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Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta

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While most large river-deltas in the world are facing the risk of subsidence and erosion in the Anthropocene, it is suspected that the Changjiang submerged delta (CSD) could be subjected to the impacts of the world's largest dam, the Three Gorges Dam (TGD). Here we firstly indicate that the CSD went through high accumulation (1958–1978); slight accumulation (1978–1997), slight erosion (1997–2002); and high accumulation (2002–2009), despite the 70% reduction of the sediment load from upstream since the operation of the TGD in 2003. Meanwhile, at the depocenter of the submerged delta, the accumulation maintained a high rate of 10 cm/yr during 1958–2009. This suggests on a longer term, the distal sediment source from the upstream had little effect on the CSD. Within this time frame the changes in the partition of sediment load among the branching channels of the Changjiang Estuary could likely control the shifting of the depocenter of the CSD on a decadal time scale. Episodic extreme floods and storm surges also increased the magnitude of deposition and erosion of the CSD on short-term scales. A re-evaluation of the impacts of TGD on the CSD is urgently needed.

River deltas are formed in the narrow zone at the land-ocean margins. Most modern deltas are young; they appeared about the last ~ 6 ka¹ after the sea-level rise stabilized². Deltas are dynamic coastal systems, comprising of only 5% of the global land. Yet, because of their low and gentle topography, high productivity and biodiversity, and navigational value, they became important habitats for over 5×10^9 of the human population in the world³.

Since deltas are also the buffer zone for land-ocean interactions, deltas are environmentally sensitive and vulnerable. Most deltas in the world are facing the threats of erosional retreat of the shoreline and land loss. Threats came from the combined influence of human activities such as damming in the drainage basin and extraction of natural gas, oil, and water in the coastal area; and natural processes such as tectonic subsidence of the continental margin, effects of compaction of the sediment column, and the global sea-level rise^{4,5}. A typical example is the Nile delta. Since 1964 the impoundment by the Aswan High Dam, the Lake Nasser captured 98% of the sediment, causing the coastal retreat of the entire delta area⁶. In the case of the Mississippi delta, the channel diversion triggered repeated alluvial changes that reduced the sediment input to the Balise River, leading to the land loss of the Balise delta at the daily rate of 0.4 ha⁷. The changes in the land development and fluid extraction affect the sediment compaction that induces deltaic substance, such as the case of the Po delta⁸.

Contrary to the intensified global attention to research^{9,10} on the shoreline retreat and erosion of the subaerial deltas in the Land-Ocean-Interaction in the Coastal Zone (LOICZ), the erosion and deposition of the submerged part of major deltas has received little attention. Even the good responses of the stratigraphic sequences, sedimentary structures and morphology produced by the high-resolution seismic reflection surveying instruments^{11–13}, it is difficult to survey the vast areas of the submerged deltas in the world, so they remain the least known part of the global deltaic systems.

The Changjiang (Yangtze River) is the largest river on the Eurasian continent. It is 6,300 km long, having the average water discharge of 905.1×10^9 m³/yr and the sediment discharge of 0.43×10^9 ton/yr between 1950–2000¹⁴ (Fig. 1). Downstream from the city of Nanjing, the ample sediment load of the Changjiang starts to be deposited in low-lying areas on the coastal plain. The relatively stable sea level since 6 ka and the increased sediment load due to high intensity of land use since 2 ka contribute to the rapid development of the modern Changjiang delta¹⁵, of which the submerged part has the area of nearly 10,000 km²¹⁶. The topset of the Changjiang Submerged Delta (CSD) is located at the river-mouth shoal (-5–10 m). The foreset of the CSD extends seaward to

