Impact of the Three Gorges Dam Overruled by an Extreme Climate Hazard

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Case Study

Impact of the Three Gorges Dam Overruled by an Extreme Climate Hazard

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Abstract: While it is generally difficult to separate the impact of extreme climate events on river catchment conditions from that of human activities, there are unique data available to document this for the catchment area of the Yangtze in the years that the Three Gorges Dam (TGD) started to have an impact. During the second impoundment phase in 2006, the suspended sediment discharge (SSD) and water stored behind the TGD was 23×10^6 t and 11×10^9 m^3, respectively, which is only 18% of the total SSD reduction and about 1% of the water discharge (901×10^9 m^3) in 2005 at Datong. The total SSD and water discharge into the Yangtze Estuary in 2006 was 60 and 24% less than those in 2005, respectively. It can be quantified that the contribution of the extreme climate (drought) on discharge and SSD reduction was 95 and 82% of the total in 2006, respectively. In addition, it was found that the periods of high salinity (>250 and 400 mg/L) at Haimen that happened during the second impoundment phase accounted for 25 and 23% of the total occurrences in 2006, respectively. This analysis shows that the impact of extreme climate conditions can overrule the human interference, even for the largest dam, the TGD. **DOI: 10.1061/(ASCE)NH.1527-6996.0000081.** *© 2012 American Society of Civil Engineers.*

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Author keywords: Extreme drought; Suspended sediment discharge; Water discharge; Salt intrusions; Yangtze (Changjiang) River; Three Gorges Dam.

Introduction

Extreme climate change and associated hazards have occurred throughout human history. Extreme events will be more frequent and intense because of global warming (IPCC 2001). These events are making world headlines today, such as tornados wreaking great havoc in the United States and severe droughts in central China (Lu 2011). There have been increased trends for natural hazards induced by human actions and extreme climate events (Ruddiman 2003). The recent study on land degradation phenomena in the Mediterranean area reveals the importance of extreme drought and anthropogenic interference (Märker et al. 2008). Some investigations indicated that high and low flows could be affected by land use and climate changes (IPCC 2001; Samaniego and Bárdossy 2007). Moreover, serious water shortage in the Icelandic water resource system was documented based on the main reservoirs and extreme droughts (Jonsdottir et al. 2005). In fact, understanding the consequences of these extreme drought events and of human actions on natural systems is becoming one of the great challenges for global climate-change scientists (Boisvenue and Running 2006; Bonan 2008), especially large dam impacts. Dam constructions and impoundments in large river basins have been one of the most consequential human actions, which can alter precipitation (Hossain 2010) and fragment the fluvial system (Graf 1999), even though the dam provides the benefits of flood protection, irrigation, and hydroelectric power.

The Three Gorges Dam (TGD), the largest hydropower dam in the world, is located in the upstream stretch of the Yangtze River, the longest river of Eurasia (Fig. 1). The expected environmental impact of the TGD has been a persistent issue, ever since the plan was raised (Boxer 1988; Gwynne and Qin 1992; Shen and Xie 2004). The general opinion is that dams drastically impact the environment on a catchment scale (Milliman 1997; Nilsson et al. 2005; Syvitski et al. 2005), e.g., leading to isolation and fragmentation of upstream and downstream catchment areas (Humborg et al. 1997). Also the TGD is expected to lead to landscape fragmentation on the scale of the Yangtze catchment basin (Boxer 1988; Shen and Xie 2004) with specific concern for increased saltwater intrusion and coastal erosion because of dam-related regulation of water and sediment discharges to the estuary (Yang et al. 2007b; Dai et al. 2008, 2011c). However, it is not clear for this epic experiment how and to what extent it will affect surrounding conditions, especially because of its coincidence with extreme drought events.

In 2006, an extreme drought along the Yangtze (Changjiang) basin happened to coincide with intensive anthropogenic activities, i.e., the second storage phase of the TGD with water level increasing from 135 to 156 m. With extremely high temperatures in this drought, evaporation of the Yangtze basin greatly increased, and the precipitation in the Yangtze River basin in 2006 was 30% lower than that in a normal year (CWRC 2007). It is noted that in 2006 suspended sediment discharge (SSD) and water discharge at Datong,

