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# Recent changing patterns of the Changjiang (Yangtze River) Estuary caused by human activities

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**Abstract**

To evaluate the controlling factors for coastline change of the Changjiang (Yangtze River) Estuary since 1974, we extracted the mean high tide line from multi-temporal remote sensing images that span from 1974 to 2014 at 2-year intervals. We chose 42 scenes to constrain the changing pattern of the Changjiang Estuary coastline, and implemented GIS technology to analyze the area change of the Changjiang (Yangtze) Subaerial Delta. Runoff, sediment discharge and coastal engineering were withal considered in the analysis of the coastline changes. The coastline has transgressed seaward since 1974, and a part of it presents inter-annual variations. The area of the Changjiang Subaerial Delta increased by 871 km$^2$, with a net accretion rate of 21.8 km$^2$/a. Based on the change of sediment discharge due to the major projects in the Changjiang River Basin, we divided the changing pattern of the coastline into three stages: the slow accretion stage (1974–1986), the moderate accretion stage (1987–2002), and the rapid accretion stage (2003–2014). Liner regression analysis illustrated that there is a significantly positive correlation between the area changes and sediment discharge in the Chongming Eastern Shoal and Jiuduansha. This suggested that sediment load has a fundamental effect on the evolution of the Changjiang Estuary. Construction of Deep Waterway in the North Passage of the Changjiang River (1998–2010) led to a rapid accretion in the Hengsha Eastern Shoal and Jiuduansha by influencing the hydrodynamics in North Passage. Coastal engineering such as reclamation and harbor construction can also change the morphology of the Changjiang Estuary. We defined a contribution rate of area change to assess the impact of reclamation on the evolution of Changjiang Estuary. It turned out that more than 45.3% of area increment of the Changjiang Estuary was attributed to reclamation.

**Key words:** remote sensing, coastline change, sediment load, coastal engineering, Changjiang (Yangtze River) Estuary

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## 1 Introduction

River deltas formed in the land-ocean interaction zone are the production of the rapid deposition of fluvial sediment at a river mouth, which is most sensitive to fluvial and oceanic changes under both steady and decreasing sea level conditions (Wright, 1977). Delta systems as natural "recorders" record abundant information about environmental changes in the catchment such as climate change and human activities (Bianchi and Allison, 2009). River deltas are also the most economically developed and densely populated areas in the world because of their fertile land, waterfowl production and convenient transportation (Chen et al., 2001). Fluvial sediment discharge to coastal ocean areas plays an important role in the changing pattern of accretion and erosion of a delta (Yang et al., 2003). Over the past century, human activities in the catchment have changed river conditions (runoff, sediment discharge) dramatically (Nilsson et al., 2005; Syvitski et al., 2005), and thus influenced the river delta strongly. Intensive dam construction, irrigation and soil conservation practices in recent years have caused a sharp decline in river sediment load (Stanley et al., 1993; Syvitski et al., 2009), which in turn led to the retreat of numerous river deltas all over the world to different degrees, including the Nile, Mississippi, Colorado, Indus, Ebro, Mekong Rivers, and Changjiang and Yellow Rivers Deltas (Stanley, 1988; Frihy and Dewidar, 2003; Kesel, 2003; Blum and Roberts, 2009; Syvitski et al., 2009; Giosan et al., 2006; Guillén and Palanques, 1997; Sanchez-Arcilla et al., 1998; Le et al., 2007; Yang et al., 2011; Chu et al., 2006). Coastal engineering such as reclamation, harbor construction, jetties, groins, and seawalls have also had a noticeable impact on the evolution of deltas (Fanos, 1995; Jiang et al., 2012; Dai et al., 2013; Wei et al., 2014b).

A coastline is the line of contact between land and a body of water (Pajak and Leatherman, 2002) and the position of a coastline always changes owing to tectonic movements, climate change, tides, and storm surges (Guariglia et al., 2006; Zhao et al., 2008). Recently, increasing attention has been paid on coastline change by governments and scientists for its important role in coastal management, social economics and scientific research.

Given its high spatial and temporal resolution, remote sensing images have been widely applied to monitor coastline change over the past decades (White and Asmar, 1999; Chu et al., 2006; Cui and Li, 2011). On the foundation of remote sensing images,

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scientists are able to extract more reliable and consistent information with GIS technology (Bausmith and Leinhardt, 1998; Durduran, 2010).

