Sedimentation in the Outer Hangzhou Bay, China: The Influence of Changjiang Sediment Load

Article · November 2014

4 authors, including:

Zhijun Dai
East China Normal University

James T Liu
National Sun Yat-sen University

Journal of Coastal Research	30	6	1218–1225	Coconut Creek, Florida	November 2014

Sedimentation in the Outer Hangzhou Bay, China: The Influence of Changjiang Sediment Load

Zhi-jun Dai[†*], James T. Liu[‡], Hua-liang Xie[†], and Wei-yong Shi[§]

[†]State Key Laboratory of Estuarine & Coastal Research
East China Normal University
Shanghai 200062, China

[‡]Institute of Marine Geology and Chemistry
National Sun Yat-sen
Kaohsiung 80424, Taiwan

[§]Second Institute of Oceanography
State Oceanic Administration
Hangzhou 310012, China

ABSTRACT

Dai, Z.-j.; Liu, J.T.; Xie H.-l., and Shi, W.-y., 2014. Sedimentation in the outer Hangzhou Bay, China: The influence of Changjiang sediment load. *Journal of Coastal Research,* 30(6), 1218–1225. Coconut Creek (Florida), ISSN 0749-0208.

Most estuaries in the world are facing the risk of subsidence due to insufficient sediment supply and relative sea-level rise. In the case of the world's fourth largest river, the Changjiang (aka Yangtze River), its river sediment load has been decreasing sharply, especially since the construction of the Three Gorges Dam. Due to the complexity in the estuarine dynamics, human activities, and the sediment supply, discerning whether the Changjiang Estuary is facing erosion or subsidence is a controversial issue. Immediately south of the mouth of the Changjiang is Hangzhou Bay. On the centennial time scale, accretion on the southern flank of the Changjiang deltaic plain has caused the seaward extension of the north bank of the Qiantang Estuary, leading to the formation of the macrotidal, funnel-shaped Hangzhou Bay. In this study, we used multiyear geographic information system (GIS)–rectified bathymetric charts of Hangzhou Bay for bathymetry and sediment-capacity change analysis. Our major findings show that the outer Hangzhou Bay has gone through the following stages: relatively steady sedimentation (1931–1997), erosional-depositional transition (1997–2002), and rapid erosion (2002–2008) at the rate of 58.5×10^6 m^3/y. Our findings also corroborate measurements of suspended sediment discharge at the Datong station in the lower reaches of the Changjiang. Our findings confirm the dependence of the sedimentation in the outer Hangzhou Bay on the sediment supplied by the Changjiang. The severity of the erosion of the outer Hangzhou Bay and the sediment load decrease of the Changjiang might serve as a warning for the impending erosion of the Changjiang Estuary.

ADDITIONAL INDEX WORDS: *Changjiang (Yangtze River), deposition, Hangzhou Bay, Qiantangjiang (Qiantang River), sediment load.*

INTRODUCTION

A majority of river deltas and estuaries in the world are risking subsidence due to insufficient supply of sediment (Milliman and Farnsworth, 2011; Syvitski *et al*., 2005). Taking the Mississippi River, for example, between 1953 and 1955 the sediment load at Fort Randall and Gavins Point dams on the South Dakota portion of the river, and in Missouri and Arkansas Rivers dropped by 75% (Wells, 1996). Because of damming in the twentieth century, the sediment load of the Ebro River is less than 1% of that of the previous century (Guillén and Palanques, 1997). The Colorado River lost 100% of its sediment load since 1941, and the Danube lost 35% of its sediment load compared to the last century, respectively (Milliman and Farnsworth, 2011). Although there are over 1800 estuaries in China, most estuarine systems have suffered from shoreline erosion due to drastic decreases in sediment load from upstream (Yun, Dai, and Wang, 2010). It is well known that the Yellow River (Huanghe) in China had the world's largest sediment load in the nineteenth century (Milliman and Meade, 1983). However, sediment discharge of the Yellow River has sharply decreased to be less than 100×10^6 t/y due to dam construction, which has led to serious degradation of the Yellow River delta (Yang *et al*., 2004). In the Pearl River, the third largest river in China, annual sediment load to the estuary declined from 79.8×10^6 t in 2001 to 25×10^6 t in 2010 (BCRS, 2004–2010) due to anthropogenic activities in the catchment basin. The Haihe had the sharpest decrease in sediment load, from an average value of 17.4×10^6 t in the past 50 y to 0.03×10^6 t in 2010 (BCRS, 2004–2010). As far as the Changjiang (Yangtze River) is concerned, since the Three Gorges Dam (TGD), located 1500 km from the river mouth in the middle reaches of the river (Figure 1A) became operational in 2003, there has been significant reduction in the sediment load entering the Changjiang Estuary, which is the largest estuary in China (Su and Wang, 1989). Consequently, the sediment exported by the Changjiang has decreased by 60%, which is reflected in the flux and concentration of suspended sediment observed at the Datong station 640 km from the mouth (Dai *et al*., 2011). However, the suspended sediment concentration at the river-mouth shoal has maintained the same order of magnitude since the operation of TGD (Dai *et al*., 2012). Therefore, whether the delta region of the Changjiang is going to experience erosion is a controversial issue (Chen *et al*., 2010; Yang *et al*., 2011).