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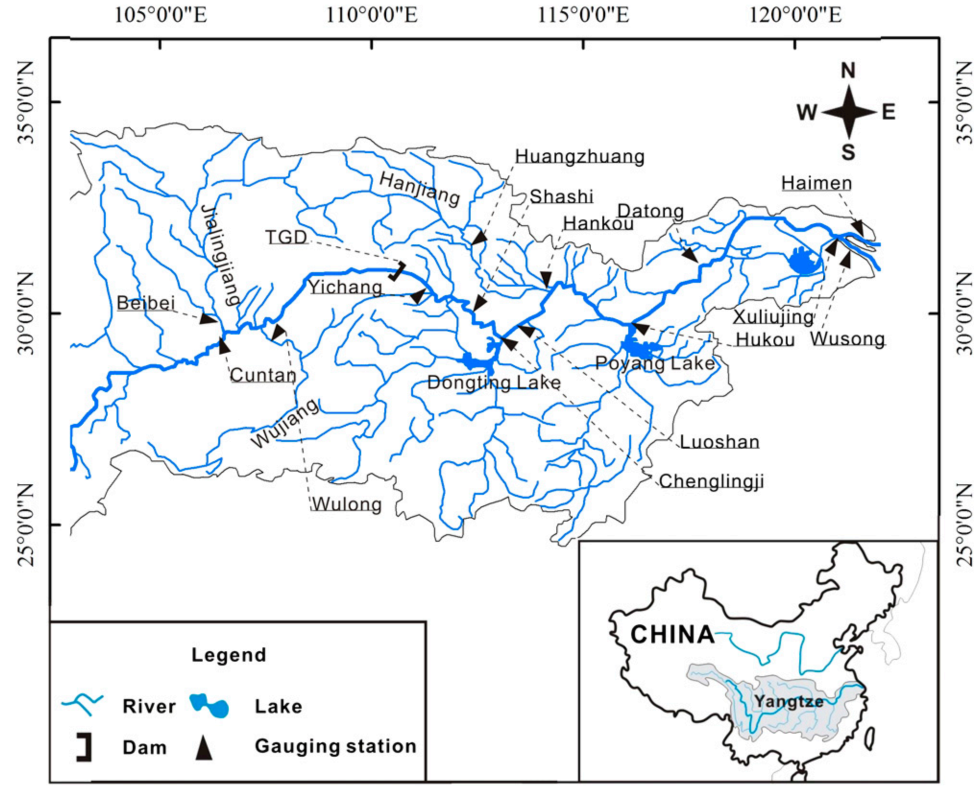

Fig. 1. Research area and hydrological gauging stations

the tidal limit of the Yangtze Estuary (Fig. 1), showed a record low (Dai et al. 2008, 2011a, 2011c). Consequently, estuarine salt intrusion and high salinity values were also observed around the salt intrusion limit, Haimen, which is near the first bifurcation point of the Yangtze Estuary (Fig. 1) (Dai et al. 2011b). It seems that abnormal records of SSD, water discharge, and salinity change in 2006 all occurred because of the impacts of the extreme drought and the TGD operation. As there is no comprehensive assessment on TGD impacts in 2006, it is widely wondered how TGD could induce or have some relation with this extreme drought. How to separate the TGD impacts from natural climate conditions could be a key to determine the degree of the effects of the TGD. Here, it was found that extreme climate conditions in the catchment area, such as those that occurred in 2006, may be of at least similar or even larger impact. Although this is the case for the TGD specifically, it might well apply to other dams in catchment areas with a similar ratio between upstream and downstream areas.

Material and Methods

Discharge and suspended sediment concentration (SSC) data at the gauging stations were provided by the Changjiang River Water Conservancy Committee, Ministry of Water Conservancy of China. The gauging stations, Cuntan, Yichang, Hankou, and Datong, are in the Yangtze River. Beibei, Wulong, and Huangzhuan are in the branches Jialingjiang, Wujiang, and Hanjiang, respectively. In addition, Chenglingji and Hukou stations gauge the sediment load from the Dongting Lake and the Poyang Lake into the Yangtze River. The total SSD (being the product of river discharge and SSC) at Cuntan, Beibei, and Wulong stations (CBW) represents the sediment discharge upstream of the TGD. The total SSD at Chenglingji, Hukou, and Huangzhuan stations (CHH) represents the sediment supply in the middle reach of the Yangtze River (Fig. 2). The SSD data at Datong represent the SSD into the estuary. This analysis also includes SSC, because it is correlated with the discharge. In addition, daily salinity data in 2006 were collected at Haimen, near the first bifurcation point of the Yangtze Estuary, where the salinity is determined by the intrusion of salt water through the different inlets and the freshwater discharge (Fig. 1). The data were made available by the Hydrological Bureau of Jiangsu Province (〈http://www.jswater.gov.cn/〉).

Comparison of the statistical hydrology parameters between 2006 and normal years (mean over the years 1955–2002), the extreme drought year in 1978 (Dai et al. 2008), the impoundment start year (2003), and the mean over the years 2004–2005 after the first impoundment phase of TGD was applied to study the characteristics of discharge and SSD delivered into the estuary. The average (M), SD, and coefficient of variation (C_V) of the discharge, SSD, and SSC parameters were calculated by the moment method (Greenwood et al. 1979), where M is the annual mean of several years of monthly observations, SD is the standard deviation of the monthly observations over a year or a period of several years, and C_V is the standard deviation divided by the mean, representing the deviation between monthly values and the mean.