The Changjiang River is well-known for its volume water discharge and high sediment load, which is the fifth and forth largest in the world, respectively (Milliman et al., 1985; Milliman and Syvitski, 1992; Eisma, 1998). According to the records at the Datong Hydrological Station, about 620 km upstream, sediment load from the Changjiang River to the East China Sea (ECS) has shown a decreasing trend since the mid-1980s primarily because of human activities, e.g., dam construction and water and soil conservation practices (WSCP) (Yang et al., 2006; Dai et al., 2008). Sediment discharge recorded by Datong Station declined sharply from $4.86\times10^8$ t/a before 1985 (Milliman et al., 1985) to $2.602\times10^8$ t/a during the period of 1987–2002. It further declined to $1.252\times10^8$ t/a during the period of 2003–2013. The dramatic decrease in runoff and sediment significantly affected the changing pattern of the Changjiang (Yangtze River) Estuary (CE) (Yang et al., 2011; Wei et al., 2014a; Li et al., 2014). Hence, it is necessary to research on the relationship between sediment discharge into the CE and accretion/erosion variation of the Changjiang Subaerial Delta.

Previous studies mainly focused on subaqueous deltas, including the changing pattern of subaqueous delta in response to sediment load change and the records of environment change in drainage basin (Gao and Wang, 2008; Syvitski et al., 2007; Yang et al., 2001, 2011; Wang et al., 2006; Liu and Fan, 2011), whereas the knowledge is limited about the subaerial delta evolution in the past decades, particularly after the construction of the Three Gorges Dam (TGD) in 2003, which sharply decreased the sediment load of Changjiang River. In addition to some research conducted on ecological aspects, e.g., wetland evolution in the gradually sediment load reduction, the evolution of wetland vegetation, the distribution of heavy metals, and the evaluation of ecosystem health (Yang et al., 2001, 2006; Wei et al., 2014; Wang et al., 2014; Zhang et al., 2009), Chu et al. (2013) analyzed the spatio-temporal features of the coastline evolution of Changjiang Subaerial Delta during 1974–2010 based on remote sensing images, and explored the effects of human activities.

The objectives of this study are (1) to quantify coastline change as well as the changing pattern of Changjiang Subaerial Delta during the period of 1974–2014 based on a systematic analysis of remote sensing images; (2) to analyze the contemporaneous relationships between the changing pattern of Changjiang Subaerial Delta and sediment load of the Changjiang River; and (3) to explore how human activities such as dam construction, WSCP and coast engineering influenced evolution of the CE.

## 2 Study area

Originating from the Qinghai-Tibet Plateau at the elevation of 5 100 m, the Changjiang River has a drainage area of $1.8\times10^6$ km$^2$ and a total length of 6 300 km. It flows east through the Sichuan Basin, the Jianghan Plain, and the Middle-Lower Reach Plain before discharging into the ECS (Fig. 1A). The CE is bifurcated by alluvial islands into four passages in the frontal zone (Fig. 1B). Since the 1980s, the sediment discharged by the CE into the ECS has been reduced significantly. In particular, since the construction of the TGD in 2003, the sediment transport is only $1.252\times10^8$ t/a (2003–2013), with a minimum of $0.718\times10^8$ t/a in 2011 (http://www.cjw.com.cn/). Water discharge and sediment load of the Changjiang River vary with seasons: flood season occurs from May to October and dry season from November to April. Tidal flats that benefit from this huge amount of sediment supply are distributed widely in front of the modern delta, such as Qidong, Chongming Eastern Shoal (CES), Nanhui Shoal (NHS), and Jiuduansha (JDS) (Yang et al., 2001). In recent years, a quantity of the tidal flats have been reclaimed in order to construct harbors, cities and developed industrial area.

The tidal regime near the river mouth is dominated by a typical semidiurnal tide, with an average tidal range of 2.8 m and a maximum tidal range of 6.0 m (Yang et al., 2001). The average and maximum wave heights are 1.0 m and 6.2 m, respectively (Yang et al., 2001). Wave height plays an important role in controlling sedimentation in the CE. The regional circulation pattern is dominated by the North Jiangsu Coastal Current, the East China Sea Coastal Current, and Changjiang River Plume (Beardsley et al., 1985; Gao and Wang, 2008). According to the tidal gauge records from Shanghai local sea level rose at an average rate of around 1.0 mm/a over the period of 1920–1987 (Chen, 1991). The Changjiang Delta subsided at a rate ranging from 0.1 to 3.0 mm/a as a result of sediment compaction and extraction of underground water (Chen, 1991).