Immediately to the south of the mouth of the Changjiang, there lies the mouth of the funnel-shaped Hangzhou Bay, which is the outer extremity of the Qiantangjiang (Qiantang River) (Figure 1B). Hangzhou Bay consists of an inner and outer bay. Upstream from Jinshanzui, there is the inner bay

DOI: 10.2112/JCOASTRES-D-12-00164.1 received 16 August 2012; accepted in revision 9 October 2012; corrected proofs received 19 December 2012; published pre-print online 5 November 2014.
*Corresponding author: zjdai@sklcc.ccnu.edu.cn

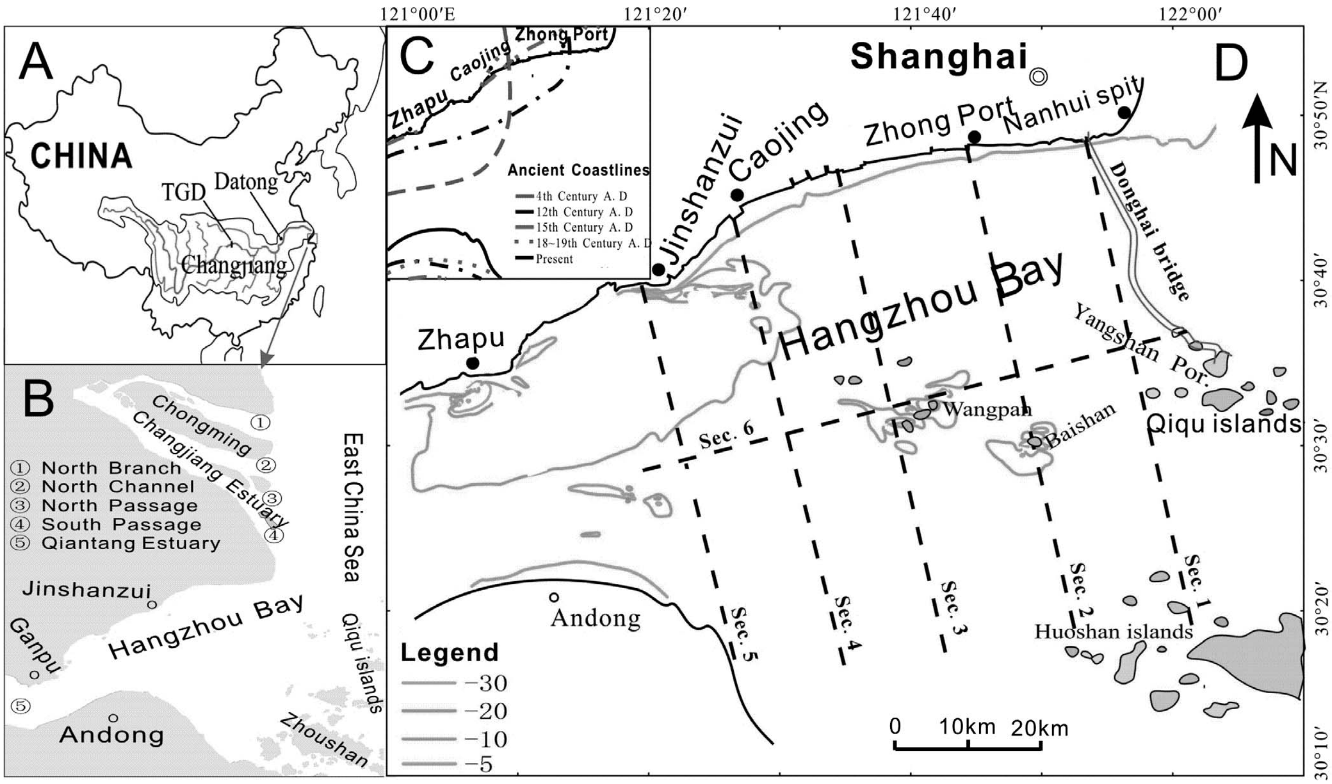

Figure 1. Maps of (A) China showing the drainage basin of Changjiang, the locations of TGD, and Datong station; (B) the mouths of Changjiang and Qiantangjiang; (C) ancient coastlines of the Hangzhou Bay; and (D) the detailed geographic setting of the study area and the cross sections in Figure 6.

(Chen *et al*., 1964). The largest river-mouth shoal in China is located here, and it is the best spot at which to watch the world-famous Qiantang Bore (a tidal bore over 6 m high having semidiurnal tidal period). Major sediment sources of this shoal are the sediment imported from the Changjiang and from the erosion of the seabed of the outer bay (Chen *et al*., 1990). The minor source is from the Qiantangjiang.

The seafloor in the outer bay is relatively flat, having the mean depth of about 10 m (Su and Wang, 1989). About 90% of the sediment entering the outer bay comes from the Changjiang (Chen *et al*., 1990; Lin, 1990; Wan, Li, and Shen, 2004). As a receptacle of the Changjiang sediment, the development of the outer bay is directly linked to the evolution of the Changjiang Estuary over the past 2500 y (Chen *et al*., 1990; Liu *et al*., 2007) (Figure 1).

However, the mouths of these two rivers have formed distinctly different morphodynamic systems. The Changjiang developed into a three-tiered branching mesotidal estuary, having four separate openings at the mouth (North and South Channels, North and South Branches). Qiantangjiang on the other hand, formed a funnel-shaped macrotidal estuary called Hangzhou Bay (Figure 1B). The formation of the latter was greatly affected by the development of the former (Pan and Huang, 2010). Because of the seaward extension of the outer bay (Figure 1C), the connection of the southern part of the bay to the East China Sea (ESC) has been blocked by the Qiqu island chain, making the outer bay a semiclosed system (Figure 1B). Recently, the construction of the Donghai Bridge and the deep-water harbor Yangshan Port has further obstructed the channels that separate these islands (Figure 1D).

Being along the sediment pathway between the Changjiang and Qiantangjiang, the outer Hangzhou Bay (OHB) could be sensitive in response to the changes in the sediment load of the Changjiang. Therefore, we hypothesized in this study that the OHB would experience seafloor erosion if the sediment load delivered to the OHB from Changjiang decreases. Subsequently, it is meaningful to study the sediment volume changes in the OHB with regard to the changes of the Changjiang sediment load to prove or disprove the hypothesis.