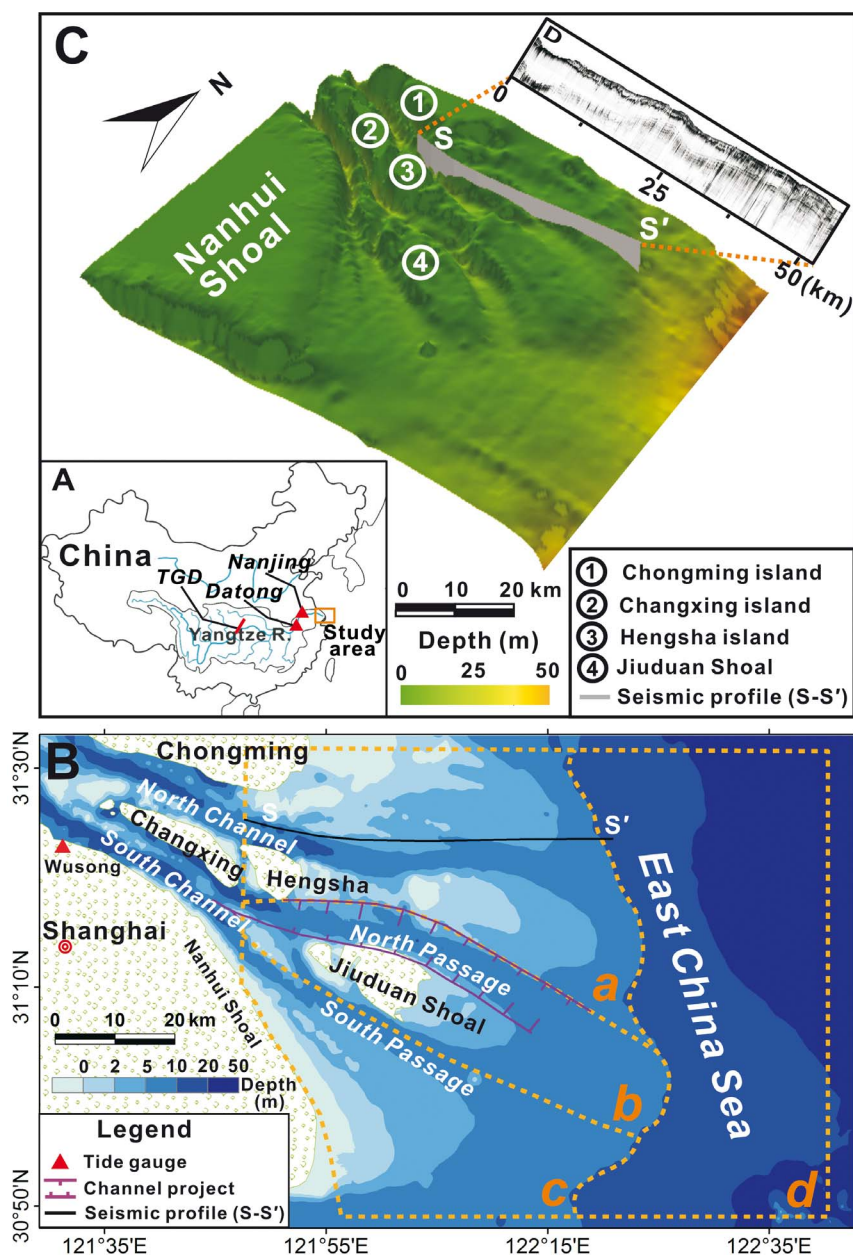


Figure 1 | (A) A map of China indicating the location of the Changjiang Estuary and the study area (red dashed polygon), (B) The area bathymetric map of the study area (features indicated by the alphabet are explained below), (C) the 3-D view of the CSD, (D) sub-surface seismic survey image. Figure 1 was drawn by software ArcGIS 9.3. Features in (B) indicate: a: the region above the -10 m isobath between the N. Channel and N. Passage; b: the region above the -10 m isobath between the N. and S. Passages; c: the region of the Nanhui Shoal and S. Passage above the -10 m isobath; d: the seaward region below the -10 m isobath.

the region between isobaths -20-40 m, whose frontal edge merges with the submerged residual sand sheet in the area between isobaths -30-50 m where noticeable clinoforms exit^{15,17} (Fig. 1). Over the CSD, the mean tidal range is ~2.6 m, mean wave height is ~1.1 m. Under storm surge conditions, wave height as large as 6 m has been recorded^{15,16} (Fig. 1). Under the influence of the summer monsoon, the river plume delivers the sediment to the inner shelf on the East China Sea (ECS)¹⁵. The sediment from summer deposits is later resuspended and transported during high-energy winter wind events. Winter transport is suspected to involve southerly setting benthic fluxes by wind-driven currents along with episodic gravity-driven downslope transport¹⁸.

Recently, the 50,000 dams and reservoirs built in the river basin in the past 50 years have caused great concerns for the sustainability of the delta region of the Changjiang. Since the world's largest river

engineering project, the Three Gorges Dam (TGD), was completed in 2003, the suspended sediment discharge from the river into the estuary has been reduced from 0.43×10^9 ton/yr for the period of 1950–2000 to be less than 0.15×10^9 ton/yr up to now (Fig. 2)¹⁴. Whether such drastic reduction in the river-supplied sediment to the delta region in a short period would trigger deltaic erosion has been the focus of international attention^{5,19–21}. Chen et al. (2010) point out that even as the sediment load from the upper reaches declined, riverbed erosion along the 1000-km stretch between TGD and the river mouth compensated the loss²⁰. Consequently, there is still a substantial amount of sediment entering the delta region. Furthermore, during the neap tide, sediment is transported into the river mouth from offshore, providing material to the coastal accretion¹⁵. Therefore, it is likely the CSD itself could also be an immediate sediment source¹⁶. There is no doubt that in the scenario

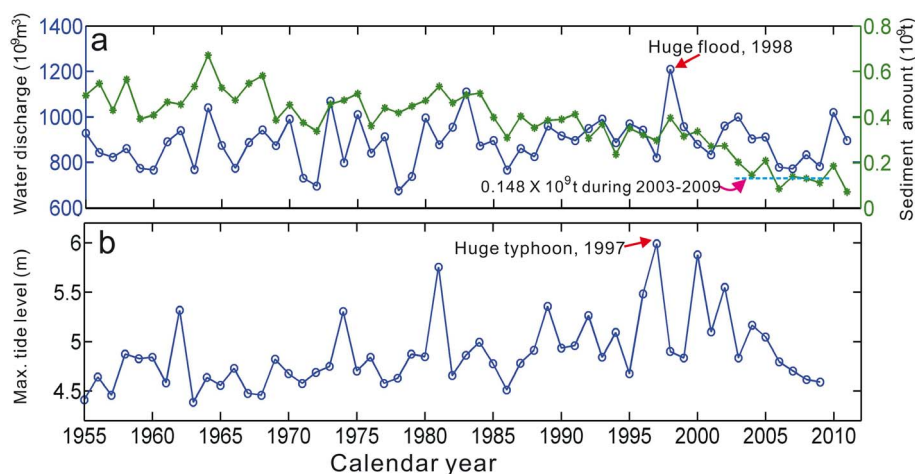


Figure 2 | Yearly changes of water and sediment discharges at Datong (a), and the maximum tidal level at Wusong (b).

of declining sediment supply from the river, the erosion or progradation of the subaerial delta is closely linked to the changes of the submerged delta²². Moreover, the CSD has been widely considered to be the most productive and valuable aquatic areas along the ECS margin, which is of a special significance to the Changjiang estuarine ecosystem²³. However, a thorough evaluation of the CSD in face of the declining sediment supply from the river due to the impacts of TGD has been lacking. Thereafter, this study examines the morphological changes in terms of the erosion and accumulation of the CSD in the past 50 years and possible impacting factors. The result should be extremely valuable in the study of the changes of the Changjiang subaerial delta and its wetlands, and can be applied to other large river deltas in the world.