## 3 Materials and methods

### 3.1 *Data source*

Multi-temporal remote sensing images from a Landsat Multitemporal Scanner (MSS), Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper (ETM+), and Landsat 8 satellite from 1974–2014, are utilized in this study (42 scenes in total, Table 1), all of which are downloaded from the USGC Website (http://glovis.usgs.gov/) for free. The effect of cloud cover has been considered in all the imagines. The spatial resolutions of MSS, TM, ETM+, and Landsat 8 data are 80, 30, 30 and 30 m, respectively. One scene alone cannot fully cover the study area, since the study area is large. We chose two scenes (Path 127, Row 38 and Path 127, Row 39; Path 118, Row 38 and Path 118, Row 39) of every period of the study area, and obtained the full coverage of the study area with Mosaic tool and Subset tool in ENVI4.8. Daily sediment discharge and runoff data during the period of 1974–2013 were provided by the Datong Hydrological Station. Monthly records of TGD sedimentation data during 2003–2013 were collected from the Changjiang Water Resources Commission (CWRC) (http://www.cjw.gov.cn/) to quantify the sediment decrease on account of the construction of TGD. Image geometric correction was applied using ERDAS IMAGINE 9.2 software to ensure the accuracy of the images. The most recent topographic map (1:50 000) of the study area was used as a reference map to rectify the remote sensing images. The resulting root mean square errors of all images are less than 0.5 pixels.

### 3.2 *Extraction of coastline*

Coastline extraction methods include visual interpretation, computational methods and interactive interpretation techniques that combine the artificial and computational productions. In this study, coastlines were extracted with the standard of Chu et al. (2006). Mean high tide line was extracted as the coastline by the same person at the same scale from combined pseudo-color imagery with Bands 4, 3, 2 as Red, Green and Blue (RGB), respectively. Chu et al. (2006) supposed mean high tide line a more appropriate coastline compared with the water/land line, which is rarely affected by sea ice and tide. The variations of water content, landform, and vegetation near the mean high tide line contribute to the differences in the spectral characteristics in

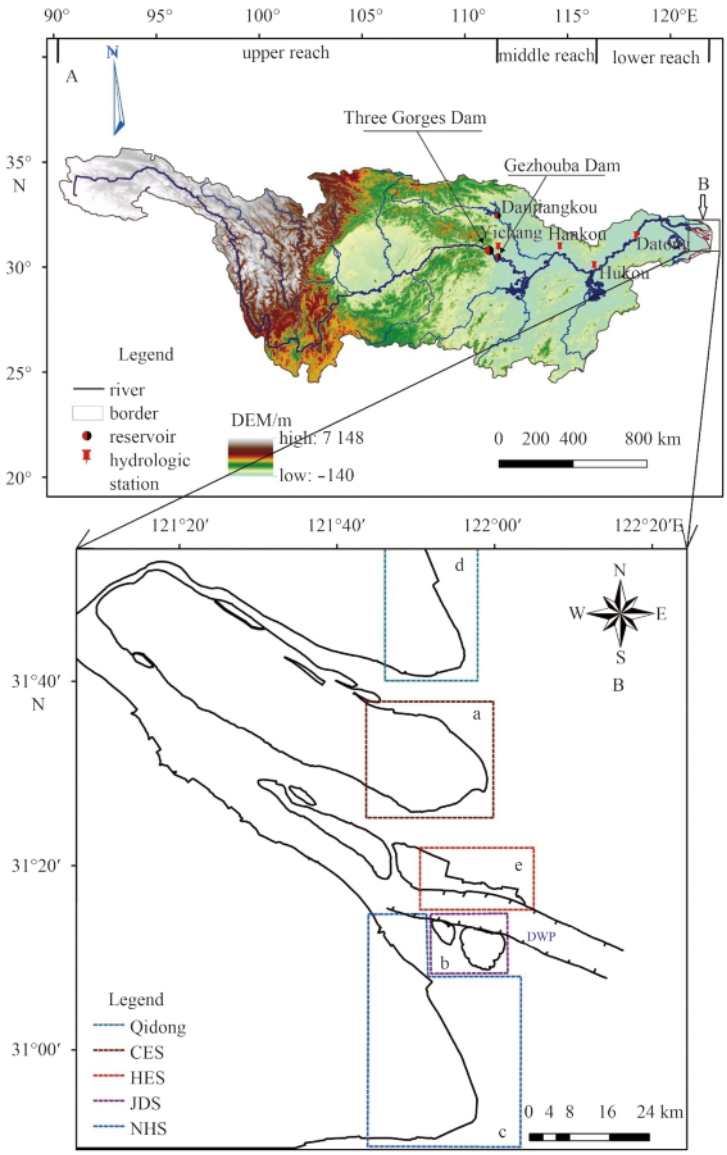



**Fig. 1.** Location of the study area. CES represents Chongming Eastern Shoal, HES Hengsha Eastern Shoal, JDS Jiuduan Shoal, NHS Nanhui Eastern Shoal, and DWP Deep Waterway Project.