Results

Water and Suspended Sediment Discharge in 2006

The first impoundment phase of the TGD started in 2003 with the water level behind the dam raised to 135 m. The water level behind the TGD was raised to 156 m during the second impoundment phase in 2006. In the same year, an extreme drought occurred in the Yangtze River basin. The drought situation occurring in the whole catchment area in 2006 was the worst in the last 50 years with an

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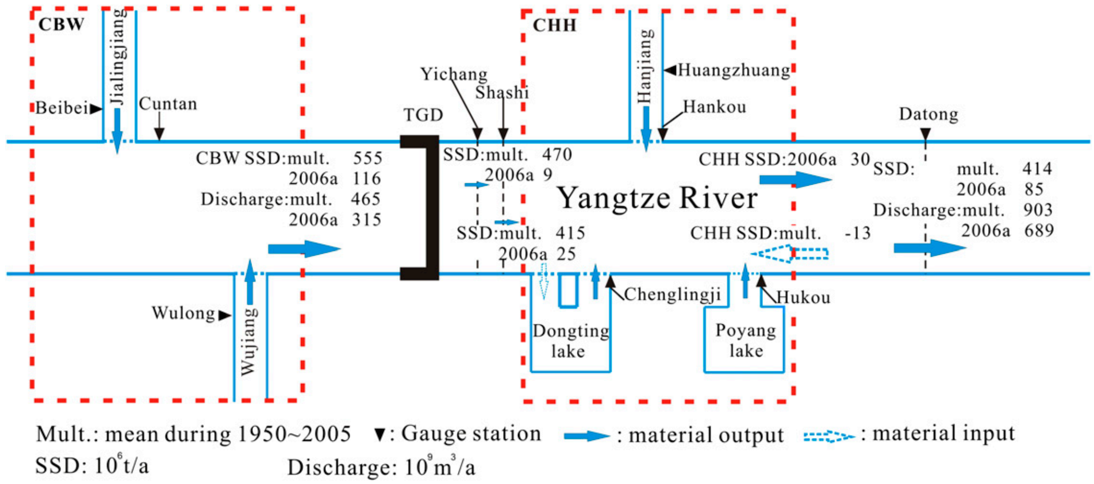

Fig. 2. Chart of SSD and water discharge change along the Yangtze River in 2006 and mean during 1950−2005 (adapted from Dai et al. 2011a): multi refers to the multiyear mean over the period 1950−2005; the SSD and the discharge at CBW and CHH represent the amounts flowing into the Yangtze River in the upstream and in the middle stream, respectively; the value of total SSD and total discharge indicate the yearly SSD (10^6 t/year) and discharge (10^9 m^3)