MATERIAL AND METHODS

Navigational charts of different years provide suitable data for studying the depositional and erosional rates in delta and estuarine regions (van der Wal and Pye, 2003). In recent years, there have been voluminous observational data of the water depth of the Hangzhou Bay, most of which have been for special purposes, such as localized navigational channels and shoreline utilization. Therefore, in this study, we collected large-scale charts of the entire Hangzhou Bay from the Navigation Guarantee Department of the Chinese Navy headquarters (NGDCNH) surveyed in 1931, 1962, 1989, 1997, and 2002 as the source of data to quantify the regional volume changes to reflect the changes in the sediment supply

Table 1. *Hangzhou Bay bathymetric charts.*

Date	Map Title	Scale	Surveyed	Published
1931	Hangzhou Bay and adjacent area; the Navigation Guarantee Department of the Chinese Navy Headquarters (NGDCNH)	1:150,000	1911–1931	03/1986
1962	The northern Hangzhou Bay; NGDCNH	1:150,000	1959–1962	03/1986
1989	Hangzhou Bay; NGDCNH	1:100,000	1989	06/1990
1997	Hangzhou Bay; NGDCNH	1:150,000	1995–1997	08/2000
2002	Hangzhou Bay; NGDCNH	1:150,000	2001–2002	06/2002
2008	Hangzhou Bay; Hydrological Bureau of the Changjiang Estuary	1:150,000 (2007); 1:100,000(2008)	2007–2008	

(Table 1 and Figure 2). Additionally, the bathymetric chart for the Hangzhou Bay between 2007 and 2008 was obtained from the Hydrological Bureau of the Changjiang Estuary (Table 1 and Figure 2). The spatial resolution for all charts is 0.5–1 km, with vertical accuracy of 0.1 m (*e.g.* Figure S1). Therefore, secular bathymetric changes greater than 0.1 m are acceptable in this study. The elevation in all the charts was based on the theoretical low-tide datum at Wusong. Similar charts for the mouth of Changjiang and its submerged delta have been evaluated and used for research (Wang *et al.*, 2012; Yang *et al.*, 2003). Thereafter, the volume we computed directly based on bathymetric charts is the volume of the water body in the confines of the Hangzhou Bay. It represents the capacity of the bay as a receptacle of sediment (Blott *et al.*, 2006). Our basic assumption is that the volume change is primarily caused by the depth change due to erosion and deposition on the seabed.

Based on the digitizing procedure by Blott *et al.* (2006), the depth data from NGDCNH were digitized and analyzed by using ArcGis9.3 software. The data were georeferenced using nine fixed landmarks that had related errors smaller than 0.01 cm. Subsequently, all the digitized data were transferred from their original projections onto Beijing 54 coordinates in ArcGIS9.3. The bathymetric data were gridded at 100×100 m resolution using

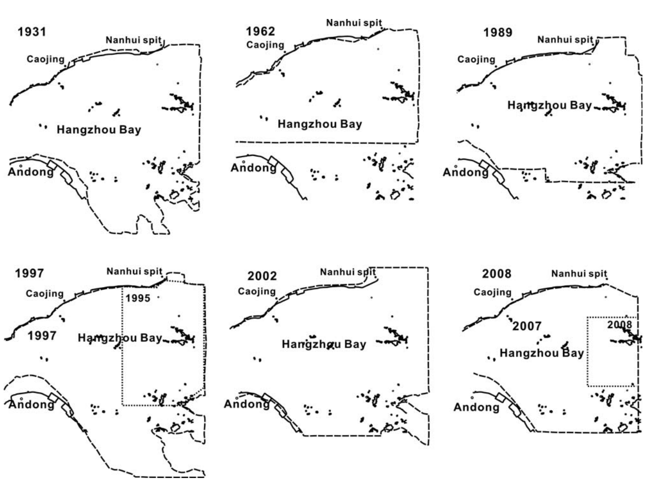

Figure 2. For bathymetric surveys of the Hangzhou Bay in different years, the coastlines are indicated in black, and the area included in this study is indicated in black dashed line. The smaller area of a different year that is used in the study is indicated in black dotted line.

kriging method (Burrough and McDonnell, 1998). Subsequently, a digital terrain model (DTM) for each digitized chart of the Hangzhou Bay was established, which further divided the bay into the northern and southern parts. On each chart, the water depths along five transverse and one longitudinal cross sections were extracted (Figure 1D) for detailed analysis.

The Datong gauging station (30°46′ N, 117°37′ E) is located about 640 km from the Changjiang's mouth beyond the tidal river (tidal limit), which is the seaward-most gauging station (Figure 1A). To provide information on Changjiang's sediment load, long-term river runoff and sediment content recorded at Datong between 1955 and 2010 were acquired from the Bulletin of China River Sediment (BCRS) (2003–2010, available on http: www.cjh.com.cn/), and the suspended sediment discharge (SSD) was subsequently estimated based on these two observed parameters. The total amount of SSD from Qiantangjiang to the Hangzhou Bay was estimated based on the SSD data (provided by BCRS) at three gauging stations at Lanxi (29°13′ N, 119°28′ E), Huashan (29°42′ N, 120°50′ E), and Zhuji (29°42′ N, 120°14′ E) (Liu, Hu, and Shi, 2011).

Since the temporal changes of the sediment texture on the seabed also reflect the erosion-depositional trends, average median grain sizes and the percentages of clay and sand from the seabed sediment in the northern OHB measured in 1982 and 2006 from the literature (Cao *et al.*, 1989; Zhao *et al.*, 2008) were used. The median grain size was based on statistic moment method (McManus, 1988). The grain-size classification was based on the scheme proposed by Folk (1954).

RESULTS

Variation of Discharge and SSD into the Changjiang Estuary

Long-term time series of yearly suspended sediment content and river discharge at Datong reflect the secular variability of the sediment load and runoff (Figure 3). In the past half a century, the river discharge has fluctuated around the mean of 900×10^9 m^3/y (Figures 3A and B), although there was a slight increase. Even when the TGD reached its full capacity of 39.3×10^9 m^3 and the water level was at 175 m above sea level, compared to the mean yearly discharge, the influence of TGD on the river flow was negligible. However, that is not the case with the SSD in the past 50 years at Datong (Figure 3C).