Results

The deposition-erosion patterns before TGD. Long-term bathymetric survey data can accurately reflect the morphological changes of the submerged delta. When incorporated into the DTM (digital terrain model), it becomes a useful tool to study

morphological changes of river mouths^{24,25}. Here we show calculated erosions and depositions on the CSD based on 8 data sets of different years.

Prior to 2003, CSD's depocenter had varying yet regular patterns of change. In 1958–1978, the deposition center was located at the -10 m isobath seaward of the opening of the South Passage (S. Passage) (Fig. 3a, 3h). The deposition amounted to 2–4 m (Fig. 3a), which is equivalent to an annual rate of 10–20 cm/yr. In 1978–1989 the deposition shifted to the area shallower than the -10 m isobath along the North Channel (N. Channel) where the deposition rate was about 10–20 cm/yr (Fig. 3b, 3h). In 1989–1997, the depocenter moved to the area shallower than the -10 m isobaths off the North Passage (N. Passage), having an accumulation rate of 12–25 cm/yr, and the accumulation fanned out to the nearby area (Fig. 3c, 3h). In 1997–2002, the depocenter again returned to the S. Passage with an accumulation rate of 10–20 cm/yr (Fig. 3d, 3h).

Meanwhile, the CSD shows different spatial patterns of deposition-erosion in the past 50 years. In 1958–1978 and 1978–1987 the N. Channel showed net deposition of $37 \times 10^6 \text{m}^3/\text{yr}$, $25 \times$

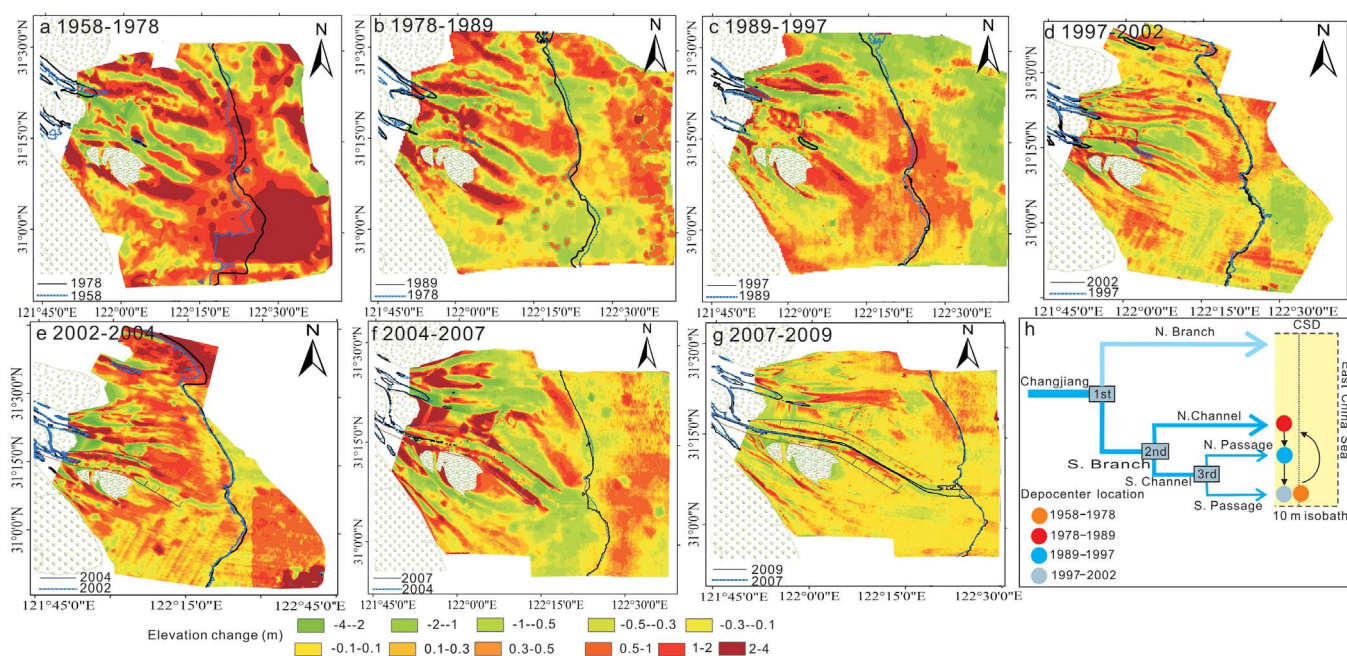


Figure 3 | Bathymetric changes and changes in the depocenter location during different periods, was drawn by software ArcGis 9.3 (a–g: bathymetric changes; h: depocenter changes; contour labeled at a–e: 10 m intervals).