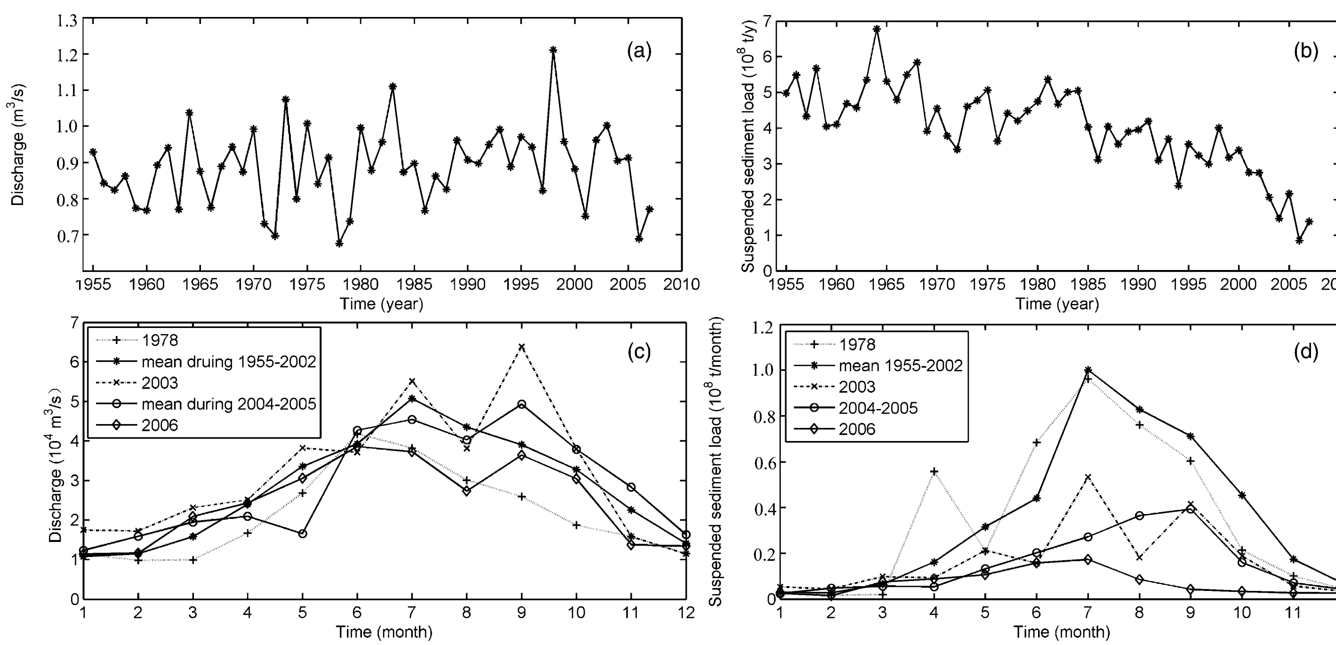

Fig. 3. Discharge and SSD into the Yangtze Estuary; the fluxes time-series station (daily measurements) is located at Datong station, the tidal limit of Yangtze Estuary; another extreme drought year occurred in 1978 in the Yangtze River basin: (a) discharge at Datong (1955−2007); (b) SSD at Datong (1955−2007); (c) monthly mean discharge at Datong in different years; (d) monthly mean SSD at Datong in different years

annual rainfall decrease of 70% compared with that in normal years (CWRC 2007). Statistical analysis [Figs. 3(a and b)] of the water discharge and the suspended sediment discharge (SSD) into the Yangtze Estuary shows that the discharges in 2006 are about 78 and 20% of the corresponding multiyear mean values. The lowest discharge and SSD in the last 50 years were observed in the flood season (April to October) in 2006, which was characterized as no flood in the flood season [Figs. 3(c and d)]. The monthly changes of SSD in 2006 are clearly anomalous compared with those in the other years. These can be characterized as lower SSD in the dry season in comparison with those in the flood season [Fig. 3(d)]. There was no obvious change in the discharge of the Yangtze River in the dry season in 2006, which was correspondingly characterized as no drought in the dry season [Fig. 3(c)] (Dai et al. 2008).

In addition, another extreme drought event occurred in the Yangtze River basin in 1978 (Chen et al. 2001), which presented an extremely low yearly mean discharge of 670×10^9 m^3 [Fig. 3(a)] comparable with that in 2006. The monthly mean discharges in 1978 were lower than those in normal years and in the extreme drought year of 2006. However, the total and monthly mean SSD values in 1978 had no obvious change and were analogous to those in normal years [Figs. 3(b and d)].

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Hydrological analysis of the observations (Table 1) shows that the ratio R between the maximum and minimum discharge at Datong in 2006 is the smallest compared with all other years (1978 was the previous record dry year) and multiyear mean values, which is also the case for the ratios of SSD and SSC. The SD and C_V further indicate that the deviations in 2006 were rather small compared with multiyear mean values (Dai et al. 2011a). In 2003 and 2004−2005, the SSD and SSC were half of the multiyear mean values, while the discharge was comparable to the multiyear mean value. This was attributed to the impact of the first impoundment phase of 2003. However, in 2006, the SSD and SSC, as well as the discharge were much smaller than those in 2003 and 2004−2005. This means that, besides the impact of the TGD, the extreme drought must have contributed to the reduction of SSD, SSC, and discharge.

Saltwater Intrusion in 2006

According to the classification of saltwater intrusion in the Yangtze Estuary, salt intrusion occurs when the salinity is higher than 100 mg/L. The intense saltwater intrusion meant the occurrence of salinity values higher than 250 mg/L, which is the limit for the drinking water quality criteria. When the salinity is over the critical quality limit for industry and agriculture, 400 mg/L, a saltwater disaster occurs (MoC 1993).

Seventeen discharge ranges with an interval of 2,000 m^3/s to assess the probability of salinity occurrence over 250 mg/L were selected, as shown in Fig. 4.

