Has Suspended Sediment Concentration Near the Mouth Bar of the Yangtze (Changjiang) Estuary Been Declining in Recent Years?

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Has Suspended Sediment Concentration Near the Mouth Bar of the Yangtze (Changjiang) Estuary Been Declining in Recent Years?

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ABSTRACT

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There are considerable concerns about the decrease in suspended sediment discharge (SSD) into the large estuaries of the world as a result of extensive anthropogenic activities in their catchment areas. With the operation of Three Gorges Dam (TGD) in 2003, the riverine loads into the Yangtze (Changjiang) Estuary have been greatly changed with the sharp decrease of SSD and suspended sediment concentration (SSC). However, according to our analysis on the SSC in the surfacial water measured at different stations in the Yangtze Estuary, we conclude that the spatial characteristics of the annual mean SSC around the mouth bar area show no apparent change yet, even though the TGD was constructed with an ascending trend at the upper part of the estuary. The spring–neap periodicity of the daily mean SSC after the TGD was constructed remained the same as before. Moreover, the seasonal and annual mean SSC at the inner side of the mouth bar was relatively low due to the large reduction of upstream sediment supply after the operation of TGD began in 2003. But the seasonal and yearly mean SSC at the outer side of the mouth bar during 2007–2009 is comparable with those before the TGD operated, even though there is a decreasing trend of SSC into the Yangtze Estuary in corresponding years.

ADDITIONAL INDEX WORDS: *Suspended load, suspended sediment concentration, dams, anthropogenic action, the Yangtze Estuary.*

INTRODUCTION

Estuaries are commonly defined as places where tidal action mixes waters from the sea and rivers (Dyer, 1997). Estuaries have a special role in sustaining flora and fauna, navigation and recreation, and shore-based industrial and residential development (Prandle, Lane, and Manning, 2005). Because of the large reduction in the suspended sediment discharge (SSD) of most estuaries in recent decades, great changes in estuarine environments have taken place including coastal retreat, changes in the benthic environments of estuaries, and vanishing coral reefs (Milliman, 1997; Syvitski *et al.*, 2005). However, because of complex factors controlling variations in river sediment loads, such as topographic gradient, basin size, and human interference, SSD changes in upper streams are sometimes not directly reflected in lower river reaches (Brizga and Finlayson, 1994; Chakrapani, 2005; Phillips, Slattery, and Musselman, 2004; Shi, Zhang, and You, 2003). In addition, the sediment output or accumulation in some rivers has been remarkably consistent, despite changes in climate, sea level, vegetation, and human impacts (Dearing and Jones, 2003; Gunnell, 1998; Phillips, 2003 Summerfield and Hulton, 1994). For example, no dam-related changes in alluvial sedimentation are noticeable in the lower river reaches of southeast Texas, although large reservoirs control 75–95% of the drainage area, and retain massive amounts of water behind dams (Phillips, 2003; Phillips, Slattery, and Musselman, 2004). A key question is therefore: how does the changing SSD upstream affect suspended sediment distribution in estuaries? This has received extensive attention in estuarine environments (Eisma, 1993; Phillips and Slattery, 2006; Syvitski *et al.*, 2005; Walling, 2006; Walling and Fang, 2003).

Recent trends in SSD into estuaries in most large rivers have been discussed by Walling and Fang (2003). Main focus has been placed on the decrease of SSD in estuaries resulting from dams (Syvitski *et al.*, 2005; Walling and Fang, 2003; Xu and Milliman, 2009; Yang *et al.*, 2005; 2007). However, Phillips and Slattery (2006) pointed out that most of the previous studies on the changes of SSD being carried into estuaries were mainly based on measurements near the tidal limits of estuaries, where the SSD may not directly represent the SSD brought into the estuaries. The distance from the tidal limit to the estuary mouth can be a long buffer, sufficient for the SSD to change from the upstream value into the estuarine value. On the other hand, because SSD and discharge are partly trapped

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Table 1. *Gauging stations and measured SSCSSD data.*

Gauging station	Position	Data Collection Span/Time Duration for Measurements
Datong	117.62° E, 30.76° N	Collected annual mean data in 1955–2007, daily mean data in 2000–2002, 2006, and monthly mean data from January 2007 to December 2009[1]
Xuliujing	120.95° E, 31.78° N	January 1999 to December 2000, recorded at 0800 and 1400 on each day with the average to represent the daily mean
		Collected hourly data from January to December in 2006[2]
Hengsha	121.83° E, 31.28° N	January 1999 to December 2000, recorded at 0800 and 1400 on each day with the average to represent the daily mean
		Collected hourly data from January to December in 2006, and monthly mean data from January 2007 to December 2009[2]
Sheshan	121.23° E, 31.42° N	January 1999 to December 2000 recorded at 0800, 1400 of each day with the mean to represent the daily mean
Niupijiao	122.25° E, 31.13° N	Collected hourly data from January to December in 2006, and monthly mean data from January 2007 to December 2009[2]
Nancaodong	122.10° E, 30.98° N	Collected hourly data from January to December in 2006, and monthly mean data from January 2007 to December 2009[2]
Yinshuichuan	122.10° E, 30.98° N	Collected monthly mean data from August 1982 to July 1983[3]

[1] Data from Bulletin of Yangtze River Sediment, 2009.
[2] Data from Science Centre of Estuarine and Coastal Research in Shanghai (http://www.ecsrc.cn/).
[3] Data from Group of Shanghai Coastal Comprehensive Investigation, 1988.

behind upstream dams, the amount of marine sediment can be increased in the estuary by relatively strong tidal currents, resulting in changes in the SSD in estuaries (Phillips and Slattery, 2006). Therefore, the variation of suspended sediment in the estuary results from the combined influences of upstream changes and the reaction in the estuary. The area around the mouth bar of an estuary is the main site of the interaction between marine and fluvial forces. It is important to study the SSC characteristics near the mouth bar to gain knowledge about morphodynamic processes within the estuary.