**Table 1.** List of remote sensing images used in the present work

| Acquisition time (year-month-day) | Image type | Resolution/m | Bands | Acquisition time (year-month-day) | Image type | Resolution/m | Bands |
|---|---|---|---|---|---|---|---|
| 1974-02-13 | MSS | 80 | 4 | 1996-04-24 | TM | 30 | 7 |
| 1976-04-24 | MSS | 80 | 4 | 1998-08-04 | TM | 30 | 7 |
| 1978-07-04 | MSS | 80 | 4 | 2000-05-21 | TM | 30 | 7 |
| 1980-09-30 | MSS | 80 | 4 | 2002-07-30 | TM | 30 | 7 |
| 1981-12-24 | MSS | 80 | 4 | 2004-07-19 | TM | 30 | 7 |
| 1984-04-23 | MSS | 80 | 4 | 2006-04-20 | ETM+ | 30 | 8 |
| 1986-05-07 | MSS | 80 | 4 | 2008-08-06 | ETM+ | 30 | 8 |
| 1988-05-09 | TM | 30 | 7 | 2010-04-23 | ETM+ | 30 | 8 |
| 1990-12-04 | TM | 30 | 7 | 2012-12-24 | ETM+ | 30 | 8 |
| 1992-09-04 | TM | 30 | 7 | 2014-12-06 | Landsat8 | 30 | 11 |
| 1994-03-18 | TM | 30 | 7 | | | | |

the remote sensing images. Therefore, we combined spectral changes and experiences to interpret the images. Coastline extraction and erosion-accretion area determination were achieved using the GIS software ArcGIS10.2.

## 4 Results and discussion

### 4.1 *Temporal variation of water discharge, and sediment load*

Located approximately 620 km upstream from the river

mouth, Datong hydrological station is the hydrological gauging station which is the closest to the Changjiang Estuary that monitors the runoff and sediment transported into the ECS (Fig. 1A). A previous study showed that the annual water discharge into the ECS is slightly larger than the annual discharge at Datong Hydrological Station, and that during the dry period, the discharge into the ECS was smaller than that measured at Datong Hydrological Station (Wang et al., 2006). For convenience, we used the runoff and sediment load measured at Datong hydrological station to represent the delivery characteristics into the CE.

Figure 2 illustrates the temporal variation of annual water discharge and sediment load at Datong hydrological station from 1974 to 2013. During this period, the average annual sediment load was $2.357\times10^8$ t/a, and the average annual water discharge was $9.302\times10^8$ m$^3$/a. There is a significant difference in the change pattern of water discharge and sediment load, especially in the period of 1987–2002. In the past 40 years (1974–2013), the overall trend of water discharge remained stable while the sediment load decreased sharply (Fig. 2). Zhao et al. (2015) evaluated the decreasing trend of water discharge and sediment load from 1953 to 2010, they found that the trend of water discharge was decreasing mildly at the rate of $-1.41\times10^8$ m$^3$/a, and that sediment load had a significant trend at the rate of $-46.5\times10^6$ t/a. The change of sediment load can be divided into three stages: 1974–1986, 1987–2002, and 2003–2013, as a consequence of the implementation WSCP in high sediment yield regions of the upper Changjiang River basin in the 1980s, and the impoundment of the TGD in June 2003. The sediment loads of the three stages are ca. $3.615\times10^8$ m$^3$/a (1974–1986), ca. $2.606\times10^8$ m$^3$/a (1987–2002), and ca. $1.252\times10^8$ m$^3$/a (2003–2013). We also calculated the water discharge corresponding to the same period of the change of sediment load: ca. $9.494\times10^8$ m$^3$/a (1974–1986), ca. $9.378\times10^8$ m$^3$/a (1987–2002), and ca. $9.182\times10^8$ m$^3$/a (2003–2013).