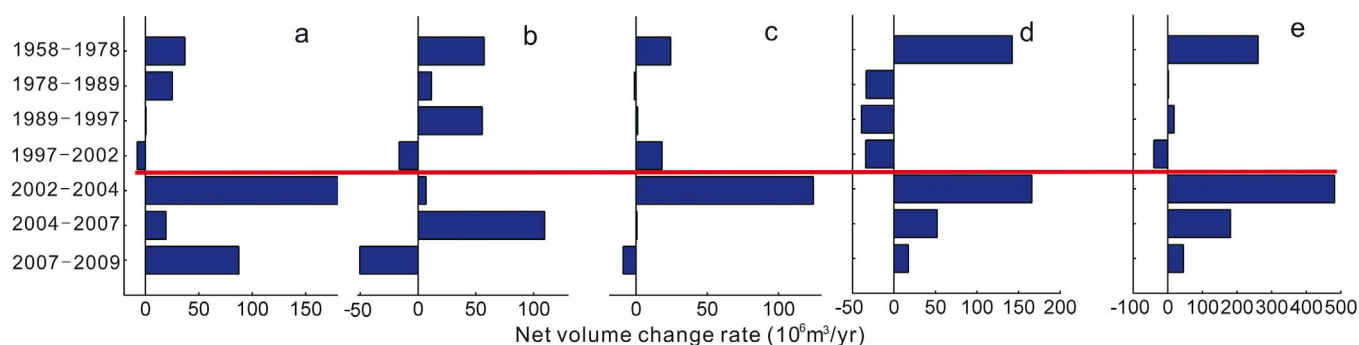


Figure 4 | Net volume changes between erosion and accretion during different intervals: a: the region above the -10 m isobath between the N. Channel and N. Passage; b: the region above the -10 m isobath between the N. and S. Passages; c: the region of the Nanhui Shoal and S. Passage above the -10 m isobath; d: the seaward region below the -10 m isobath; e: the entire submerged delta; The red line shows the demarcation between the pre-TGD and post-TGD eras.

10^6 m³/yr, respectively (Supplementary Tab. S2, online). The number was reduced to 0.62×10^6 m³/yr between 1987–1997. Reversal in the deposition-erosion pattern occurred between 1997–2002 in which the volume change rate showed negative value of -7.6×10^6 m³/yr, indicating erosion in the N. Channel (Figs. 3a–d, Fig. 4a, Supplementary Tab. S2, online).

In the same 4 periods the volume change rates of the N. Passage showed rates of fast accumulation (57×10^6 m³/yr), moderate accumulation (12×10^6 m³/yr), fast accumulation again (56×10^6 m³/yr), and slow erosion (-16×10^6 m³/yr), respectively (Figs 3a–d, Fig. 4b, Supplementary Tab. S3, online). At the S. Passage, the patterns show slow accumulation (24×10^6 m³/yr), slow erosion (-1×10^6 m³/yr), slow accumulation (1×10^6 m³/yr), and moderate accumulation (18×10^6 m³/yr (1997–2002) (Figs. 3a–d, Fig. 4c, Supplementary Tab. S4, online). However, the outer areas of the CSD showed a fast rate of accumulation of 143×10^6 m³/yr in 1958–1978. In the following three periods, each had roughly the same erosion rate of $\sim 35 \times 10^6$ m³/yr (Fig. 3a–d, Fig. 4d, Supplementary Tab. S5, online). Between 1958–2002 the CSD had a net accumulation rate of 241×10^6 m³/yr. Also, the area-wide accumulation over the CSD was 1.05 m, which is equivalent to an accumulation rate of 2.6 cm/yr (Supplementary Tab. S6, online). Over the 40-year span between 1958–2002, the individual periods of 1958–1978, 1978–1987, 1987–1997, and 1997–2002 showed fast accumulation, slow accumulation, and slow erosion, respectively (Fig. 4e, Supplementary Tab. S6, online).

The deposition-erosion patterns after TGD. Compared to changes in the 40-yr pre-TGD period, in general, between 2002–2009 the overall CSD was in a state of accumulation with an accreted volume of 709×10^6 m³/yr and thickness of 5 cm/yr, despite of scattered small-scale erosions (Fig. 3e–g, Supplementary Tab. S6, online). The location of the depocenter in the upper CSD between 2002 and 2004 was similar to that in 1958–1978 (Figs. 3a, 3e). The accumulation rate in depths deeper than -10 m in the seaward segment of the S. Passage was 50–100 cm/yr (Fig. 3e). The net volume change rate of CSD in this period was 482×10^6 m³/yr and corresponding accreted thickness was 9 cm/yr (Fig. 4e, Supplementary Tab. S6, online). These numbers are higher than those in the 40 years predated the TGD operation.

Between 2004–2007 the depocenter of the CSD was located on the SE side of the S. Passage in water depths deeper than 10 m, having an averaged accumulation rate of 16–33 cm/yr (Fig. 3f), and the volume change rate of CSD was 182×10^6 m³/yr with accreted thickness of 4.33 cm/yr (Supplementary Tab. S6, online). In depths shallower than -5 m the deltaic plain was depositional. Between -5 and -10 m isobaths, the bathymetric changes of the CSD showed erosion of 1 to 0.5 m in the areas NE of N. Channel and SE of S. Channel. Also, erosion occurred within the N. Channel by 4 to 2 m (Fig. 3f).

In 2007–2009 the depocenter shifted to N. Branch around the -10 m isobath, having an average accumulation rate of 25–50 cm/yr (Fig. 3g). Although there was slight erosion in areas shallower than the -10 m isobaths in N. and S. Passages (Figs. 3g, 4b, 4c, Supplementary Tab. S3, S4, online), the average accumulation rate and volume change rate of the entire CSD were 1.5 cm/yr and 45×10^6 m³/yr, respectively (Supplementary Tab. S6, online).