The Yangtze River, the largest river in China, is a special example of the above situation. Because of intense human activities in the Yangtze River basin, including vegetation destruction, deforestation, and dam construction, the SSD in the Yangtze Estuary has changed (Dai *et al.*, 2011a,b; Liu *et al.*, 2007; Xu *et al.*, 2006; Yang *et al.*, 2005–2007). It has been reported that the annual SSD entering the Yangtze Estuary has significantly decreased since the late 1960s, as the annual mean SSD in the 1990s of 343×10^6 t, accounting for two-thirds of that in the 1960s (500×10^6 t) (Yang *et al.*, 2004). Subsequently, since the world's largest hydroelectric dam, the Three Gorges Dam (TGD), started trapping water in 2003, the SSD at Datong, the tidal limit of the Yangtze Estuary about 640 km from the mouth, decreased to 206, 147, and 216×10^6 t in 2003, 2004, and 2005, respectively. In 2006, the historical lowest annual SSD and the annual mean SSC at Datong in last half century, were recorded as 85×10^6 t and 0.123 kg/m^3, respectively. As a result of the large sediment reduction upstream after the first impounding phase of the TGD in 2003, the sediment supply into the Yangtze Estuary has significantly decreased. However, until now, SSC change in the Yangtze Estuary or around the mouth bar area in the estuary had not been reported after the TGD construction. Thus, on the basis of our analyses of the SSC measurement near the mouth bar in the Yangtze Estuary and at Datong before and after the TGD construction, this paper presents the nature of the SSC near the mouth bar area in the past two decades and the associated controlled factors are also addressed.

MATERIALS AND METHODS

The SSC data were collected at various stations, shown in Figure 1 and Table 1. Xuliujing and Hengsha are located around the bifurcation points for the North/South Branches and the North/South Channels, respectively. Hengsha is also located at the inner side of the mouth bar and is a representative of the inner side of the mouth bar, whereas the data at Xuliujing represent the upper part of the Yangtze Estuary. Sheshan, Niupijiao, and Nancaodong are located at the mouths of the North Channel, the North Passage, and the South Passage of the Yangtze Estuary, respectively. The water samples at Xuliujing, Hengsha, and Shenshan were collected at 1 m below water surface at 0800 and 1400 every day from January 1999 to December 2000 with 500-ml bottles. The suspended sediment concentration (SSC) was analyzed in the laboratory (Chen *et al.*, 2006) and the mean value of two SSC values from the same day is regarded as the daily mean. The data at Niupijiao, Nancaodong, and Hengsha in 2006 were measured hourly by Optical BackScatter Sensor (OBS) instruments at the same water depth and calibrated against discrete water samples with the method of Buchanan and Ruhl (2000) (Table 1). The mean value of SSC at each hour of the same day is used to represent the daily mean value. In addition, the monthly mean data at Niupijiao, Nancaodong, and Hengsha during 2007–2009 from hourly OBS observations were available from the Science Centre of Estuarine and Coastal Research of Shanghai (Table 1). Moreover, because of the occasional instrument fault or typhoon/storm passing over this region, the lost data were obtained by interpolated analysis.

Frequency statistical analysis and spectrum analysis of the SSC data were applied to study the characteristics of the SSC. Frequency statistical analysis was useful for describing discrete categories of data having multiple choice or different response formats, which involves constructing a frequency distribution. Here, the frequency distribution with intervals of 0.1 kg/m^3 for values of the daily SSC at different stations and related statistical parameters (*e.g.,* the mean value, standard

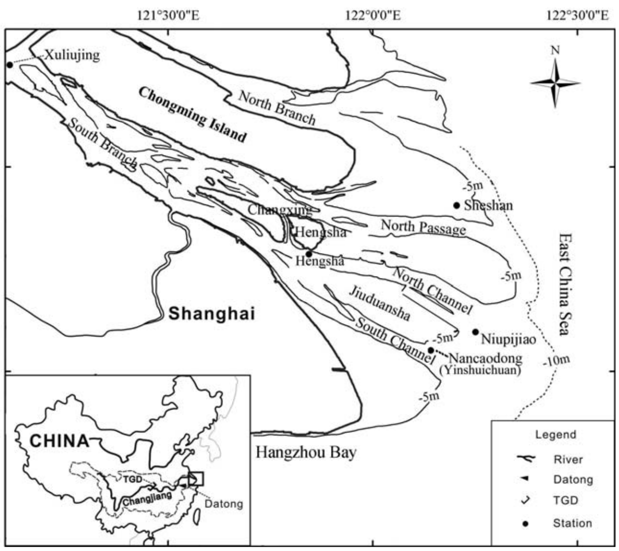

Figure 1. Study area and stations.

deviation) were processed by frequency statistical analysis. Moreover, the spectrum analysis can describe a signal in two-dimensional form, showing the changing characteristic over time with the frequency and phase of the signals (Xu *et al.*, 2010). In this paper, fast Fourier transform is used to obtain the temporal characteristics of the daily mean SSC in a year at the different stations.

RESULTS

Changes of SSD into the Yangtze Estuary

The historical total runoff and SSD at Datong are shown in Figure 2. There is a mainly decennial fluctuation for runoff around a mean of 900×10^9 m^3/y in the past 50 years (Figure 2a). In general, the annual SSD shows a decreasing trend with a negative gradient over time since the 1960s. The decreasing trend was enhanced with a large gradient after 2003 with the TGD operation. From the 1950s to the 1960s, SSD remained roughly constant at 5.0×10^8 t/y. Decrease in SSD ranged from 5.0×10^8 t/y in the 1960s to 3.4×10^8 t/y in the subsequent three decades. However, the lowest annual SSD of 0.85×10^8 t was observed in 2006 (Figure 2b).

Moreover, it should be noted that the daily mean SSC at the Datong in 2006 is lower than that in 1999, and subsequently during 2007–2009 (Figure 3a, Table 2). The seasonal change of SSC within a year can be found in 1999 and 2000, as mean SSC in flood season (May to October) is higher than that in dry season, as well as during 2007–2009 (Figure 3b, Table 2). However, it can be found that the annual mean SSC of 2006 remained almost the same order of magnitude of about 0.1 kg/m^3 (Figure 3a, Table 2). The annual mean SSC at Datong after TGD construction reveals the deceasing trend in comparison with that before. The magnitude decreased from larger than 0.2 kg/m^3 to smaller than 0.2 kg/m^3.

