; SD: standard deviation; C_V: coefficient of variation; R: ratio between maximum and minimum.

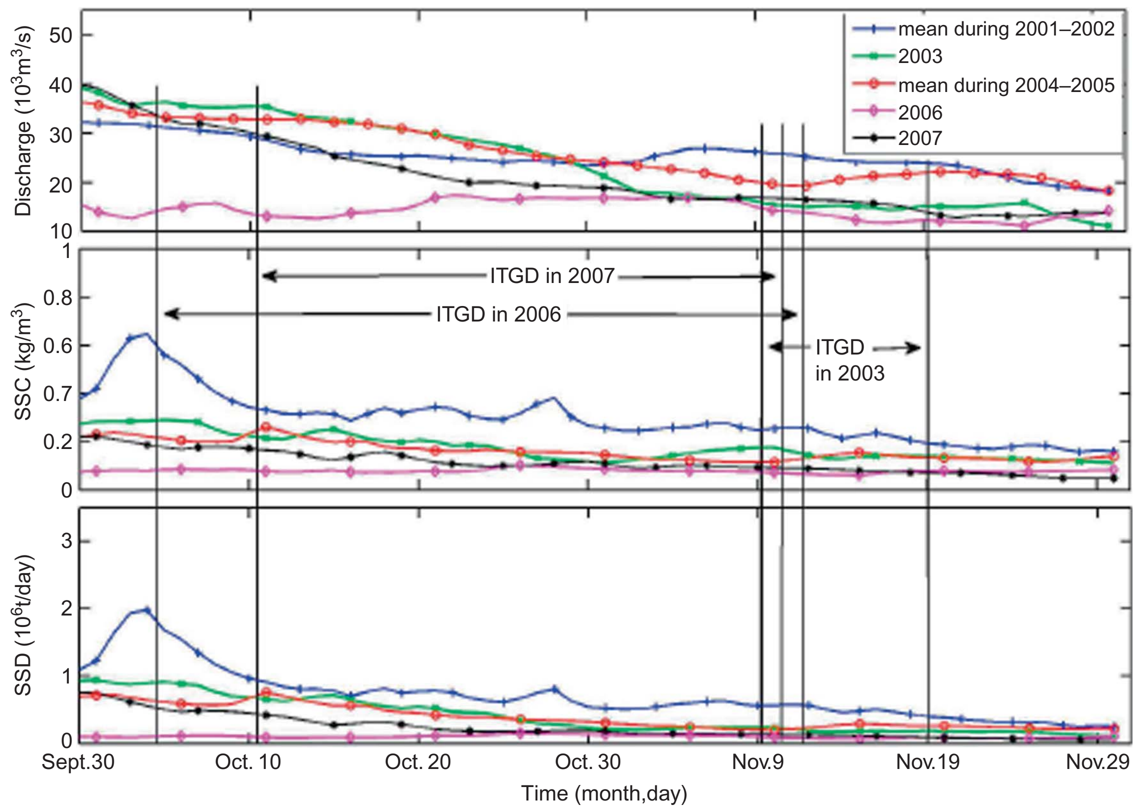

Fig. 3 The daily discharge, SSC and SSD at Datong during the impoundment phase (ITGD: impoundment phase of the TGD).

much larger than that downstream of the TGD (compare the stations in the upstream, CBW, and in the downstream, CHH), while SSD is gradually decreasing from the upstream towards Datong. The total SSD at CHH during mean multi-years, 2001 and 2002, before the construction of the TGD, indicates negative values when compared to those after the impoundment of the TGD. The loss of sediment to Dongting Lake appears to have shifted to a net input to the main river in recent years (Yang *et al.* 2007, Xu and Milliman 2009). Dongting Lake was the main sediment reservoir, reducing SSD in the lower reaches. Since the TGD started impounding water, most of the sediment was deposited behind the TGD. However, it can be observed from Table 2 that before the first impoundment phase (before 2003), the amount of net SSD around CHH is below 13×10^6 t, which is rather small compared to that from the upstream. Although the amount of the net SSD around CHH rose slightly after the first impoundment phase, it is one order smaller than that from the upstream. Thus, the amount of SSD into the estuary after the first impoundment is not determined by SSD in the middle reach.

According to the data represented in Table 2, although the SSD output at CHH increased significantly more compared to the other years with a comparable increase of net SSD at Shashi in 2006, the SSD at Datong was at a historical extreme low. On the other hand, SSD decreased to 21% of its long-term mean value at CBW in 2006 with a similar decreasing magnitude at Datong. We must thus conclude that this significant decrease at CBW directly contributed to the extremely low SSD at Datong.