First of all, the decadal change in the SSD increased from 4.8×10^8 t/y in the 1950s to 5.06×10^8 t/y in the 1960s. Secondly, compared to the 1960s, the SSD in the 1970s decreased by 14%. From the 1970s to 1980s, the SSD increased slightly by about 6×10^6 t/y (Figure 3D). After further smoothing by applying a 10

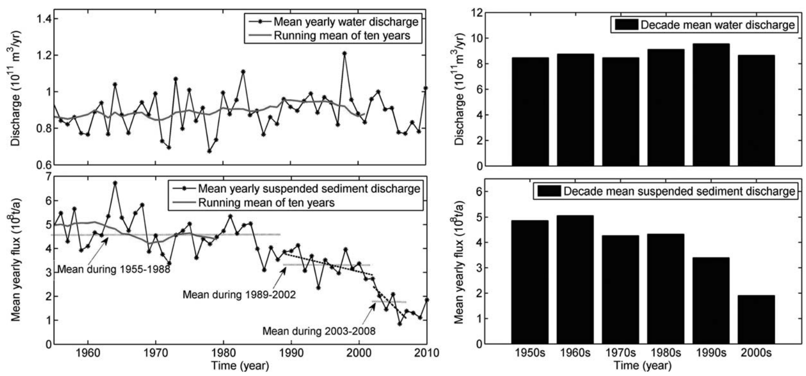

Figure 3. Observed at Datong: (A) yearly river runoff; (B) decadal mean runoff; (C) yearly suspended sediment discharge (SSD); and (D) decadal mean SSD at Datong. The red curve is the smoothed 10 y running mean. Dashed lines show trends.

y running mean to the data, between 1955 and 1988, the SSD fluctuating around 4.5×10^8 t/y (Figures 3C and D). It then dropped sharply from 3.39×10^8 t/y in the 1990s to 1.75×10^8 t/y in the 2000s. The two lowest yearly SSD values of 2.06×10^8 t/y and 0.86×10^8 t/y occurred in 2003 and 2006, corresponding to the first-stage impoundment of TGD, which raised the water level behind the dam to 135 m above sea level in 2003, and the second stage, which further raised the water level to 175 m in 2006. Between 2003 and 2006, the amount of sediment intercepted by the TGD has been 1.24×10^8 t, 1.02×10^8 t, 1.51×10^8 t, and 0.93×10^8 t, respectively (BCRS, 2004–2010). Comparing to the multiyear average of the sediment load of the Changjiang, the intercepted amount is significant, which can explain the link between SSD decrease and the TGD.

Decennial Sedimentation in the OHB

The accumulation/erosion can be visualized in the seafloor elevation changes in sequential time periods. Between 1931 and 196,2 there was slight erosion in northern OHB, but accretion over 1 m occurred in other areas (Figure 4A), and the average accumulation rate was 52.3×10^6 m^3/y (Table 2) (Lin, 1990). The areas of accretion between 1962 and 1989 were smaller than the previous period, but localized erosion in the Zhapu-Jinshanzui area exceeded 2 m (Figure 4B).

Between 1931 and 1989, the volume of OHB was reduced by 7 $\times$ 10^8 m^3 (Table 3), suggesting the Hangzhou Bay became shallower by 0.19 m due to accretion. In the past 58 years, the volume reduction rate is equivalent to a sediment accumulation rate of 12.1×10^6 m^3/y (Table 2), which is equivalent to the accumulation (10.67×10^6 m^3) in the subtidal zone of the outer Mersey Estuary between 1948 and 1988 (Blott *et al.*, 2006).

Between 1989 and 1997, the volume of the OHB increased slightly by about 87×10^6 m^3, corresponding to a narrow range of elevation change between –0.3 and ~0.3 m (Table 2 and Figure 4C). The volume increase of the OHB between 1997 and 2002 was 90×10^6 m^3, accompanied by the erosion of southern OHB, which was smaller than that during 1989–1997. During this period of 1989–2002, the deposition rate was 8–10 $\times$ 10^6 m^3/y (Tables 2 and 3). In contrast, the volume increase was 351 $\times$ 10^6 m^3 between 2002 and 2008, which suggests a higher erosion rate of 58.5×10^6 m^3/y (Table 2). In general, the secular sedimentation in OHB could be characterized as rapid accumulation between 1931 and 1962, and slow accumulation between 1962 and 1997. A period of transition from accumulation to erosion existed between 1997 and 2002. Between 2002 and 2008, rapid erosion occurred, which coincided with the operation of TGD.

Furthermore, in the past 20 years, the spatial and temporal patterns of erosion and deposition are shown in Figures 4D and 4E. Comparing to the period of 1997–2002, the outer bay showed area-wide erosion of –0.3 to –0.5 m (Figures 4D and 5E). Even when the inner bay maintained a steady accumulation, the outer bay underwent erosion, especially in the southern area, which has shown erosion since 1997. Between 2002 and 2008, the southern outer bay had an average erosion rate of –27 $\times$ 10^6 m^3/y (Table 2) for areas under the 0 m elevation, despite accretion of the upper tidal flat, while the northern part of the outer bay changed from depositional (with a rate of 29.9×10^6 m^3/y) to erosional (having a rate of -31.3×10^6 m^3/y) between 1997 and 2002 (Table 2).

The morphological changes in the Hangzhou Bay between 1989 and 2008 were further examined along five transverse transects from the bay opening to Jinshanzui. Transect 4 is the spatial demarcation that separates areas of erosion to the east and deposition to the west (Figures 5A–F). This suggests that the imported sediment from Changjiang and sediment eroded from the outer bay were transported westward. The downcutting of the deep channels in the northern part of the bay is conspicuous. Compared to other areas, the deepening of the channel near Wangpan Island over 15 m suggests erosion (Figure 5F). It is noted that in the southern part of the outer bay, there were localized anomalous areas of deposition and erosion around the Qiqu Islands.