Discussion

Declining river sediment load. The sediment input into the delta area of the Changjiang declined about 70% since 2003, and yet, the CSD continued to accumulate and prograde. Although Yang et al. point out that erosion occurred in the areas between isobaths -5 and -8 m on the CSD in 2004–2007¹⁹, their study area only covered less than 2000 km², which cannot represent the behavior of the entire CSD.

Despite the declining river sediment load after 2003, the amount of accumulation on CSD in 2002–2004 was the highest among all the time periods in this study (Figs. 2, 3e, 4e). To understand this discrepancy, one needs to consider the lag effect between the river discharge and delta accumulation/erosion. The Changjiang sediment load reached the lowest level of 0.21×10^9 ton and 0.085×10^9 ton in 2003 and 2006 respectively. If the volume changes of the CSD reflect the sediment load of the Changjiang, through a period of 3–6 years of equilibrium adjustment, the CSD should show erosion. However, the accumulation status of the CSD in 2002–2009 remained almost unchanged (Fig. 4e, Supplementary Tab. S6, online). Conversely, in 1958–2002 even the river sediment discharge did not show significant reduction, and yet areas deeper than -10 m showed erosion in periods of 1978–1989, 1989–1997, 1997–2002 (Figs. 2, 3b–d, Supplementary Tab. S5, online). Furthermore, there is almost no direct relationship between the accumulated sediment discharge into the estuary and correspondingly net changes in the sediment volume of the CSD during different time intervals (Supplementary Fig. S2, online). This suggests that the erosion of the CSD is not linked to the river sediment discharge from upstream. This raises the question about the validity of the river sediment load threshold for CSD erosion^{26,27}.

Based on a simple model of fluviodeltaic progradation, Swenson et al. (2005) discovered that the reduction of the peak flood frequency and river runoff causes the delivery of external sediment to the shallow marine environment to increase, which leads to the progradation on the submerged delta²². This provides an explanation for the accretion of the CSD when the river flow of peak floods were noticeably reduced due to the regulation by the TDG during the flood season from July to September²⁸ and the dynamic condition off the river mouth remained the same. Another possibility is the seaward sediment transport by wave and hyperpycnal plume-induced gravity



flows, which have been observed at the mouth of high-load rivers such as Atchafalaya, Fly, Ganges-Brahmaputra, Klamath, Mad, Mississippi, Po, Rhone, Yellow¹⁸, and also possibly Changjiang. Meanwhile, in a conceptual model for the dispersal of the Changjiang sediment on the shelf, Oguri et al. (2003) show the possible alongshore sediment transport by currents and across-shelf transport within the downslope migrating nepheloid layers seaward of the mouth of Changjiang²⁹.

Moreover, the slope of the CSD seabed between 0 and -10 m isobaths is about 0.02% ~ 0.06%, and the slope between -10 and -20 m isobaths is 0.05% ~ 0.1% (Fig. 1). The sediment texture in areas shallower than the -10 m isobaths is coarser, mostly sand, than that in deeper areas, which is mostly clay (Supplementary Fig. S3, online). It seems the -10 m isobath is the demarcation between gentle-slope and steep-slope sediment transport regimes (Fig. 1). The relatively steep slope is conducive to forming gravity flows during higher river discharge and transport fine sediment to the deeper part of the CSD and also causing localized erosion on the seabed³⁰. Meanwhile, even on gentle slope, wave- or current-induced velocity shear could keep sediment in suspension, allowing long-distance gravity-driven transport on most shelves¹⁸. Therefore, the river runoff is not the only factor controlling the sediment erosion/deposition on the CSD.

Changes of Sediment Load Partition of the Branching Changjiang Estuary. At the mouth of the Changjiang there are three tiers of bifurcation forming a branching estuary that have four openings to ECS (Fig. 3h). The change in the partition of the sediment load among the branching channels caused the shifting of depocenters at the openings of different channels (Fig. 4)¹⁶.

In 1958–1978 over 55% of the Changjiang sediment load went through the S. Passage (Supplementary Fig. S4, online). Correspondingly, the depocenter was located at the opening of the S. Channel. In 1978–1989 the majority (60%) of the Changjiang sediment discharge passed through the N. Passage. Consequently, the depocenter moved to the region around the opening the N. Passage. In 1989–1997, most sediment was discharged through the N. Channel. In the S. Channel more sediment passed through the N. Passage than that of the S. Passage (Supplementary Figs. S3a, 3b, online). Therefore, the depocenter was located between the openings of the N. Channel and Passage (Fig. 3c). In 1997–2002, more than 50% of the sediment went into the S. Passage rather than the N. Channel. Subsequently, the depocenter of the CSD was relocated in the vicinity of the opening of the S. Passage. These patterns confirm that whenever there is unequal partition of sediment load between the N.-S. Branches and between the N.-S. Channels, the location of the depocenter on the CSD would change correspondingly (Fig. 3h). Therefore, comparing the distal influence of the river sediment discharge of the Changjiang, the proximal factor of sediment load partition among the branches has more direct influence on the erosion/deposition patterns and the location of the depocenter on the CSD. When it compared with the Mississippi delta, after each channel switching, the old channel was abandoned and a new delta, a new dynamic equilibrium, is formed at the location of the new channel^{18,32}. However, the whole Changjiang deltaic system remains at the same location; only the active center of deposition shifts locations in response to the changing major sediment supply from the branching channels. Obviously, the close and long-term link between the sediment load partition among branching channels and the depocenter location on the CSD is unique among major river systems in the world^{13,31}.