In 1974–1986, water discharge and sediment load both present an overall decreasing trend as shown in Fig. 2. We performed linear regression analysis in order to find out the relationships between water discharge and sediment load. The result indicated a strong correlation between water discharge and sediment load with $R^2$ being 0.7 (not shown here). This is consistent with the previous study which stated that annual sediment load increased with annual precipitation and water discharge (Trenhaile, 1997). Thus, water discharge and sediment load have a strong correlation during 1974–1986 when the human activities were less intense in the catchment.

In the period of 1987–2002, the change pattern of annual water discharge is different from sediment load. Water discharge exhibits a slight decrease, and the mean value is also slightly lower than that in 1974–1986. In contrast, sediment load displayed a sharp decrease, and the mean value is only 72% of that in 1974–1986. This decline might be attributed to the dam construction, sand extraction and WSCP (Yang et al., 2006). During 1987–2002, the primary sediment supply to the upper Changjiang River (Jingshajiang, Wujiang, Minjiang and Jialingjiang Rivers) declined substantially due to the dam construction in the drainage basin. For example, the construction of Shenzhong Dam Reservoir and Baozhushi Reservoir in Jianglingjiang River accounted for decrease of 68 mt/a (Mao and Pei, 2002). To expedite soil and water conservation in the upper reaches of the Changjiang River, WSCPs have been carried out in the upper Changjiang drainage basin since 1989, and expanded gradually to the middle reaches. The sand extraction from the mid-lower Changjiang River also had a significant effect on the sediment load. Chen et al. (2005) suggested that sand extraction from the mid-lower Changjiang River increased rapidly from 26 mt/a in the 1980s to 40–80 mt/a by the end of the 1990s.

In the period of 2003–2013, both annual water discharge and sediment load reveal a decreased trend. Water discharge decreased slightly owing to dam constructions, water consumption, and climate change (Zhao et al., 2015; Yang et al., 2006; Wei et al., 2014a). As a contrast, the sediment load reduced drastically in this period and had a mean value of $1.252\times10^8$ m$^3$/a. We ascribed this change pattern to the impoundment of TGD in June 2003, which led to a large amount of sediment being trapped in the reservoir. According to the statistical results, the average sediment load after the TGD accounted for only 34.6% and 48% of the averages during 1974–1986 and 1987–2002, respectively. A record as low as $0.718\times10^8$ t was reached in 2011, it suggests that the sediment load of Changjiang River decreased sharply due to human activities.

To understand the effect of the impoundment of the TGD on sediment discharge, we acquired the annual sedimentation of the TGD during 2003–2013 from the CWRC. Figure 3 exhibits the temporal variation of annual sedimentation of TGD, with a min-