DISCUSSION

Changjiang is the Main Contributor of Sediment to Hangzhou Bay

As the conduit for sediment transport between the Changjiang and the inner Hangzhou Bay, the OHB is the

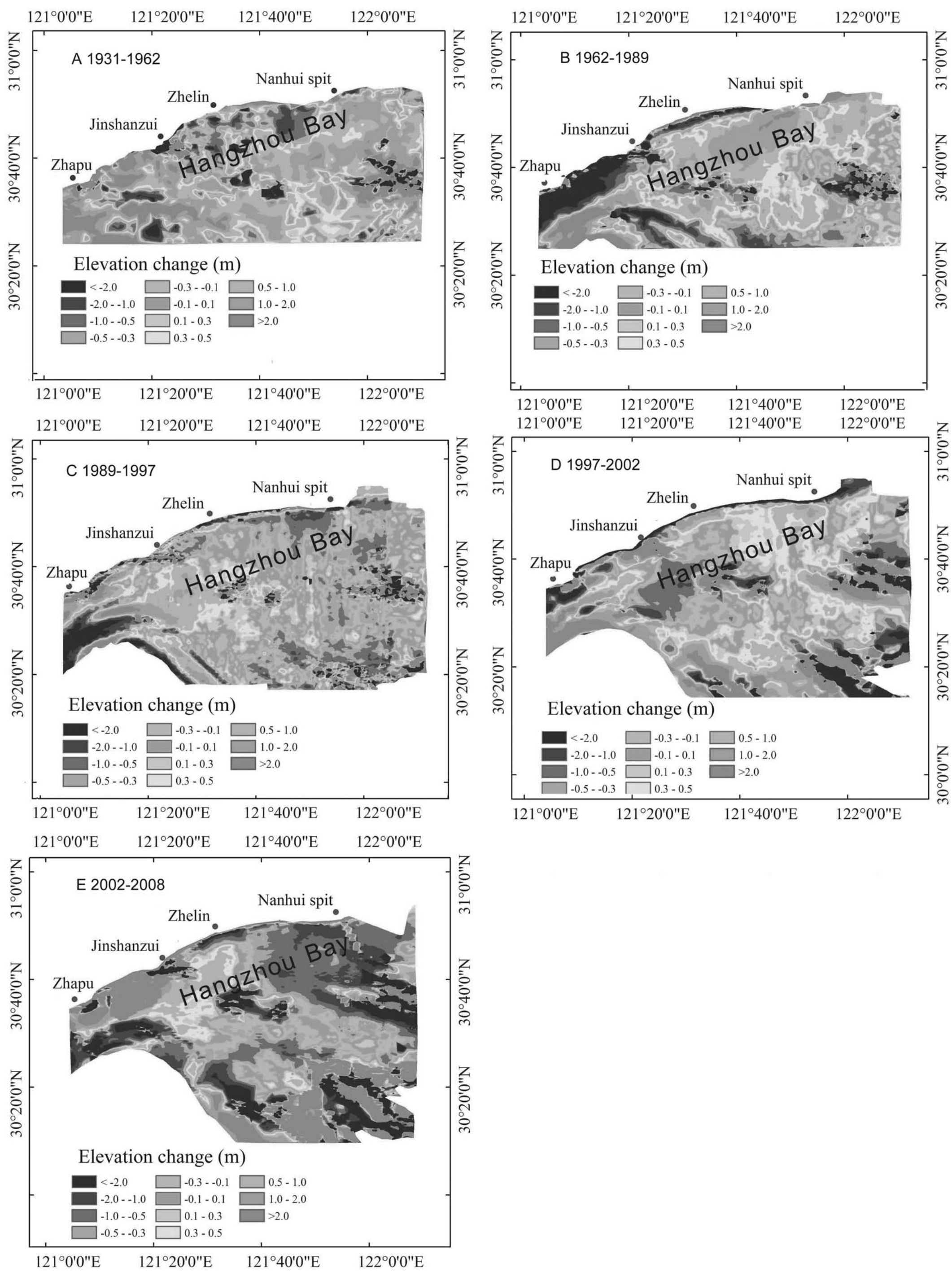

Figure 4. Topographical changes of Hangzhou Bay over different time intervals showing the overall bathymetric differences between (A) 1997–2002, (B) 1962–1989, (C) 1989–1997, (D) 1997–2002, and (E) 2002–2008.

area of changes and transition (Chen *et al*., 1990; Su and Wang, 1989). Sediment comes from two major sources. Between 1956 and 1965, the Qiantangjiang had an average yearly runoff of 42×10^9 m^3/y and suspended sediment load of 7.9×10^6 t/y, respectively (Pan and Huang, 2010; Su and Wang, 1989). However, due to the dam construction in Xinanjiang, the sediment delivered to the Hangzhou Bay has been decreasing. Between 1977 and 2010, the mean sediment

Table 2. *Accretion and erosion ('–') of the OHB below 0 m over different time intervals.*

	Northern OHB		Southern OHB		OHB		
Time Intervals	Volume Changes (10^6 m^3)	Deposition Rate (10^6 m^3/y)	Volume Changes (10^6 m^3)	Deposition Rate (10^6 m^3/y)	Volume Changes (10^6 m^3)	Deposition Rate (10^6 m^3/y)	Input[a] SSD (10^6 m^3/y)
1931–1962	562.4	18.1				52.3[b]	102.34[c]
1962–1989	492.5	18.2					99.35
1989–1997	22.7	2.84	64.3	8.04	87.02	10.8	74.27
1997–2002	149.9	29.9	−59.4	−11.9	90.4	18.1	68.65
2002–2008	−188.1	−31.3	−162.8	−27.1	−350.9	−58.5	36.82