The influences of extreme storm surge and floods on the CSD. As Hurricane Katrina devastated the subaerial and submerged portions of the Mississippi Deltas in 2004³², major typhoons in the past 50 years also caused significant erosional/depositional changes on the CSD (Fig. 4b, Supplementary Tab. S7, online). The CSD is composed

mostly of fine-grained (greater than 4 ϕ) sediment¹⁶. In the southern part of the CSD the substrate consists of fine-grained (7 ~ 8 ϕ) sediment (Supplementary Fig. S4, online), which could be easily entrained under weak currents. The flows seaward of the mouth of the Changjiang are strong. Even in the water depth of 40 m, the observed current speed is 0.85 m/s¹⁵. According to the classic Hjulstrom's diagram, this kind of sediment can be theoretically entrained by flows as weak as 0.2 m/s³³. Moreover, the river plume in summer can deliver the sediment to the inner shelf on the East China Sea (ECS), and then the deposited sediments of the CSD in summer can be later resuspended and transported onward by wind-driven currents along with episodic gravity-driven downslope transport during high-energy winter wind events¹⁸. Obviously, a major typhoon could generate turbidity currents on the delta front, causing significant changes on the bathymetry of the CSD³⁴, and redistribution of seabed sediment³⁰. Taking No. 9711 Typhoon for example, it passed through the mouth of the Changjiang in Aug. 1997. During the typhoon, the maximum tidal elevation reached 5.99 m above sea level (Fig. 2b, Supplementary Tab. S7, online), the NE side of the CSD underwent severe erosion (Fig. 3c), and most of the eroded sediment by typhoon waves was transported landward, probably by the storm surge, leading to general deposition in areas shallower than the -10 m isobath (Fig. 3c). Our study confirms that major erosion/deposition changes that occurred deeper than the -10 m isobath were also related to typhoons (Fig. 4d, Supplementary Tab. S7, online).

Furthermore, floods of historical proportion delivered large amounts of sediment to the ECS, even to depths beyond the -50, -60 m isobaths¹⁶. The runoff of the flood in 1998 exceeded 1200×10^9 m³. The strong flows associated with this typhoon actually removed the accumulated sediments deposited around the channel openings left by the No. 9711 Typhoon in the previous year and re-deposited them on the shelf. Additionally, erosion occurred in the channels themselves. Because of the erosion caused by this typhoon, the CSD experienced erosion in the period of 1997–2002 (Figs. 3d, 4e).

It is also worth mentioning that the channel maintenance project deepened the shipping channel in the N. Passage from the -6.5 m to the -12.5 m isobaths over a period of 12 years and removed river-bed sediment about 6 m thick³⁵. This caused the apparent 'erosion' of the N. Passage (Figs. 3e–3g). Yet, the loss of sediment did not noticeably affect the erosion/deposition pattern of the CSD.

Conclusions

As a major river in the world, the sedimentation and eco-geomorphology of the Changjiang delta has received international attention, especially under the condition of declining river sediment load. Our findings show that the CSD went through the following phases on multi-decadal time scales: high accumulation (1958–1978); slight accumulation (1978–1997), slight erosion (1997–2002); and high accumulation (2002–2009), despite the 70% reduction of the sediment load due to the operation of the TGD since 2003. The location of the depocenter on the CSD varied according to the partition in the sediment load in the 3-tiered branching system of the adjacent estuary on the same time scale. Extreme events of large floods and typhoons caused large short-term fluctuations in the erosion/deposition of the CSD that affected long-term changes. Many major rivers in the world are facing deltaic erosion due to similar trends of declining river sediment load⁵; and yet the CSD has not shown corresponding erosion, even though there was significant threat from the influence of the TGD. At the seaward end of a branching estuary, the CSD provides a typology for a deltaic system that responds to distal and proximal sediment sources on different spatial and temporal scales that is unique in the world. Thereafter, it is suggested that re-evaluation of the impacts of TGD on the world's CSD is urgently needed.



Methods

Navigational charts of different years provide suitable data for studying the depositional and erosional rates in delta and estuarine regions^{19,24,25,35,36}. In recent decades, there have been voluminous observational data of the water depth of the Changjiang Estuary, most of which have been for special purposes, such as for localized navigational channel and shoreline utilizations. Therefore, in this study, we collected published largescale charts of the entire Changjiang Estuary from the Navigation Guarantee Department of the Chinese Navy headquarters (NGDCNH) surveyed in 1958, 1978, 1989, and 2004 as the source of data to quantify the regional volume changes to reflect the changes in the sediment supply (Supplementary Fig. S1, Tab. S1, online). Additionally, the bathymetric charts for the Changjiang Estuary in 1997, 2002, 2007 and 2009 were obtained from the Hydrological Bureau of the Changjiang Estuary and Shanghai Institute of Geological Survey, China (Supplementary Tab. S1, Fig. S1, online).

The DESO-17 echo-sounder was used for the depth measurements for these charters including 2002, 2004, 2007 and 2009. The vertical error was 0.1 m, and a GPS by Trimble was used that gave the positioning error within 1 m. However, the positioning errors for the 1958 and 1978 charts were 50 m. The compilation periods for older charts were on the order of years. For example, the 1978 chart was surveyed in 1976 and 1978, and the 1989 chart was surveyed in 1987 and 1989 (Supplementary Tab. S1, online). Moreover, 1958, 1978, 1989, and 1997 data were surveyed by line echo-sounder. All surveys were carried out between early May and early June, prior to peak discharge, and completed before August.