SSC in the Yangtze Estuary before the TGD Was Constructed

The temporal changes of daily mean and monthly mean SSC at Xuliujing, Hengsha, and Sheshan in 1999 were similar to those in 2000, as shown in Figures 3c–3h. The SSC at Xuliujing in 1999 and 2000 shows a seasonal change with the seasonal mean of 0.19 kg/m^3 and 0.13 kg/m^3 in flood seasons larger than those of 0.11 kg/m^3 and 0.09 kg/m^3 in dry seasons (Figures 3c, 3d, Table 2). However, the seasonal mean SSC of 0.32 kg/m^3 and 0.34 kg/m^3 at Hengsha in flood seasons of 1999 and 2000, respectively, is slightly lower than those of 0.38 kg/m^3 and 0.38 kg/m^3 in dry seasons (Figures 3e, 3f, Table 2). There is no apparent seasonal variation of SSC at Hengsha in the observed periods. However, according to Figures 3g and 3f, the daily mean SSC and monthly mean SSC at Sheshan exhibit seasonal changes with higher values of 0.51 kg/m^3 and 0.48 kg/m^3 in the dry seasons of 1999 and 2000, respectively, and lower values of 0.31 kg/m^3 and 0.32 kg/m^3 in the flood seasons, which is opposite the seasonal change of SSC at Xuliujing in 1999 and 2000 (Figures 3g and 3f, Table 2). A similar SSC seasonal change at Nancaodong, formerly called Yinshuichuan, to that at Sheshan, can be also seen in 1982 from Figures 3i and 3j.

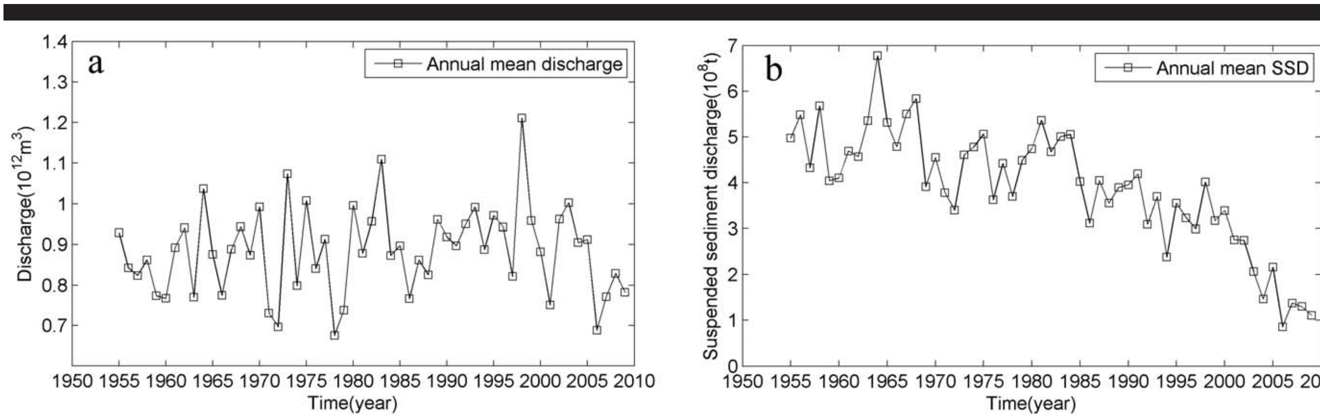

Figure 2. Annual discharge and suspended sediment discharge at Datong.