[a] Input: Based on the previous research (Wan, Li, and Shen, 2004). Input represents mean yearly sediment moved into the outer Hangzhou Bay from Changjiang Estuary, which is equal to 27% of the corresponding amount at Datong station, and the sediment density is 1.24 t/m^3 (Lin, 1990).
[b] Data from Lin (1990).
[c] Calculated value of mean yearly SSD into outer Hangzhou Bay based on SSD at Datong during 1955–1962.

input from the Qiantangjiang was 2.5×10^6 t/y (Figure 6A). Compared to the sediment load of the Changjiang (Figure 3C), that of the Qiantangjiang is 80–300 times lower (Figure 6B). In addition, because of the control by the river-mouth shoal and the tidal boar, the Qiantangjiang sediment load is mostly deposited at Zhapu (Figure 1), and little sediment is exported beyond this point to the OHB (Chen *et al*., 1990). Additionally, the isolation of the southern part of OHB from the ESC by the Qiqu Islands makes the Changjiang's sediment load the primary controlling factor of the sedimentation in the OHB.

Previous research showed that 27% of the Changjiang's seagoing sediment load entered the OHB by the flooding tide (Chen *et al*., 1990; Wan, Li, and Shen, 2004). Changjiang's contribution to the sediment budget of the Hangzhou Bay is 20–100 times that of the Qiantangjiang. Results from a recent numerical modeling study also indicate that Changjiang provides most of the sediment that enters Hangzhou Bay (Yu *et al*., 2012). Linear regression analyses of the relation between the deposition/erosion rates of OHB, southern OHB, and northern OHB and the early SSD of the same time periods (1962–1989, 1989–1997, 1997–2002, and 2002–2008) showed that there are close correlations with statistical significance (Figure S2). This indicates that the sedimentation in the OHB is directly related to the sediment exported by Changjiang.

Erosion of the Seafloor in the OHB as a Contributor to the Inner Hangzhou Bay

Previous studies (Table 2) showed that between 1931 and 1962 the sediment imported from the Changjiang to Hangzhou Bay was 102.34×10^6 m^3/y. The OHB's sedimentation rate was 52.3×10^6 m^3/y. Consequently, there was a differential of 50×10^6 m^3/y that had to be deposited in the inner bay, west of Ganpu. This demonstrates that, firstly, the inner Hangzhou Bay has a large capacity, which is an important reason that the largest river-mouth shoal in China exists at this location. Secondly, past studies have shown that between 1972 and 1982 the accumulation rate at Ganpu was 102×10^6 m^3/y (Chen *et al*., 1990). During the same period, the sediment import from Changjiang was under 100×10^6 m^3/y (Table 2). This suggests that the sediment from erosion in the OHB made up the differential.

During 1997–2002, when the Changjiang sediment load decreased, sedimentation from erosion of the OHB made up the sediment budget deficit of the inner bay. This implies that the decrease in the Changjiang sediment supply would trigger erosion in OHB, so that the sedimentation characteristics of the OHB readjust to maintain a balanced sediment budget.

The Impact of TGD on the Sedimentation in the Hangzhou Bay

Taking one step further, decadal increases in SSD from the 1950s to 1960s could be attributed to the 'Great Leap Forward' and the 'Cultural Revolution' political movements, which resulted in large-scale soil erosion along the upper reaches of the Changjiang. However, when the impoundment of TGD started in 2003, the record at Datong shows that the sediment load was down by 150×10^6 t/y during 2003–2008 (Dai *et al*., 2011; Figure 3C), and the OHB had already undergone minor local erosion (Figure 4). This decrease is equivalent to 65% of the average amount of the sediment load between 1960 and 1990 (Figures 3C and D). Similarly, the sediment entering Hangzhou Bay decreased sharply by about 36.82×10^6 t/y (Table 2). This chronology coincides with the period between 2002 and

Table 3. *Volume statistics below 0 m of the outer Hangzhou Bay (OHB) in different years.*

	Northern OHB		Southern OHB		OHB	
Year	Area (10^9 m^2)	Volume (10^9 m^3)	Area (10^9 m^2)	Volume (10^9 m^3)	Area (10^9 m^2)	Volume (10^9 m^3)
1931	1.72	15.06	2.02	17.73	3.74	32.8
1962	1.73	14.5	–	–	–	–
1989	1.71	14.01	2.01	18.08	3.72	32.09
1997	1.71	13.98	2.05	18.01	3.76	32.01
2002	1.69	13.84	1.99	18.07	3.68	31.91
2008	1.71	14.02	2.06	18.24	3.76	32.26

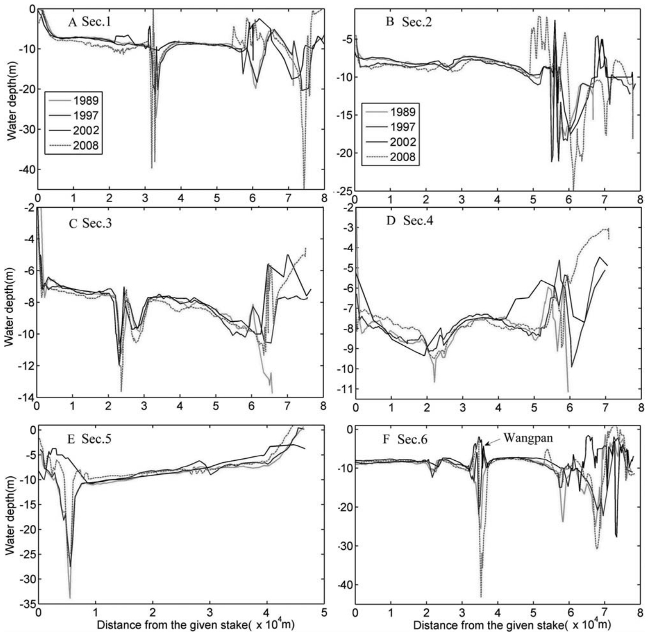

Figure 5. Depth changes along the cross-sections 1 (A), 2 (B), 3 (C), 4 (D), 5 (E), and 6 (F) of Hangzhou Bay in 1989, 1997, 2003, and 2008.