The spatial resolution for all charts is 0.5–1 km, having the average density 5–20 survey points/km². Therefore, the sufficient data density made secular bathymetric changes greater than 0.1 m acceptable in this study. The elevation in all the charts was based on the theoretical low-tide datum at Wusong. The volume we computed directly based on bathymetric charts is the volume of the water body in the confines of the Changjiang submerged delta (CSD) (Fig. 1). It represents the capacity of the CSD as a receptacle of sediment³⁶. Our basic assumption is that the volume change is primarily caused by the depth change due to erosion and deposition on the seabed^{19,24,25,35}.

Based on the digitizing procedure by Blott et al.³⁶, the depth data from charts were digitized and analyzed by using ArcGis9.3 software. The data were georeferenced using twenty 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 ArcGIS 9.3. Subsequently, a standardized digital terrain model (DTM) for each digitized chart of the Changjiang Estuary was established. The digitized chart was further divided the CSD into the shallow (depths less than 10 m) areas around the N. Channel, N. Passage, and S. Passage; and deep (depths greater than 10 m) areas for detailed analysis (Fig. 1). Moreover, our coverage extends to 2009. Our data enables us to examine the drastic decline of sediment load since 2003 and reveal a more complete trend of the CSD in the past 50 years.

The Datong gauging station (30° 84' 60" N, 117° 83' 70" E) is located about 640 km from the Changjiang's mouth above the tidal river (tidal limit), which is the seaward-most gauging station (Figure 1A). It is a Grade A station in China. The monitoring of the river flow and suspended sediment concentration (SSC) strictly follows the national stands as stipulated in the 'Protocol for River Suspended Sediment Measurements-GB 50159-92'³⁷. It requires that the SSC be measured at the surface, the 0.2, 0.4, 0.6, 0.8 depths, respectively, and near the bottom. The water-sampling device should collect the water in the horizontal orientation. The sampling should be done 5–10 times per month. For each flood surge, the measurements should be at least 5 times. SSC is obtained by filtering and drying of the samples and expressed as kg/m³. The measured SSC is multiplied by the measured river flow to render the SSC flux (see GB 50159-92 for the formulas). Rating curves are generated to render the continuous daily values of the river flow and SSC flux (GB 50159-92). After compilation and quality check, the data from the previous year are posted on the Bulletin of China River Sediment (<http://www.cjh.com.cn>) in the beginning of the following year for the general public. We acquired the data of water and sediment discharge at Datong between 1955 and 2011. Records of the maximum tidal level at Wusong since 1955 were obtained from Hydrological Bureau of the Changjiang Estuary. In addition, the data of the sediment load into the S. Channel and S. Passage came from the Hydrological Bureau of the Changjiang Estuary, China. Seismic profile (Profile SS') data was available from Shanghai Institute of Geological Survey. The data from the analysis of sediment samples came from the State Key Laboratory for Estuarine Research based on the sieving method. The computation of the medium grain size was based on Folk et al. (1970)³⁸.

Since TGD became operational in 2003, the Changjiang sediment discharge has drastically declined (Fig. 2a). Compared to the pre-1970 values, the sediment load after 2003 dropped by about 70%. It is reasonable to assume that 2003 is a critical year. Therefore, in this study comparisons are made between pre- and post-2003 eras.

1. Amorosi, A. & Milli, S. Late quaternary depositional architecture of Po and Tevere river deltas (Italy) and worldwide comparison with coeval deltaic successions. *Sediment. Geol.* **144**, 357–375 (2001).
2. Syvitski, J. P. M. et al. *Dynamics of the coastal zone. In: Coastal Fluxes in the Anthropocene*. Kremer, H.H., Lendebloom, H.J., Marshall, J.I., Crossland, C.J., Le Tissier, M.D.A. Eds. (Springer Press, 2005).
3. Overeem, I. & Syvitski, J. P. M. Dynamics and Vulnerability of Delta Systems. LOICZ Reports & Studies No. 35. GKSS Research Center, Geesthacht, p. 54 (2009).