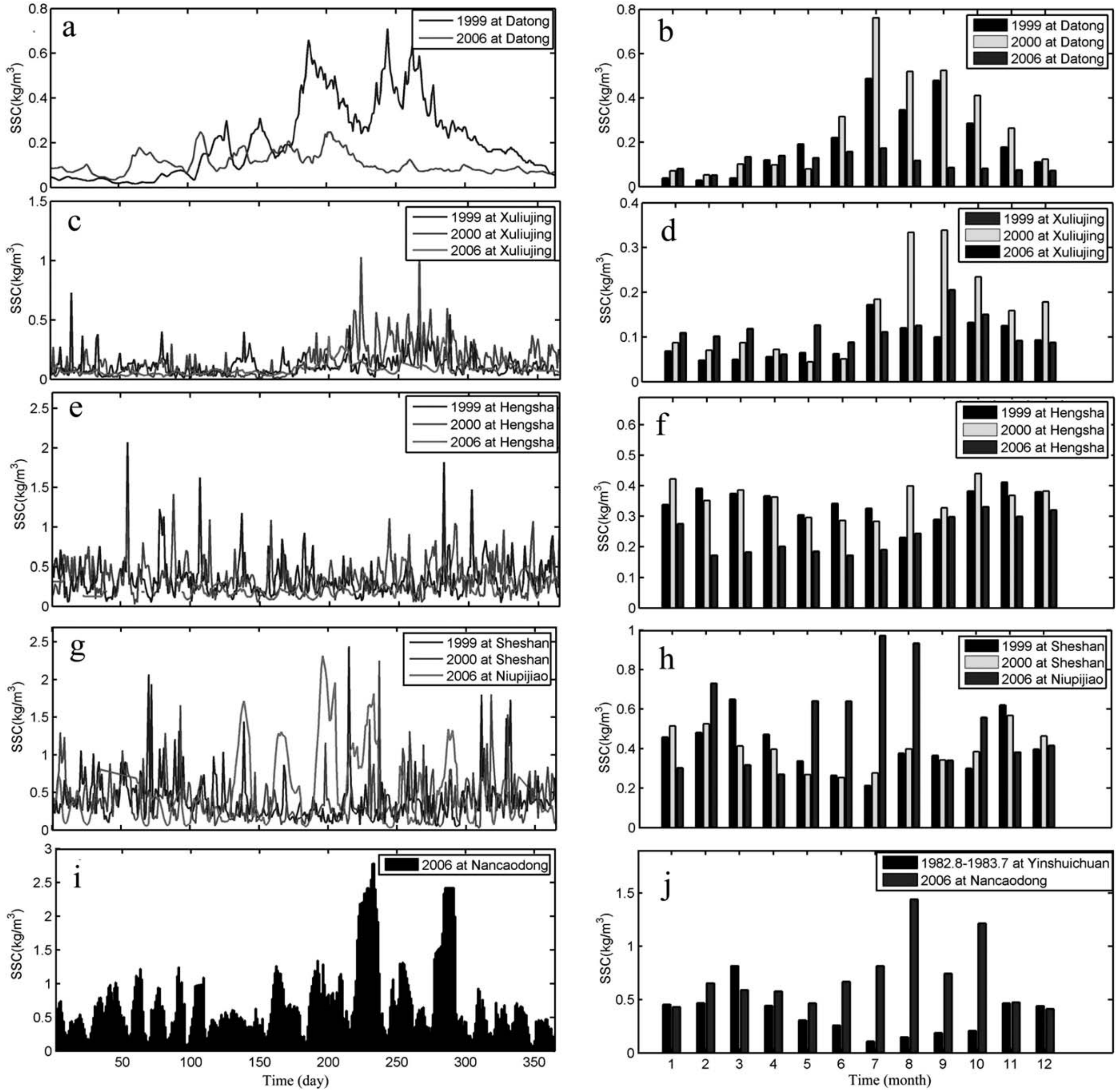

Figure 3. The daily and mean monthly SSC at the stations.

The annual mean SSC in 1999 and 2000, as well as the seasonal mean in dry seasons, at Sheshan was larger than those at other stations before the TGD was operated (Table 2). In addition, mean SSC over seasons and a year at Nancaodong was comparable with that at Sheshan in the same period before the TGD was constructed. The mean SSC over different periods at Nancaodong in 1982 is comparable with that at Sheshan in 1999 and 2000. This reveals minor changes in the SSC around this area in the last two decades despite the large upstream SSD reduction, as the SSD at Datong decreased by 90×10^6 t in the 1990s compared with the 1980s, which agrees with the previous research (Chen *et al.*, 2006).

Table 3 shows the cyclical period of the daily mean SSC at stations. The table shows a clear spring–neap cycle of SSC with a period of half a month. In addition to the spring–neap cycle, a period of 9 days is also visible. The spatial characteristics of the annual mean shows an increased trend in seaward direction, reaching a maximum at the mouth bar, *e.g.,* increasing from

Table 2. *Mean SSC in different periods of a year at stations.*

	Datong (kg/m³)			Xuliujing (kg/m³)			Hengsha (kg/m³)			Sheshan (kg/m³)			Niupijiao (kg/m³)			Nancaodong (kg/m³)		
Period	FS	DS	Whole	FS	DS	Whole	FS	DS	Whole	FS	DS	Whole	FS	DS	Whole	FS	DS	Whole
1999	0.33	0.09	0.21	0.13	0.09	0.12	0.32	0.38	0.34	0.31	0.51	0.41	/	/	/	0.2**	0.52**	0.36**
2000	0.44	0.12	0.28	0.19	0.11	0.15	0.34	0.38	0.35	0.32	0.48	0.40	/	/	/	/	/	/
2006	0.12	0.09	0.11	0.1	0.07	0.08	0.24	0.24	0.24	/	/	/	0.68	0.40	0.54	0.89	0.52	0.71
2007	0.22	0.14	0.18	/	/	/	0.28	0.32	0.30	/	/	/	0.81	0.31	0.55	0.73	0.42	0.58
2008	0.18	0.10	0.16	/	/	/	0.32	0.33	0.32	/	/	/	0.38	0.36	0.37	0.81	0.48	0.65
2009	0.17	0.12	0.14	/	/	/	0.27	0.29	0.28	/	/	/	0.50	0.38	0.44	0.69	0.52	0.62

Numbers with "**" are the mean monthly SSC observed from August 1982 to July 1983 at the Yinshuichuan.
FS = flood season of May–October; DS = dry season of November–next April; Whole = the period of the whole year.

0.13 kg/m³ at Xuliujing to 0.31 kg/m³ at Hengsha and Sheshan in the flood season 1999 (Table 2). This becomes even more prominent in the dry season from 0.11 to 0.48 kg/m³.

Moreover, a frequency analysis of 13 SSC grades with an interval of 0.1 kg/m³ is applied to discern the frequency of the different daily mean SSC levels. Figure 4a indicates that the daily mean SSC at Datong in 1999 was in the range of 0.1–0.3 kg/m³, with the frequency accounting for over 75%. Figure 4b shows that the daily mean SSC values at Xuliujing in 1999 mainly varied in the range of 0–0.1 and 0.1–0.2 kg/m³, with the frequency accounting for about 52% and 35.5%, respectively. The frequency distributions of the daily mean SSC at Hengsha and Sheshan are similar (Figures 4c and 4d). The dominant daily mean SSC levels at both Hengsha and Sheshan differ from those at Xuliujing (Figures 4b–d). During most time in 1999, the daily mean SSC at Hengsha and Sheshan were about 0.2–0.3, 0.3–0.4, and 0.4–0.5 kg/m³ with the total occurrence of 72% and 60%, respectively. Obviously, from the upper part of the Yangtze Estuary to the mouth bar, the more seaward the location, the larger the variation of the SSC.

Meanwhile, the correlation between the monthly mean SSC at the stations and the monthly mean discharge and SSD at Datong is shown in Figures 5 and 6. We can find a positive correlation between the monthly mean SSC at Xuliujing and the upstream discharge, but negative correlation at the other stations before the dam was constructed (Figure 5). A negative correlation between the monthly mean SSC at Hengsha and the monthly mean SSD at Datong can be obtained in 1999, as shown in Figure 6. A negative correlation between the monthly mean SSC at Sheshan (the outer side of the mouth bar) and the monthly mean SSD at Datong can also be obtained in 1999 (Figure 6), as Sheshan is also located in the winter estuary turbidity maximum (ETM) zone in 1999. However, a positive correlation in 2006 can be found between the monthly mean SSC at the outer side of mouth bar and the monthly mean SSD at Datong, according to Figure 5.