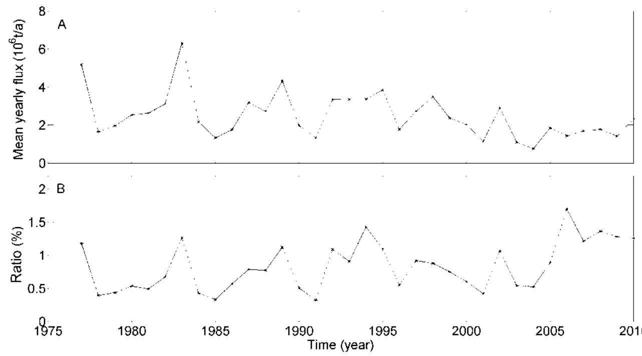

Figure 6. Changes in SSD from the Qiantangjiang to the Hangzhou Bay (A), and SSD ratio between Qiantangjiang and Changjiang (B).

2008 when the OHB turned from depositional to erosional. This decrease of sediment supply was likely to trigger bay-wide erosion.

Furthermore, the median grain size and coarse fraction in the seafloor sediment in the northern OHB were 556 μm and 46.1% in 1982, and 587 μm and 58.5% in 2006, respectively (Zhao *et al.*, 2008). This coarsening is an indication of long-term erosion (Dietrich *et al.*, 1989; Topping *et al.*, 2000). The textural change corroborates well with the erosional change between 2002 and 2008 in the OHB.

The reduction in the Changjiang sediment load in 2002–2008 not only caused reduced supply of sediment to Hangzhou Bay, but the area around the Qiqu Islands, which is between the southern OHB and the Changjiang submerged modern delta, also underwent phase change, from net deposition in 1960–1989 to erosion in 1997–2004. The erosion reached 32.3×10^6 m^3/y between 1997 and 2004 (Table 4). Facing the declining sediment load, despite the lack of conclusive evidence, the lower reaches of the Changjiang dispersal system might be entering an era of higher erosion risks.

CONCLUSIONS

The outer Hangzhou Bay is located in the pivotal position along the sediment conduit linking the Qiantangjiang and Changjiang. Its sedimentation is directly controlled by the sediment input from the Changjiang and, therefore, is the buffer zone for the Changjiang's influence on the entire Hangzhou Bay. The two systems appear to be independent, and yet, they are not, which makes them special in the world. Particularly, the way in which the reduced sediment supply affects the future evolution of the macrotidal Qiantang Estuary and the maintenance of the famous tidal bore in the outer Hangzhou Bay deserve further investigation. Although there has been overall accretion in the Hangzhou Bay in the past 77 years, the outer bay underwent a phase change from depositional to erosional after 2002 when the TGD began operations. Between 2002 and 2008, the outer Hangzhou Bay showed extensive erosion, which is detrimental to the entire Hangzhou Bay, but also to the deltaic region of the Changjiang. We believe the risks caused by the TGD on the environmental stability of the lower reaches of the Changjiang need to be reevaluated.

ACKNOWLEDGMENTS

This study was supported by the Natural Science Foundation of China (grant number: 50939003, 41076050), the Funds for Ministry of Science and Technology of China (SKLEC: SKLEC-2012KYYW06), and the National Science Council of Taiwan (grant number: NSC 101-2811-M-110-003) for Z. Dai's visit to Taiwan. We are grateful to the three anonymous

Table 4. *Erosion ('–') and accretion at the adjacent sea area of the southern Changjiang Estuary (modified from Fu* et al., *2007).*

Covered Region (Coordinates)	Time Intervals	Accreted Amount (10^6 m^3)	Eroded Amount (10^6 m^3)	Net Erosion/Accretion (10^6 m^3)	The Net Mean Yearly Accreted/ Eroded Volume (10^6 m^3/y)
30.65–30.85° N, 121.9–122.15° E	1960–1989	451	348	103	3.55
	1989–1997	378	344	34	4.5
	1997–2004	314	539	–226	–32.3

reviewers and editor for their helpful comments and suggestions to improve the manuscript.

LITERATURE CITED

Blott, S.J.; Pye, K.; van der Wal, D., and Neal, A., 2006. Long-term morphological change and its causes in the Mersey Estuary, NW England. *Geomorphology*, 81(1–2), 185–206.

Burrough, P.A. and McDonnell, R.A., 1998. *Principles of Geographical Information Systems*. Oxford, UK: Oxford University Press, 352p.

BCRS (Bulletin of China River Sediment). 2004–2010. *Press of Ministry of Water Resources of the People's Republic of China*. http://www.cjh.com.cn/.

Cao, P.-K.; Dong, Y.-F.; Yan, S.-H., and Gu, G.-C., 1989. Basic characteristic of the tidal flat on the northern coast of Hangzhou Bay. *Oceanologia et Limnologia Sinica*, 20(5), 412–421 [in Chinese with English abstract].

Chen, J; Luo, Z.; Chen, D., and Qiao, P., 1964. The forming and historical evolvement of the big sand bar inside the Qiantangjiang Estuary. *Acta Geologica Sinica*, 30, 109–123 [in Chinese with English abstract].

Chen, J.-Y.; Liu, C.-Z.; Zhang, C.-L., and Walker, H.J., 1990. Geomorphological development and sedimentation in Qiantang Estuary and Hangzhou Bay. *Journal of Coastal Research*, 6(3), 559–572.

Chen, Z.-Y.; Wang, Z.-H.; Finlayson, B.; Chen, J., and Yin, D.W., 2010. Implications of flow control by the Three Gorges Dam on sediment and channel dynamics of the middle Yangtze (Changjiang) River, China. *Geology*, 38(11), 1043–1046.