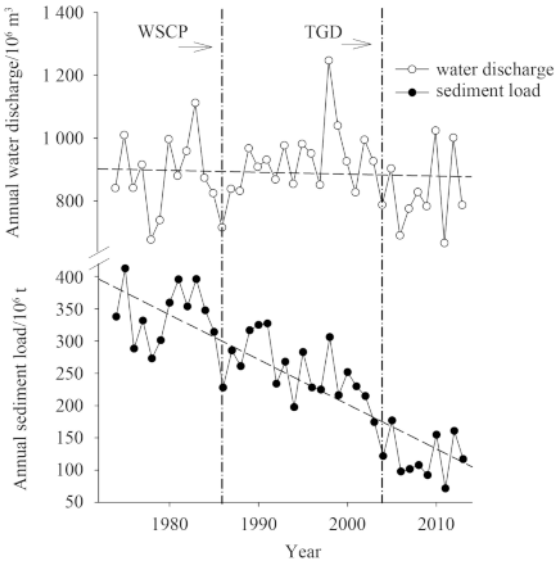



**Fig. 2.** Temporal variations in annual runoff and sediment load.

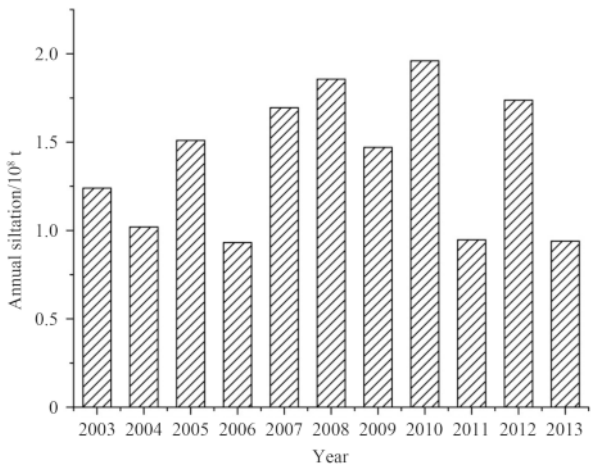



**Fig. 3.** Annual sedimentation in the TGR (data collected from CWRC, http://www.cjw.com.cn/).

imum of $0.93\times10^8$ t/a and maximum of $1.96\times10^8$ t/a. We calculated that the annual average sedimentation amount as $1.39\times10^8$ t during 2003–2013. This is 1.11 times of the sediment delivered into ECS recorded by Datong hydrological station in the same period. Thus, a large amount of sediment was intercepted by TGD, which led to the observed sharp decrease in sediment delivery to the ECS.

### 4.2 *Variation of CE and the relationship with sediment load*

Figure 4 displays the coastlines that are delineated with the remote sensing images, suggesting that the CE changed considerably during the period of 1974–2014. The coastline of the CE has extended seaward since 1974, and parts of the coast present inter-annual erosion and accretion alternation. The most prominent changes appear in CES, HES, JDS, and NHS. Figure 5a reveals the area change of the Changjiang Subaerial Delta at 4-year intervals from 1974 to 2014. The area of the Changjiang Subaerial Delta increased by about 871 km$^2$ in the study period at a rate of 21.8 km$^2$/a in average. We calculated the area increment for each of the three stages respectively: 251 km$^2$ (1974–1986), 341 km$^2$ (1987–2002), and 279 km$^2$ (2003–2014). The area change rates were calculated as 20.9 km$^2$/a (1974–1986), 21.3 km$^2$/a (1987–2002), and 23.3 km$^2$/a (2003–2014). In this case, we defined the three stages for the changing pattern of the Changjiang Subaerial Delta as: the slow accretion stage (1974–1986), the moderate accretion stage (1987–2002), and the rapid accretion stage (2003–2014).

There is a typical landform in the CE, i.e., it is bifurcated by four fluvial islands, and forms a three-tiered branching estuary and four openings to the ECS (Fig. 1B). We can divide the entire study area into five parts according to this landform pattern: CES, JDS, NHS, Qidongzui and HES (Figs 1Ba, b, c, d and e). Each part has a different changing pattern because of the different sediment transportation channels and changing hydrodynamics. The most drastic accretion occurred in CES, JDS, and NHS, with increased areas of 350 km$^2$, 71 km$^2$, and 192 km$^2$, respectively. Figure 4 and Table 2 also show that the area changes of each part of the study area during different periods are inconsistent.

#### 4.2.1 *Changes of CES and the relationship with sediment load*

As shown in Fig. 4b, CES has a remarked trend of coastline change. The coastline has extended seaward in the north and northeast but retreated landward in the southeast during the study period, this result is consistent with Li et al. (2014). The area change pattern was modified after 2002, which is characterized by slow accretion or erosion, and this change is consistent with the results in Fig. 5b, which show that the area change in CES has three different stages. From 1974 to 1990, the area of CES increased by 210 km$^2$, with an average rate of 13.1 km$^2$/a. In the period of 1990 to 2002, the area increased by 82 km$^2$, with an average rate of 6.8 km$^2$/a. During 2002–2014, the area increased by 48 km$^2$, with an average rate of 4 km$^2$/a. Thus, the changing pattern of area increment in CES shows a significant decreasing trend which corresponds well to the reduction of sediment load.

In order to understand the response of CES to the change of sediment discharge from the Changjiang River, we performed a linear regression analysis, analyzing the possible linkage between decreased sediment load and variations in CES area change. The data of sediment load and the values of area change were averaged for every four years for the study period. Our results indicated a statistically significant positive relationship between CES area change and sediment discharge at Datong Station from 1974 to 2013 (Fig. 6a). The relationship can be described by Eq. (1):