Table 3. *Cyclical period of the daily mean SSC at the stations.*

Year	Gauging Station	Cycle Time (d)	
1999	Xuliujing	9.2	14.5
	Hengsha	8.9	15
	Sheshan	9.2	15.2
2006	Xuliujing		14.5
	Hengsha		15
	Nancaodong		16.5
	Niupijiao		17.2

SSC in the Yangtze Estuary after the TGD Was Constructed

An apparent decrease in the monthly mean SSC at Datong, Xuliujing, and Hengsha can be found in 2006 compared with the other years, according to Table 2 and Figure 3, although no clear seasonal variation can be observed from Figures 3d and 3f, similar to before the TGD was constructed. However, the seasonal and yearly mean SSC at Hengsha durng 2007–2009 are comparable with those during 1999–2000 (Table 2), even though there is a decreasing trend in SSD and SSC into the Yangtze Estuary in corresponding years, as well as those observed at Niupijiao and Nancaodong (Figure 2, Table 2). From Table 2, we observe that the mean SSC in the flood season at Niupijiao is larger than in the dry season, which is opposite the nearby station, Sheshan, before the TGD was constructed (Figures 3g and 3h). Similar seasonal characteristics of the monthly mean SSC at Nancaodong and Niupijiao can be found in 2006–2009 from Figure 3 and Table 2, although they had opposite seasonal variations in 1982, before the TGD was constructed (Figures 3i and 3j).

Table 3 shows that the periodicity of the daily mean SSC in the estuary was about 15–17 days in 2006. The periodicity of half the spring–neap cycle (7–9 days), which was found before the TGD was constructed, could not be found.

The same spatial characteristics of the annual mean SSC after the TGD was constructed can be found with an increasing trend toward the sea up to the mouth bar (Table 2). However, the annual mean SSC at Xuliujing and Hengsha were respectively much smaller in 2006 than in 1999, as were its standard deviation and coefficient of variation (Figures 4b and 4g, 4c and 4h). The annual mean SSC at the outer side of the mouth bar, at Nancaodong and Niupijiao, in 2006, as well as their standard deviations and coefficients of variation, were larger than those at the inner side (Figures 4e, 4h, and 4i), as indicated by the large deviation of the daily values of SSC at these two stations.

Moreover, Figures 4b and 4g indicate that the daily mean SSC variation at Xuliujing in 2006 was smaller than in 1999, as well as that at Hengsha (Figures 4c and 4h). The occurrence possibilities of daily mean SSC of 0.1–0.2 kg/m³ were about 96% and 48% of the time in 2006 at Xuliujing and Hengsha, respectively. In contrast, the larger variation of SSC at