Dai, Z.-J.; Chu, A.; Li, W.-H.; Li, J.-F., and Wu, H.-L., 2012. Has suspended sediment concentration near the mouth bar of the Yangtze (Changjiang) Estuary been decline in recent years? *Journal of Coastal Research*, doi: 10.2112/JCOASTRES-D-11-00200.1.

Dai, Z.-J.; Du, J.-Z.; Zhang, X.-L.; Su, N., and Li, J.-F., 2011. Variation of riverine material loads and environmental consequences on the Changjiang Estuary in recent decades. *Environmental Science and Technology*, 45(1), 223–227.

Dietrich, W.E.; Kirchner, J.W.; Ikeda, H., and Iseya, F., 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature*, 340, 215–217.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Geology*, 62(4), 344–359.

Fu, G.; Li, J.-F.; Dai, Z.-J.; Wu, R.-R., and Yu, Z.-Y., 2007. Primary discussion on seabed evolution of Nanhuizui and Qiqu Archipelago. *Journal of East China Normal University (Natural Science)*, 4, 34–41 [in Chinese with English abstract].

Guillén, J. and Palanques, A., 1997. A historical perspective of the morphological evolution in the low Ebro River. *Environmental Geology*, 30(3–4), 174–180.

Lin, C.K., 1990. The construction of the Shanghai Port and its sea-entering channel, influenced by the sediments and the fluvial processes at the Changjiang river estuary and the Hangzhou Wan. *Acta Geographica Sinica*, 45(1), 78–89 [in Chinese with English abstract].

Liu, C.; Hu, C.-H., and Shi, H.-L., 2011. Changes of runoff and sediment fluxes of rivers in mainland of China discharged into Pacific Ocean. *Journal of Sediment Research*, 1, 70–75 [in Chinese with English abstract].

Liu, J.-P.; Xu, K.-H.; Li, A.-C.; Milliman, J.D.; Velozzi, D.M.; Xiao, S.-B., and Yang, Z.-S., 2007. Flux and fate of Yangtze River sediment delivered to the East China Sea. *Geomorphology*, 85(3–4), 208–224.

McManus, J., 1988. Grain size determination and interpretation. *In:* Tucker, M. (ed.), *Techniques in Sedimentology*. Oxford, UK: Blackwell, pp. 63–85.

Milliman, J.D. and Farnsworth, K.L., 2011. *River Discharge to the Coastal Ocean—A Global Synthesis*. Cambridge, UK: Cambridge University Press, p.392.

Milliman, J.D. and Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology*, 91(1), 1–21.

Pan, C.H. and Huang, R.W., 2010. Numerical modeling of suspended sediment transport affected by tidal bore in Qiangang Estuary. *Journal of Coastal Research*, 26(6), 1123–1132.

Su, J.L. and Wang, K.-S., 1989. Changjiang River plume and suspended sediment transport in Hangzhou Bay. *Continental Shelf Research*, 9(1), 93–111.

Syvitski, J.P.M.; Vörösmarty, C.J.; Kettner, A.J., and Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, 308(15), 376–380.

Topping, D.J.; Rubin, D.M., and L.E., Jr., Vierra, 2000. Colorado River sediment transport: Part 1: natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resource Research*, 36(2), 515–542.

Van der Wal, D. and Pye, K., 2003. The use of historical bathymetric charts in a GIS to assess morphological change in estuaries. *The Geographical Journal*, 169(1), 21–31.

Wan, X.-N.; Li, J.-F., and Shen, H.-T., 2004. Suspended sediment flux at the typical cross sections in the offshore area of Changjiang Estuary. *Journal of Sediment Research* 6, 64–70 [in Chinese with English abstract].

Wang, Z.-H.; Li, M.-T.; Zhang, R.-H.; Chen, Z.-Y.; Liu, Y.; Satio, Y.; Xie, J.-L., and Zhao, B.-C., 2011. Impacts of human activity on the late-Holocene development of the subaqueous Yangtze delta, China, as shown by magnetic properties and sediment accumulation rates. *The Holocene*, 21(3), 393–407.

Wells, J.T., 1996. The lower Mississippi River delta. *In:* Milliman, J.D. and Ha, B.U. (eds.), *Sea-Level Rise and Coastal Subsidence*. Dordrecht, Netherlands: Kluwer, pp. 281–311.

Yang, S.-L.; Belkin, I.M.; Belkina, A.I.; Zhao, Q.-Y.; Zhu, J., and Ding, P.-X., 2003. Delta response to decline in sediment supply from the Yangtze River: evidence of the recent four decades and expectations for the next half-century. *Estuarine, Coastal and Shelf Science*, 57(4), 689–699.

Yang, S.-L.; Milliman, J.D.; Li, P., and Xu, K., 2011. 50, 000 dams later: erosion of the Yangtze River and its delta. *Global and Planetary Change*, 75(1–2), 14–20.

Yang, Z.-S.; Wang, H.-J.; Satio, Y.; Li, G.-X., and Sun, X.-X., 2004. Phase change of the modern Huanghe delta evolution since its last end channel shift in 1976 (and its phase change). *In:* Jarupongsakul, T. and Saito, Y. (eds.), *5th International Conference on Asian Marine Geology*, AGCP-475 DeltaMAP, and APN Mega-Delta.

Yu, Q.; Wang, Y.-W.; Gao, W., and Flemming, B., 2012. Modeling the formation of a sand bar within a large funnel-shaped, tide-dominated estuary: Qiantangjiang Estuary, China. *Marine Geology*, 299–302, 63–76.

Yun, C.-X.; Dai, Z.-J., and Wang, D.-C., 2010. *Crisis of the River-Delta in China*. Beijing: China Ocean Press [in Chinese].

Zhao, J.-C.; Dai, Z.-J.; Li, J.-F., and Li, W.-H., 2008. Study on the characteristics of temporal and spatial changes in properties of surface sediment on near-shore seabed of strong-tide bay: a case from the north bank of Hangzhou Bay in Shanghai. *Acta Sedimentologica Sinica*, 26(6), 49–57 [in Chinese with English abstract].