Impact of the TGD on the decrease in SSD

Although a similarly low discharge occurred in the extreme drought years, 1978 and 2006, due to the decreased precipitation in the Yangtze River basin, relatively low SSD in 1978 cannot be found in comparison to that in 2006. The aggravated soil erosion from disordered hillside reclamation in the Yangtze River basin during the 1960s–1970s (Yang *et al.* 2002) could counterbalance the impact of decreased precipitation on the SSD produced in 1978. In addition, decreasing trends in SSD started in 1984 or

Table 2 Comparison of SSD between at gauging stations and at Datong station.

	CBW[1]			Yichang			Shashi		CHH[2]		Datong		Accretion behind TGD (10^6 t)
	SSD[3]	R1[4] (%)	R2[5] (%)	SSD	R1 (%)	R2 (%)	SSD	R3[6]	SSD	R2 (%)	SSD	R1 (%)	
Multiyear[7]	555	–	134	470	–	114	415	−55[8]	−13		414	–	
2001	353	64	128	299	64	108	313	14	−10		276	67	
2002	224	40	81	228	49	83	241	13	−4		275	66	
2003	251	45	122	98	21	47	138	40	29	14	206	50	124
2004	201	36	137	64	14	44	96	32	19	13	147	36	102
2005	317	57	147	110	23	51	132	22	24	11	216	52	151
2006	116	21	137	9	2	11	25	16	30	36	85	21	93
2007	248	45	179	53	11	38	75	22	19	14	138	33	169
Distance from TGD (km)	620[9]			37			137		992[10]		1177		

[1] total in the upstream (10^6 t/year); [2] total in the middle stream (10^6 t/year); [3] yearly average (10^6 t/year); [4] ratio of SSD of a certain year to the multiyear one; [5]: ratio of SSD at a certain station to that at the Datong; [6] net SSD in the section between Yichang and Shashi; [7] average during 1950–2005 (10^6 t/year); [8] positive values represent SSD increasing and negative represent SSD decreasing; [9] distance between Cuntan and TGD; [10] distance between TGD and Hukou.

1985 at Datong, due to afforestation and soil protection countermeasures along the upper reaches of the Yangtze River (Yang *et al*. 2002). Dam constructions in recent decades in the Yangtze River basin could also be one of the important factors in the sharp drop in SSD. Some studies have been conducted on the influence of the TGD on the sediment discharge into the estuary (Yang *et al*. 2007, Xu and Milliman 2009). However, the influence of the TGD on the SSD into the Yangtze Estuary has not been investigated in an extreme drought year. The amount of sediment accumulation behind the TGD in 2006 was about 93 $\times$ 10^6 t (Table 2), which is comparable to the SSD at Datong. The TGD could be one of the factors influencing the SSD into the estuary. To assess the impact of the TGD, the following aspects were considered: (1) the second impoundment phase of the TGD that started on 20 September, which means the influence of the TGD should be effective after that date; and (2) the sediment accumulated from 20 September to the end of 2006 as a result of the deposition after the second impoundment phrase of the TGD. The SSD captured by the second impoundment is about 23 $\times$ 10^6 t (Fig. 4), which is about 27% of the SSD at Datong. Moreover, accretion behind TGD in 2006 was also the lowest compared to the accretion in different impoundment years (Table 2 and Fig. 4). This implies that the TGD is not the dominant factor of the SSD reduction at Datong in 2006.

Combined contribution of TGD and the extreme drought condition on SSD

While it is difficult to separate the impact of climate on SSD from human activities in general (Walling and Fang 2003), we have the data available to document this for the Changjiang River. During the second impoundment phase in 2006, the sediment accumulated behind the TGD was 23 $\times$ 10^6 t, which is calculated from Fig. 4. The SSD at Datong in 2006 was 85 $\times$ 10^6 t, which is about 40% of the SSD (216 $\times$ 10^6 t) in 2005. In other words, the SSD in 2006 is 60% (130 $\times$ 10^6 t) less in comparison with that in 2005. Meanwhile, it is noted that the increase of SSD due to river bed scouring in downstream to Yichang in 2006 is about 46 $\times$ 10^6 t, which is comparable to those in other impoundment years (Table 2). This means that the change of river bed scouring during the second impoundment phase of TGD has little influence on the reduction of SSD in 2006. Thus, this reduction can be attributed to the effects of the extreme drought condition and the second impoundment phase in 2006. Although there is no information about the climate effects on the SSD, we have information about the sediment accumulated behind the TGD during the second impoundment phase. Thus, we may infer that the contribution of the TGD to the reduction of the SSD at Datong was 23 $\times$ 10^6 t, which is only 18% of the total SSD reduction. Although many studies