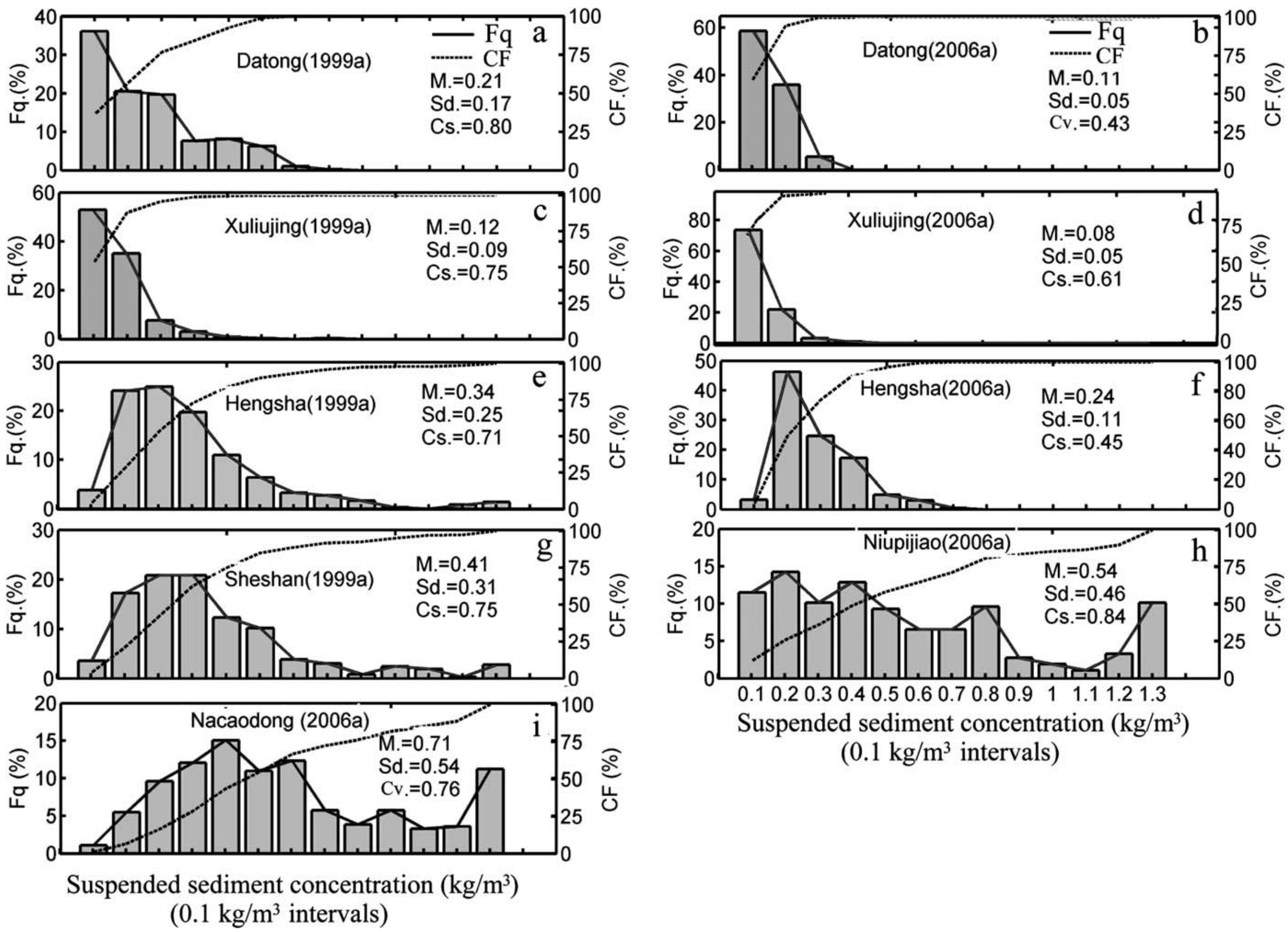

Figure 4. SSC occurrence at stations in 1999 and 2006 (Fq: frequency curve; CF: cumulative frequency curve; M: monthly mean; Sd: standard deviation; Cv: variation coefficient, Cv = Sd/M, representing the deviation of the SSC from the monthly mean).

Nancaodong and Niupijiao was found in 2006 in comparison with that at the outer side of the mouth bar (Sheshan) in 1999 from Figures 4d, 4e, and 4i. In addition, the monthly mean SSC around the mouth bar in the Yangtze Estuary, especially at the outer side of the mouth bar, remained at the same level, if we compare the monthly mean SSC at Nancaodong in 1982 (Figure 3j) with that at Sheshan in 1999 (Figure 3h), despite the large reduction of upstream SSD in the 1990s compared with the 1980s.

DISCUSSION

Correlation between the Monthly Mean SSD at Datong and the Monthly Mean SSC in the Eestuary

Our analysis indicates a positive correlation between the monthly mean SSD at Datong and monthly mean SSC at Xuliujing, as shown in Figure 5. This could imply that the upstream sediment supply is one of the important factors affecting the SSC change in the inner part of the Yangtze Estuary. However, although the large reduction of SSD in the 1990s compared with the 1980s occurred, the relatively constant SSC around the mouth bar in the Yangtze Estuary, especially at the outer side of the mouth bar area, remained in recent decades when compared with the mean monthly values of SSC at Nancaodong in 1982 with that at Sheshan in 1999 (Figure 3). Similarly, relatively constant SSC was also observed at Niupijioa and Nancaodong during 2007–2009, even though there is decreased trend in SSC at Datong in these years (Table 2). This implies that, in addition to the upstream sediment supply, other factors, such as the local sediment supply in the estuary, are also important for maintaining the SSC level. Moreover, the positive correlation between the monthly mean discharge at Datong and monthly mean SSC at Xuliujing shows that the upstream discharge has some influence on the SSC changes in the estuary. However, there is a weak relationship between the monthly mean SSC in the estuary and the upstream discharge. The discharge in 2006 with minor seasonal variations due to the dam has less influence on the SSC changes in the estuary (Dai *et al.*, 2008), which agrees well with the argument of Gao and Wang (2008).

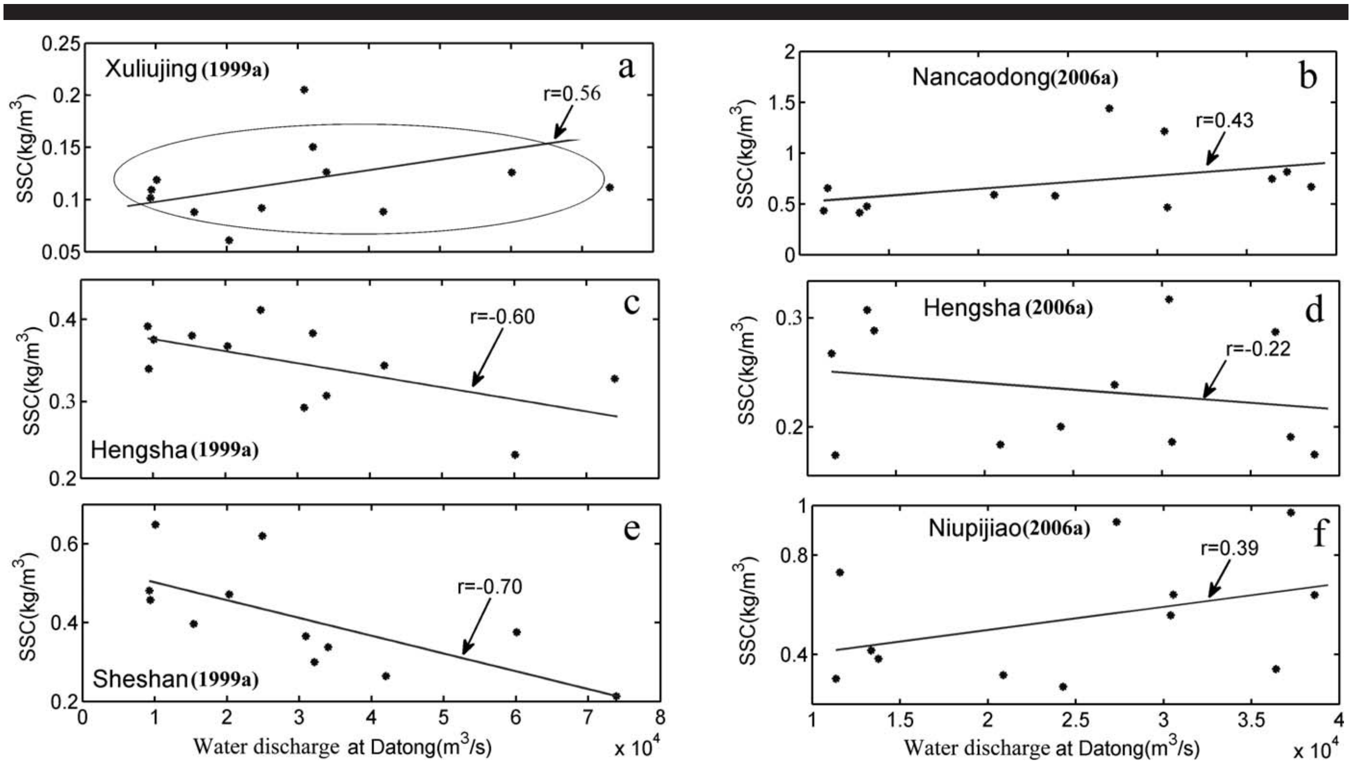

Figure 5. Relationships between the discharge at Datong and the SSC at the other station.