In cumulative terms, it was observed (Fig. 4) that saltwater intrusion occurred for about 276 days in the estuary in 2006. This is the most frequent recorded occurrence with the second most frequent

Table 1. Moment's Method Statistics of Hydrological Parameters at Datong Station

	DIS				SSD				SSC			
Year	M	SD	C_V	R	M	SD	C_V	R	M	SD	C_V	R
1978	21376	11080	0.52	4.27	11671	12966	1.11	51.28	0.41	0.35	0.86	13.19
1955–2002	28125	13545	0.48	4.72	13413	12620	0.94	34.63	0.38	0.24	0.64	7.48
2003	31700	16304	0.51	5.59	6511	5855	0.9	15.92	0.18	0.07	0.41	3.39
2004–2005	28774	13485	0.47	4.01	5744	4911	0.86	17.14	0.18	0.09	0.54	4.70
2006	21909	9718	0.44	3.39	2693	2012	0.75	10.69	0.11	0.04	0.35	3.32

Note: Parameters DIS, SSD, and SSC refer to the flow discharge (m^3/s), the suspended sediment discharge (kg/s), and the suspended sediment concentration (kg/m^3) in different years; M is the yearly averaged value, SD the standard deviation, C_V the coefficient of variation, and R the ratio between maximum and minimum in a year.

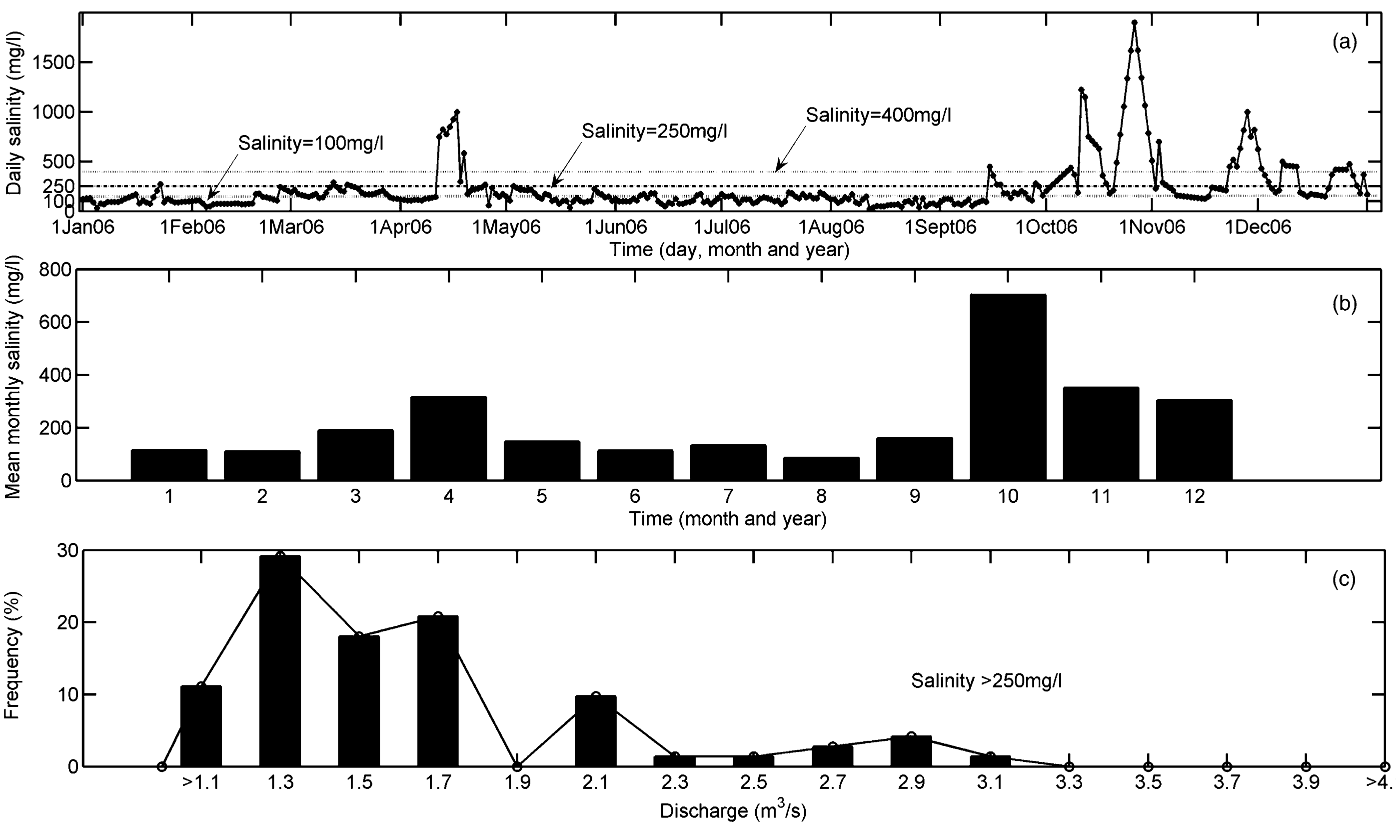

Fig. 4. Salinity and corresponding discharge in 2006; the salinity time-series station (daily measurements) is located at Haimen, 550 km downstream of Datong: (a) daily salinity values in 2006; (b) monthly mean salinity; (c) probability of occurrence of intense saltwater intrusion as a function of the discharge at Datong