4. Ericson, J. P. et al. Effective sea-level rise and deltas: causes of change and human dimension implication. *Global and Planetary Change* **50** (1–2), 63–82 (2006).
5. Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J. & Green, P. Sinking deltas due to human activities. *Nature Geosci.* **2**, 681–689 (2009).
6. Frihy, O. E., Dewidar, K. M. & El Banna, M. M. Natural and human impact on the northeastern Nile delta coast of Egypt. *J. C. R.* **14**, 1109–1118 (1998).
7. McManus, J. Deltaic response to changes in river regimes. *Mar. Chem.* **79**, 155–170 (2002).
8. Cencini, C. Physical processes and human activities in the evolution of the Po delta, Italy. *J. C. R.* **14**, 774–793 (1998).
9. Woodward, J. C. *Patterns of erosion and suspended sediment yield in Mediterranean river basins. In: Sediment and Water Quality in River Catchments*. Foster, I.D.L., Gurnell, A.M., Webb, B.W. Eds., pp. 65–389 (John Wiley and Sons Ltd., New York, 1995).
10. Poulos, S. E. & Collins, M. B. *Fluvial fluxes to the Mediterranean Sea: a quantitative evaluation of riverine/water sediment fluxes. In: Sediment Flux to Basins: Controls and Consequences*. Frostick, L.E., Jones, S. Eds., **191**, 227–245 (Geological Society of London Special Publication, 2002).
11. Briggs, S. E., Cartwright, J. & Davies, R. J. Crustal structure of the deepwater west Niger delta passive margin from the interpretation of seismic reflection data. *Mar. Petrol. Geol.* **26**, 936–950 (2009).
12. Okyar, M., Ergin, M. & Evans, G. Seismic stratigraphy of late quaternary sediments of western Mersin Bay shelf, (NE Mediterranean Sea). *Mar. Geol.* **220**, 113–130 (2005).
13. Kuehl, S. A., Levy, B. M., Moore, W. S. & Allison, M. A. Subaqueous delta of the Ganges-Brahmaputra river system. *Mar. Geol.* **144**, 81–96 (1997).
14. Bulletin of China River Sediment (BCRS), 2010-2011: Press of Ministry of Water Resources of the People's Republic of China. <<http://www.cjh.com.cn/>>.
15. Chen, J. Y. *Research and practice of estuary and coast in China*. Higher Education Press, Beijing, China (2007).
16. Chen, J. Y., Zhu, H. F., Dong, Y. F. & Sun, Y. M. Development of the Changjiang estuary and its submerged delta. *Cont. Shelf Res.* **4** (1/2), 47–56 (1985).
17. Liu, J. P. et al. Flux and fate of Yangtze River sediment delivered to the East China Sea. *Geomorphology* **85** (3–4), 208–224 (2007).
18. Wright, L. D. & Friedrichs, C. T. Gravity-driven sediment transport on continental shelves: a status report. *Cont. Shelf Res.* **26**, 2092–2107 (2006).
19. Yang, S. L. Milliman, J. D., Li, P. & Xu, K. 50,000 dams later: erosion of the Yangtze River and its delta. *Global and Planetary Change* **75**, 14–20 (2011).
20. Chen, Z. et al. 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 (2010).
21. Fearnside, P. M. China's Three Gorges Dam: fatal project or step toward modernization? *World Dev.* **16**, 615–630.
22. Swenson, J. B., Paola, C., Pratson, L. & Voller, V. R. Fluvial and marine controls on combined subaerial and subaqueous delta progradation: morphodynamic modeling of compound clinoform development. *J. Geophys. Res.* **110**, F02013, doi:10.1029/2004JF000265 (2005).
23. Yun, C. X., Dai, Z. J. & Wang, D. C. *Crisis of the estuarine delta in China*. Chinese Ocean Press, Beijing, China (2010).
24. Lane, A. Bathymetric evolution of the Mersey Estuary, UK, 106-1997: causes and effects. *Estuar. Coast. Shelf S.* **59**, 249–263 (2004).
25. Van der Wal, D., Pye, K. & Neal, A. Long-term morphological change in the Ribble Estuary, northwest England. *Mar. Geol.* **189**, 249–266 (2002).
26. Gao, S. Modeling the growth limit of the Changjiang Delta. *Geomorphology* **85**, 225–236 (2007).
27. Yang, S. L., Zhang, J. & Xu, X. J. Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, Yangtze River. *Geophys. Res. Lett.* **34**, L10401, doi:10.1029/2007GL029472 (2007).
28. Dai, Z. J. et al. Runoff characteristics of the Changjiang River during 2006: effect of extreme drought and the impounding of the Three Gorges Dam. *Geophys. Res. Lett.* **35**, L07406, doi:10.1029/2008GL033456 (2008).
29. Oguri, K. et al. Sediment accumulation rates and budgets of depositing particles of the East China Sea. *Deep-Sea Res.* **50**, 513–528 (2003).
30. Lowe, D. R. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. *J. Sediment. Petrol.* **52**, 279–297 (1982).
31. Nittroer, C. A. & DeMaster, D. J. The Amazon shelf setting: tropical, energetic, and influenced by a large river. *Cont. Shelf Res.* **16**, 553–573 (1996).
32. Törnqvist, T. E., Bick, S. J., van der Brog, K. & DE Jong, A. F. M. How stable is the Mississippi delta? *Geology* **34** (8), 697–700 (2006).
33. Sundborg, Å. The river Klarälven. A study of fluvial processes. *Geogr. Ann.* p.38 (1956).
34. Hu, K. L., Ding, P. X., Wang, Z. B. & Yang, S. L. A 2D/3D hydrodynamic and sediment transport model for the Yangtze estuary, China. *J. Marine Syst.* **77**, 114–136 (2009).
35. Dai, Z. J. & Liu, J. T. A thirteen-year record of bathymetric changes in the North Passage, Changjiang (Yangtze) estuary. *Geomorphology* **187**, 101–107 (2013).
36. Blott, S. J., Pye, K., van der Wal, D. & Neal, A. Long-term morphological change and its causes in the Mersey Estuary, NW England. *Geomorphology* **81**(1–2), 185–206 (2006).



37. The Ministry of Water Resources of the People's Republic of China. *Protocol for River Suspended Sediment Measurements-GB 50159-92*. Chinese plan press, Beijing, China (2007).
38. Folk, R. L., Andrews, P. B. & Lewis, D. W. Detrital sedimentary rock classification and nomenclature for use in New Zealand. *Geol Geophys* **13** (4), 937–968 (1970).

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Author contributions

Z.J.D. and J.T.L. conceived the study and wrote the main manuscript. W.W. contributed to the partly calculation of the results. J.Y.C. contributed to the discussion. Z.J.D. and W.W. prepared figures 1–4. All authors reviewed the manuscript.

Additional information

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