$$y = 0.002x - 6.131 \quad \left(R^2 = 0.579, P = 0.01\right), \tag{1}$$

where $x$ is the total value of sediment discharge of every four

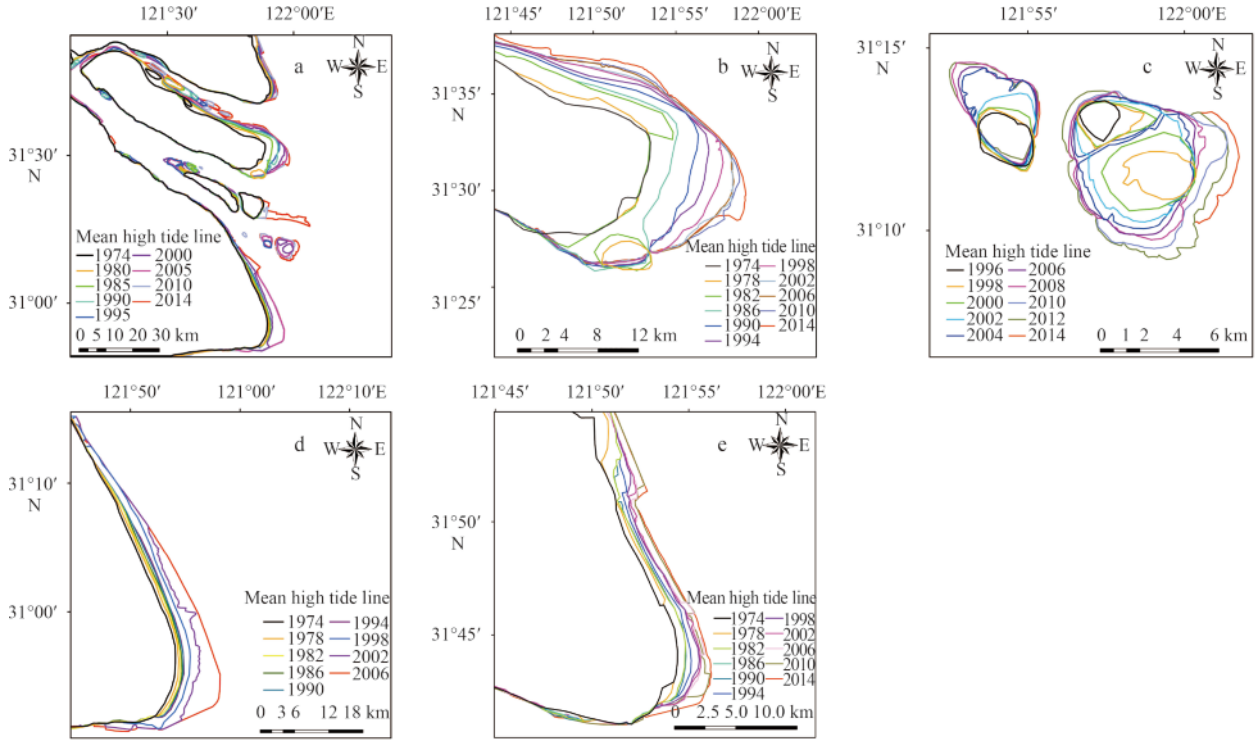



**Fig. 4.** The coastline change of study area. The line with different colors indicate the coastline of different years. a. Changjiang Subaerial Delta, b. Chongming Eastern Shoal, c. Jiuduansha, d. Nanhui Shoal, and e. Qingdong.