being the 236 days measured at Wusong station in the other historically dry year of 1978. Moreover, for 75 days the salinity was greater than than 250 mg/L in the estuary in 2006 with 60% of them in October and December. The occurrence of salinity greater than 400 mg/L in 2006 was 48 days, of which 40% occurred in October [Figs. 4(a and b)]. During these days, the salinity was so high that there was no water of suitable quality available for drinking, industry, or agriculture in the Yangtze Estuary. In terms of events, 10 intense saltwater-intrusion events in the Yangtze Estuary in 2006 with a salinity value of greater than 250 mg/L were observed [Fig. 4(a)]. The earliest intense saltwater-intrusion event occurred on September 15 with a maximum salinity of 450 mg/L, occurring 3 months earlier than occurs in normal years (Dai et al. 2011b). It is interesting that six of the seven intense saltwater-intrusion events with durations over 5 days occurred in the autumn and winter of 2006. Thus, the dominant features of the saltwater-intrusion events in the Yangtze Estuary in the extreme drought year 2006 can be summarized as historically abnormal with larger frequency, longer duration, and earlier occurrence (Dai et al. 2011b).

Discussion

Obviously, the second impoundment phase of the TGD must have contributed to the events of 2006 described above. For instance, the amount of sediment accumulation behind TGD in 2006 was about 93×10^6 t, which is comparable to the yearly total SSD at Datong. In addition, the total stored discharge during the second impounding period of TGD was fairly large, amounting to 11×10^9 m^3. The SSD at CBW, the three stations upstream of the TGD, was much larger than that at CHH, the three stations downstream of the TGD in the middle reach (Figs. 2 and 5). Before the construction of the TGD (Yang et al. 2007a), there was obvious deposition between Yichang and Shashi, and Dongting Lake was the main sediment-retaining reservoir reducing SSD in the lower reaches. Since the TGD started operating, most of the sediment was retained behind the TGD, and the amount of deposition between Yichang and Shashi was dramatically decreased (Fig. 5). In addition, Fig. 5 shows that the year-mean SSD around CHH was less than 13×10^6 t before the first impoundment phase of the TGD (before 2003), which is rather small compared with that from upstream. However, the mild increase in trend of the SSD at CHH can be found after the impoundment of the TGD. Although SSD at CHH increased significantly in 2006 compared with other years, with a similar increase of SSD at Shashi in 2006, SSD at Datong was at a historical extreme low (see Fig. 5). The SSD decreased to about 20% of its long-term mean value at Datong in 2006 with a similar decline in magnitude at CBW. In addition, as indicated, the amount of sediment accumulated behind the TGD in 2006 was about 93×10^6 t, which is comparable to the yearly total SSD at Datong. Hence, the TGD could affect the SSD into the estuary.

To quantify the impact of the TGD, the following aspects were considered: (1) The second impoundment phase of the TGD started on September 20th, which means that the impact of the TGD should be taken into account only after that date. (2) The sediment accumulated from September 20th to the end of 2006 is a result of the deposition after the second impoundment phase of the TGD. The deposition of sediment attributable to the second impoundment phase was about 23×10^6 t, which is only 27% of the yearly total SSD at Datong. This implies that the TGD was not the dominant factor influencing SSD reduction at Datong in 2006. It is concluded that this significant decrease at CBW directly contributed to the extreme low SSD at Datong.

Similarly, it was concluded that the discharge from the upstream basin of the TGD (CBW) accounted for about 50% of discharge at Datong (Fig. 2), and discharge from downstream of the TGD accounted for the remaining part, which includes the effects of the main lakes of Dongting and Poyang and of one of the main distributaries of the Yangtze River, the Hanjiang River, in its middle reach (Dai et al. 2008). Because of the extreme drought, the discharge at the CBW stations only amounted to 68% of the multiyear mean values, i.e., a decrease of the discharge amounting of 150×10^9 m^3 (Fig. 2). This means that the water discharge reduction because of the TGD was only 7% $[(11 \times 10^9)/(150 \times 10^9)]$ of the total discharge decrease upstream of the TGD, without accounting for the decreased discharge from the whole river basin because of the impacts of the extremely dry conditions. In addition, frequent occurrence of saltwater-intrusion events coincides with discharges in the range of 12,000–14,000 m^3/s, which mainly occur in the dry season (December to February) [Figs. 4(a and b)]. With the