In reality, the upstream sediment supply in 2006 reached the historical lowest level, with SSD of 85×10^6 t (Figure 2) at Datong, accounting for one quarter of the multiyear mean value. This resulted in the annual mean SSC at the inner side of the mouth bar, at Hengsha, in 2006 accounting for two-thirds of that in 1999 (Table 2). As pointed out by Yang et al. (2007), the Yangtze Delta suffers from erosion when the SSD at Datong is below about 151×10^6 t. Therefore, there can exist a threshold of upstream sediment supply for the change in the SSC in the inner part of the estuary, as the SSC changes and the inner side of the mouth bar of the estuary is not sensitive to the upstream sediment supply, unless the SSD at Datong reaches its threshold. Thus, although the SSD at Datong continued to decrease since the 1990s without reaching this threshold value, the annual mean SSC remains the same level in the estuary as that when TGD was constructed. In 2006, the SSD at Datong could be below the threshold, as a consequence of the SSC lower than before. Further study is still needed to fully understand to what degree the SSD decrease reached threshold, which can induce obvious decline of SSC near the mouth bar area.

Influence of the Shift in ETM Zone

Besides the influence of the upstream SSD, other factors, such as mixing of salt water and freshwater, tides, waves, and winds, can also affect the SSC change in estuary (Chen *et al.*, 1999; Li *et al.*, 1999). The interaction of the river and sea results in the shift of the ETM zone with seasonal changes in upstream discharge. In the Yangtze Estuary, the ETM zone shifts seaward in the summer due to strong freshwater discharge, and landward in the winter (Shi, 2002; Shi and Kirby, 2003). It means that the SSC change around the ETM zone can be sensitive to such ETM shifting caused by the seasonal runoff into the Yangtze Estuary.

Dyer (1997) also pointed out that the SSC changes in the stratified water of the ETM zone are higher than those of the other estuarine zone because of the frequent internal entrainment that occurs in the layer between the freshwater and salt water, advection and flocculation, desolation and resuspension. Therefore, Hengsha, located in the dry-season ETM zone, has a higher SSC, as expected in the dry season, and lower one in the flood season (Table 2). In contrast, both Nancaodong and Niupijiao have related higher SSC in flood season than those in dry season, because these two stations are located in the flood-season ETM zone due to shifted ETM by runoff pushing (Table 2).

The change of the relation between the monthly mean SSC changes at the outer side of mouth bar and the monthly mean SSD at Datong is due to the shifting of the ETM zone because of a change in flow regime, caused by the TGD regulation and an extreme drought event in 2006. Both the flow regime change and the extreme drought event resulted in the much weaker river discharge (Dai *et al.*, 2008), as the ETM zone could not be pushed as far outward as usual. This led to a more uniform and lower SSC than that in 1999 at Hengsha (Figures 3e and 3f). The outer side of the mouth bar might have remained in the ETM zone throughout 2006, unlike in 1999. It deserves further

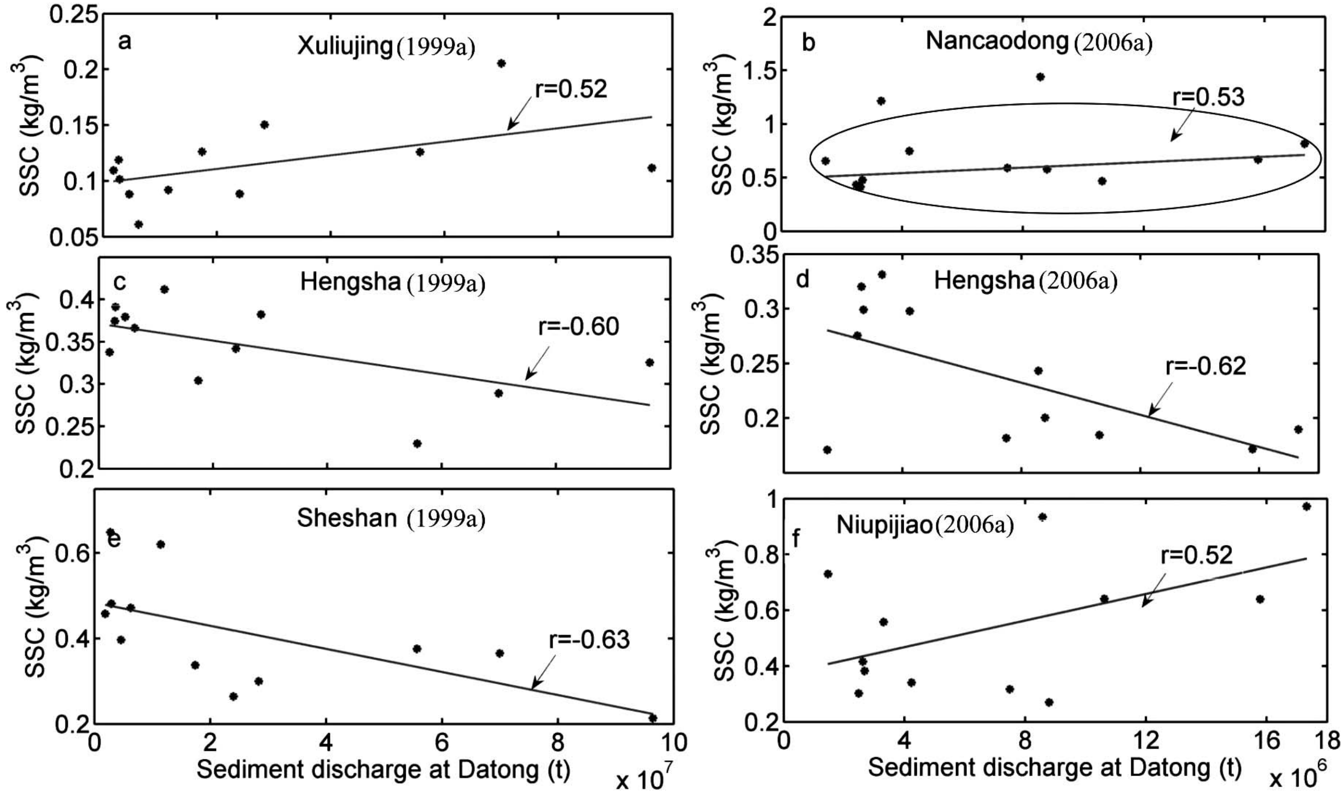

Figure 6. Relationship between the SSD at Datong and the SSC at the other station.

analysis by modeling on the relationships between the SSC variations in the ETM zone and flow regime changes. Thus, the seasonal ETM zone shifting due to the flow regime change and extreme climate events can induce a SSC change in the estuary.