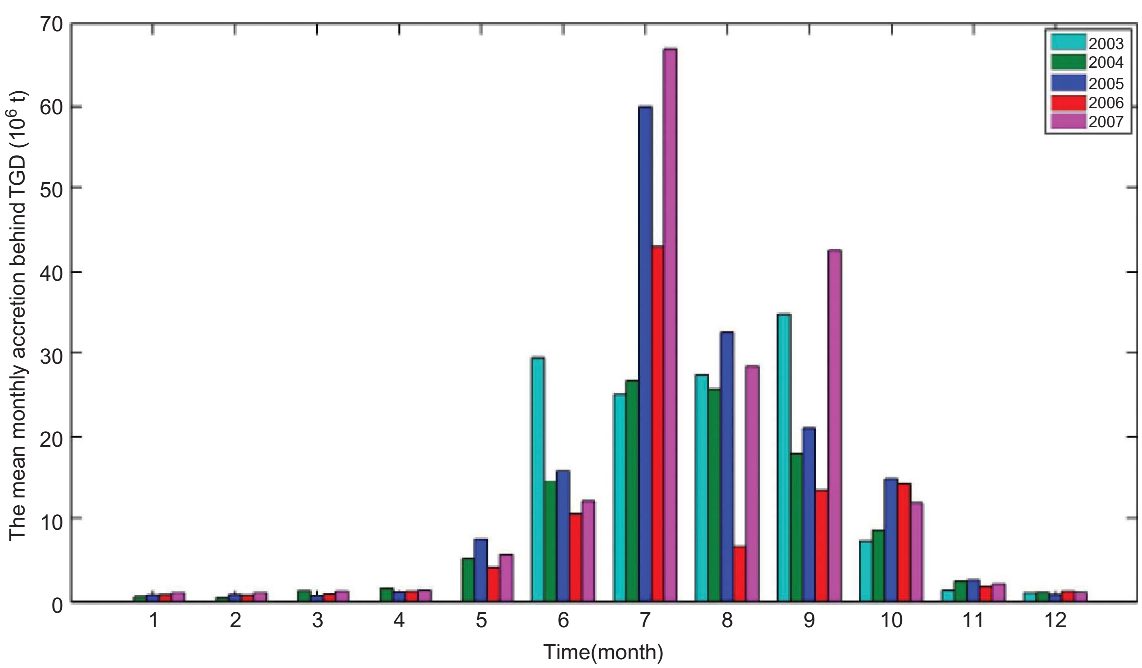

Fig. 4 Accumulation of sediment discharge behind the TGD.

hypothesize that the regulation of water and sediment discharge in most rivers is due to dams alone (Nilsson *et al*. 2005), it is our hypothesis that the SSD discharge is impacted by the combination of the extreme drought in 2006 and the second impoundment phase of the TGD. Hence, we quantify the contribution of the extreme drought on the SSD reduction to be 82% in 2006. Therefore, the extreme drought in 2006 played a dominant role in the extremely low SSD into the estuary.

CONCLUSIONS

Extreme drought occurred in the catchment area of the Yangtze River in 2006, simultaneously with the second impoundment phase of the TGD. It can be concluded that the SSD into the Yangtze Estuary in that year has the following characteristics:

1. The change of SSD into the Yangtze Estuary can be characterized as "low SSD in the flood season, lower SSD in the dry season" (LSFS-LSDS), and SSD has been regulated both by the TGD and the extreme drought condition.
2. The SSC in the Yangtze Estuary experienced no changes around the second impoundment phase of the TGD in 2006.
3. The extremely low SSD into the Yangtze Estuary occurring in 2006 was caused by the low SSD in the upstream area, with less influence from the TGD.
4. The SSD at Datong in 2006 was 60% less than that in 2005. We estimate that this reduction is due to the second impoundment phase of the TGD and to the extreme drought in 2006, at 18% and 82%, respectively.

In other words, the extreme drought in 2006 is the main reason for the extremely low SSD to the estuary in that year.

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