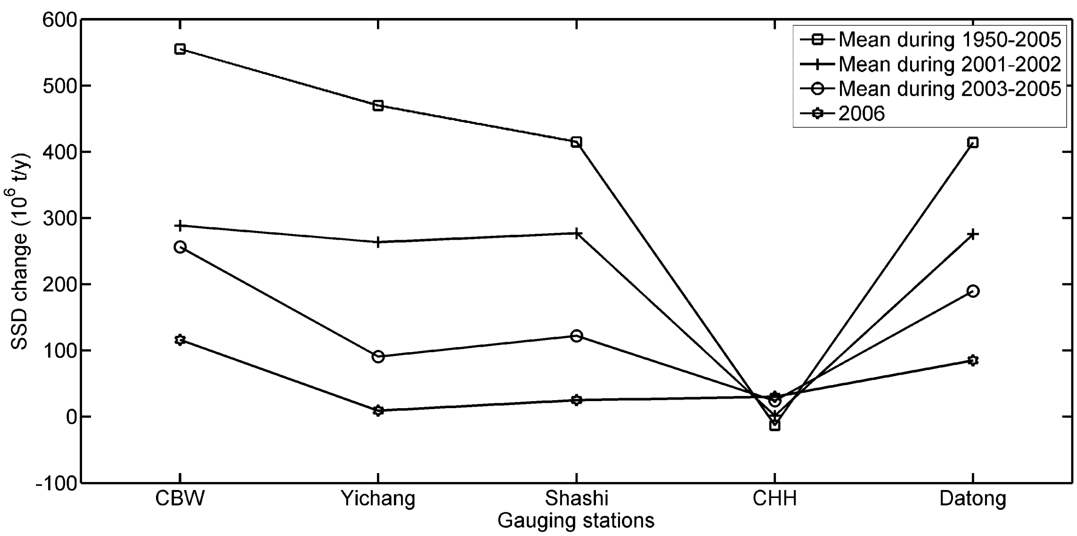

Fig. 5. Changes of SSD at gauging stations in different years: multi refers to the multiyear mean over the period 1950–2005; SSD changes labeled on *y*-axis represent net SSD of the section labeled on *x*-axis with +/− indicating that SSD was increasing/decreasing

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discharge increasing to 16,000−18,000 m^3/s in April and May, the saltwater-intrusion magnitudes in the estuary decrease first, but frequent occurrence of saltwater intrusion still happened [Fig. 4(c)]. In addition, saltwater-intrusion events even occurred in the flood season, before September 15th, when the impact of the second impoundment phase of the TGD had not started yet. Although four of the ten intense saltwater-intrusion events (salinity $>$ 250 mg/L) occurred during the second impoundment period of the TGD in 2006, the majority of the intense saltwater-intrusion events occurred before the impoundment period. These data make us conclude that the extreme drought in 2006 was largely responsible for the abnormal salinity in the Yangtze Estuary, while the TGD aggravated these conditions.

These further results clearly show the change of discharge and SSD during the second impoundment phase of the TGD (Fig. 6). A significant decrease of discharge and sediment can also be found around November 8 in 2003, which is exactly the starting date of the first impoundment. During the first impoundment phase and afterward, slight changes of discharge and sediment can be noticed in 2003. In 2006, around the second impoundment phase of TGD, few changes of SSC and SSD at Datong station are observed, and there is only a mild change of discharge (Fig. 6).

Conclusions

While it is generally difficult to separate the impact of extreme climate events on discharge, SSD, and salinity from that of human activities (Walling and Fang 2003), the data along the Yangtze River were used to document the impact of the impoundment of the TGD and the extreme drought event in 2006. During the second impoundment phase in 2006, 23 $\times$ 10^6 t of sediment accumulated behind the TGD. The yearly total 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 was 60% less compared to that in 2005. This reduction is because of both the effect of the extreme dry condition and the second impoundment of the TGD in 2006. Although there is no direct information about the effects of climate on the SSD, there is the observation of the accumulated sediment behind the TGD accounting for only 18% of the total SSD reduction at Datong. Similarly, the total stored water was 11 $\times$ 10^9 m^3 behind the TGD in 2006, which is only about 1% of the runoff (901 $\times$ 10^9 m^3) in 2005. The total runoff in 2006 was 24% less than that in 2005. This reduction can be attributed to the combined effects of the extreme climate and the second impoundment phase of the TGD in 2006, while the relative effect of the TGD is estimated to amount to only 5% of the total runoff reduction. Hence, the contribution of the extreme drought on discharge and SSD reduction at 95 and 82% in 2006, respectively, is quantified. Accordingly, the contribution of the TGD impacts on discharge and SSD reduction are 5 and 18%, respectively. In addition, there were 19 days with salinity greater than than 250 mg/L and 11 days with salinity greater than 400 mg/L in the estuary during the second impoundment phase of the TGD in 2006. This implies that salinity events with values greater than 250 and 400 mg/L that occurred during the second impoundment phase accounted for only 25 and 23% of the total occurrences, respectively, in 2006.