Periodicity of the SSC

The cyclical period of daily mean SSC with a cycle of 15–17 days in 1999 (Table 3) could be related to tidal movements. The tidal current had received attention as regards sediment transport and resuspension in the estuary (Chen *et al.*, 2006; Dyer, 1997; Esima, 1993). Strong tidal currents in the spring tide lead to higher SSC, with sediment being suspended due to the large velocity of the water. Consequently, the periodic SSC change is synchronous with the spring–neap tidal cycle in the Yangtze Estuary. However, the weaker periodic cycle of 8–9 days (Table 3) of the SSC can be related to tidal pumping (Dyer, 1997) and relative increases of the riverine flow currents in neap tides with plenty of discharge available before the TGD was constructed. A periodicity of the SSC with a cycle of 15–17 days is also obtained in 2006, except for the shorter periodic feature due to much weaker riverine processes compared with that before the TGD was constructed.

Influences of Waves and Storms on the SSC

The stations Shenshan, Niupijiao, and Nancaodong are located outside the mouth bar, and are directly influenced by the waves and winds from the East China Sea. Waves with a height of about 0.6 m can easily resuspend sediments at the bottom around this area with a water depth of about 5 m (GSICI, 1988). Relatively high wave heights occurred in 2006 at Niupijao corresponding to a relatively large SSC (Figures 3 and 7a) (Yan *et al.*, 2011). Further correlative analysis indicates that there was a positive correlation between the daily wave height and the daily SSC at Niupijiao in 2006 (Figure 7b). It is clear that sediments located in the mouth-bar zone area will be moved, with intense resuspension due to wave action (Li and Zhang, 1998; Yan *et al.*, 2011). In contrast, in the landward direction, the wave energy is dissipated quickly due to bottom friction and breaking on the mouth bar, resulting in the higher SSC outside the mouth bar compared with inside the estuary, *e.g.,* at Hengsha and Xuliujing (Table 2).

In the flood season, the typical monsoons, typhoons, frequently affect this area, resulting in large wave heights on the outer side of the mouth bar. Especially in 2006, several severe typhoons from the southeast affected the estuary. During these typhoon periods in August and October 2006, the maximum wind speed in the estuary exceeded 24 m/s, accompanied by large waves, resulting in the high SSC at Nancaodong and Niupijiao in these months (Figure 3). This can also partly explain the positive correlation between the SSC in this area and the SSD at Datong after the TGD was constructed, compared with the negative correlation that existed previously (Figure 6). Moreover, as various dynamic

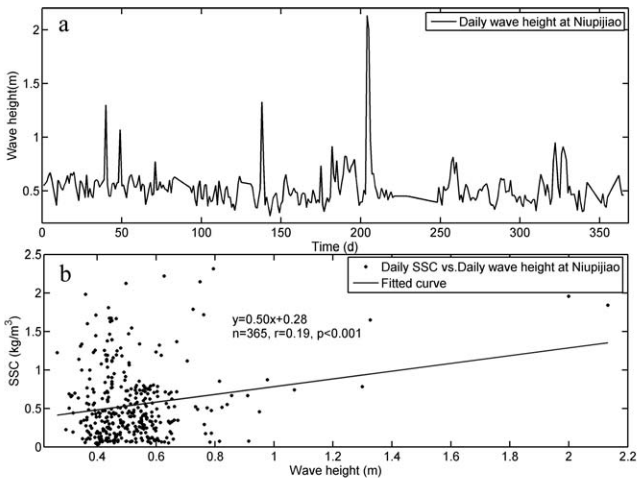

Figure 7. Daily changes of wave height and relationships between wave height and SSC at Niupijiao.

processes, such as tides, discharge, waves, winds, and flocculation, are involved, the SSC varies in a larger range on the outer side of the mouth bar than inside (Figure 4). These are also essential for further investigation on the SSC change in the estuary.

CONCLUSIONS

The SSC changes in the estuary can play an important role in the geochemical cycle, contaminant migration, and biological adsorptions. Analysis of the SSC changes in the estuary is one of the important factors to water environment management and shore protection. By using comparative methods, we analyzed two SSC data sets in recent years, representative for the conditions before and after the operation of TGD to discuss the SSC change near the mouth bar of the Yangtze Estuary. Meaningful conclusions are shown as follows:

(1) The annual mean SSC at the inner side of the mouth bar are lower after the TGD was constructed than before, due to the SSD reduction upstream. However, at the outer side of the mouth bar, the annual mean SSC was comparable with that before the TGD was operated.
(2) Spatially, the annual mean SSC in the Yangtze Estuary increases from the upper part (Xuliujing) to the mouth bar. The tidal force apparently influences the SSC in the estuary, with the periodic characteristics of the spring–neap cycle.
(3) The monthly mean SSC around the mouth bar of the Yangtze Estuary is not sensitive to the upstream SSD, except that the SSC at the inner side is sensitive to the threshold low-sediment supply from upstream.
(4) The shift of the ETM zone due to seasonal variation of river discharge causes seasonal characteristics of the SSC near the mouth bar. The SSC at the inner part of the mouth bar is lower in flood season than that in dry season, and SSC at the outer side of the mouth bar was higher in flood season than that in dry season.

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