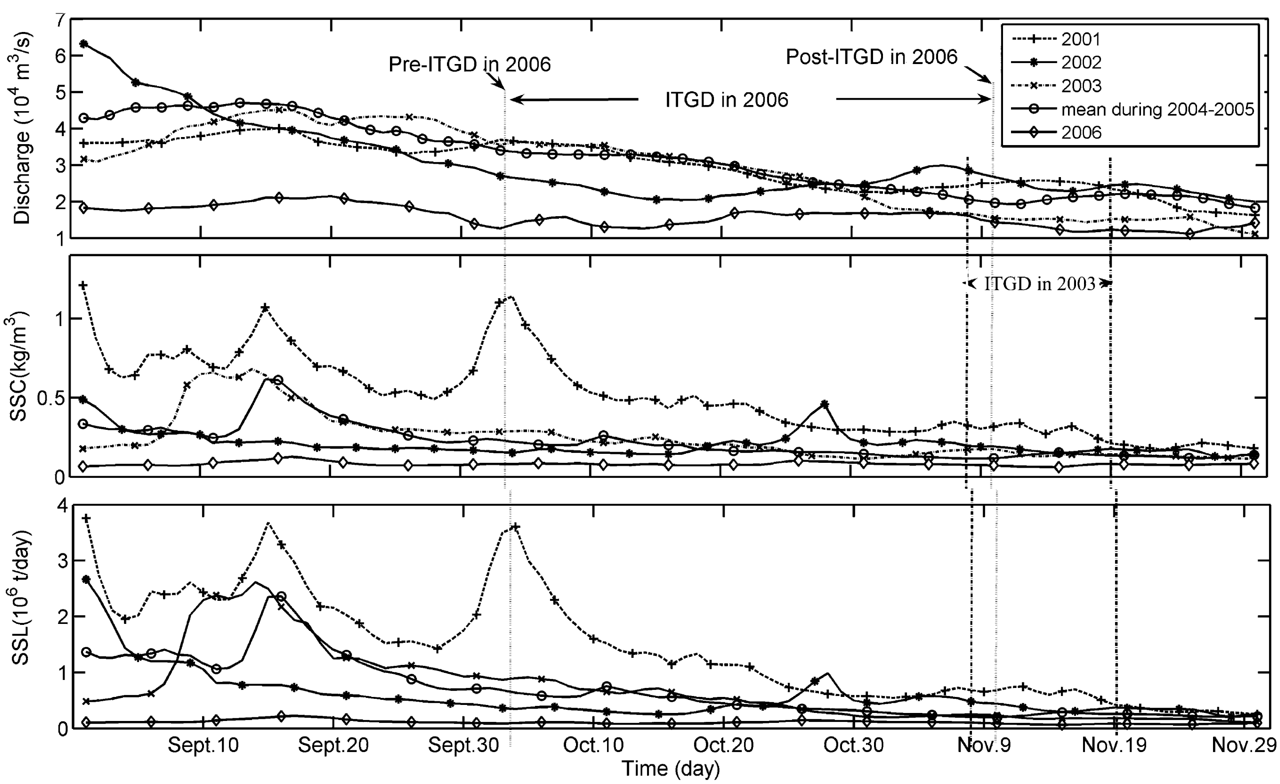

Fig. 6. Daily discharge, SSC, and SSD during the two impoundment phases at Datong (data from Dai et al. 2011a); this station is considered as the tidal limit of the Yangtze Estuary: ITGD2006 is the impoundment period in 2006; ITGD2003 is the impoundment period in 2003; from September 20 to October 27 in 2006, the second impoundment phase of TGD took place; it takes about 14 days for the water flowing from the TGD to reach Datong station (Chu and Zhai 2006); hence, we concentrate this analysis of the daily SSD change at Datong on the period 14 days later, i.e., from October 4 to November 11

This analysis shows that the impact of extreme climate conditions can overrule the impact of a large dam like the TGD. A historically extreme low-flow discharge, SSD, and unusually frequent saltwater intrusions occurred in 2006 compared with what happens in normal years, and these events were mainly because of the extreme drought over the Yangtze River basin. Although many studies hypothesize that the regulation of discharge and sediment discharge in most rivers is because of dams alone (Nilsson et al. 2005), these data support the hypothesis that extreme climate conditions in a catchment area, such as the extreme drought that occurred in 2006 in the Yangtze River basin, may be of at least similar or even larger impact. Although this is the case for the TGD specifically, it can be argued that it is significant for other cases of human interference versus extreme climate conditions.

Acknowledgments

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