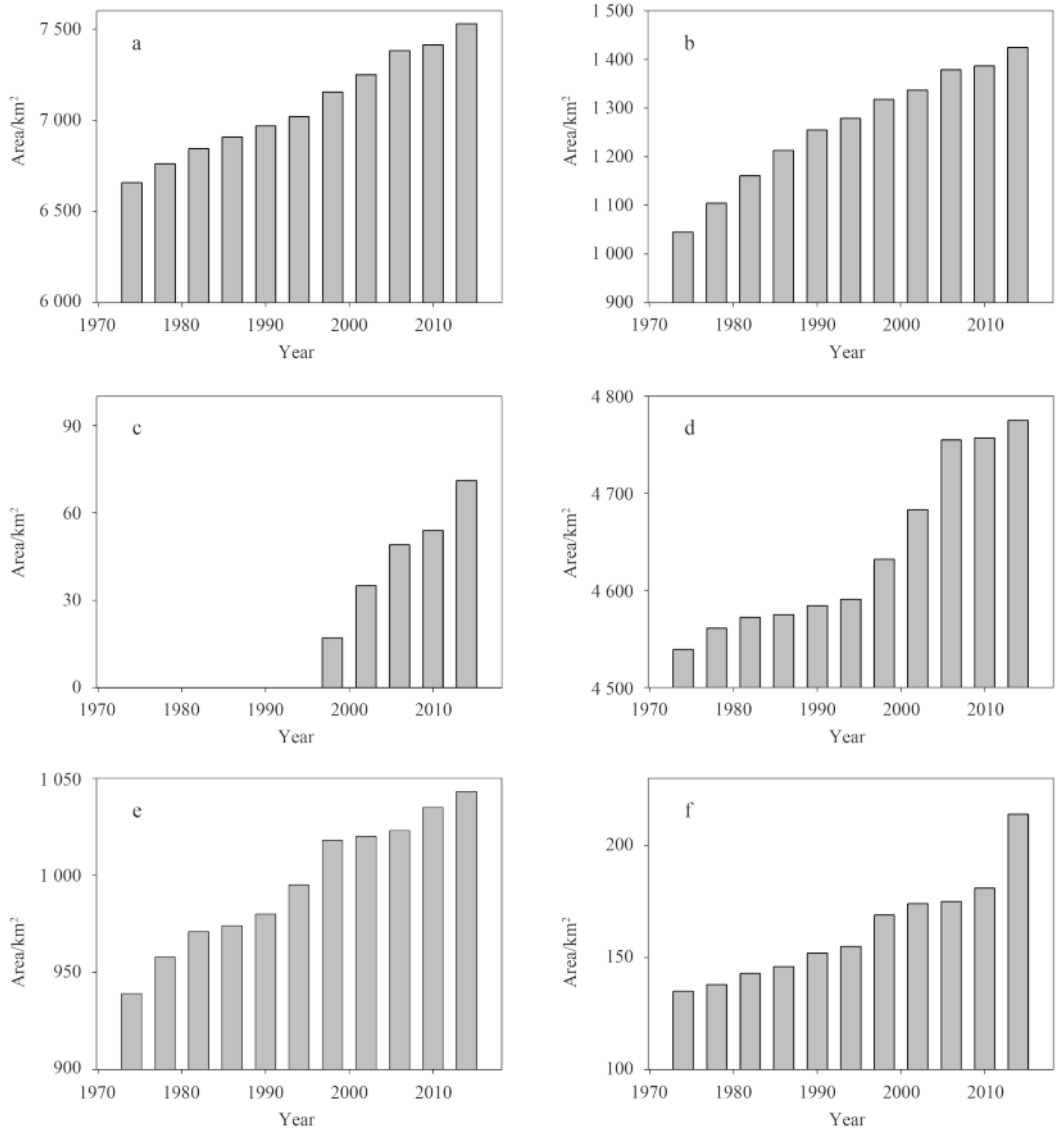



**Fig. 5.** The area change of study areas. a. Changjiang Subaerial Delta, b. Chongming Eastern Shoal, c. Jiuduansha, d. Nanhui Shoal, e. Qingdong, and f. Hengsha Eastern Shoal.

**Table 2.** Area change of each part of study with three stages

| | 1974–1986 | | 1987–2002 | | 2003–2014 | |
|---|---|---|---|---|---|---|
| | Area change/km² | Rate of change/km²·a⁻¹ | Area change/km² | Rate of change/km²·a⁻¹ | Area change/km² | Rate of change/km²·a⁻¹ |
| Qidong | 38.5 | 2.75 | 39.6 | 3.3 | 22.1 | 1.84 |
| CES | 207 | 14.8 | 82 | 6.8 | 61.4 | 5.12 |
| HES | 15.9 | 1.1 | 22.3 | 1.9 | 40.7 | 3.39 |
| JDS | 0 | 0 | 35.3 | 5.9 | 35.7 | 2.98 |
| NHS | 42.4 | 3.0 | 98.4 | 8.2 | 51.1 | 4.26 |

years ($10^6$ t), and $y$ is the total value of area change of every four years (km²). Figure 6a and Eq. (1) indicates that land area increments correspond positively to the change of sediment load, which means the accretion of CES will slow down and even appear eroded with a decreasing sediment load.

Combining with the linear regression analysis and sediment load information, we can understand the change pattern of CES and the controlling factors of the change. The coastline of CES advanced to the ECS because of the sediment that gradually accumulated in the front of CES. With the gradual reduction of sediment load, the advancing speed of coastline declines correspondingly. In Eq. (1), when $y$ is 0, $x$ is $3.065\times10^8$ t/(4 a). This indicates that the critical value is $0.77\times10^8$ t/a for the sediment load to maintain the annual balance of CES over the time period of 1974–2014. Thus, when the sediment load is lower than $0.77\times10^8$ t/a, the equilibrium of the CES accretion will be broken and the CES will be eroded as a result of the gradual reduction of sediment load.

The results of the linear regression analysis support that a good correlation between the area increment in CES and the sed-

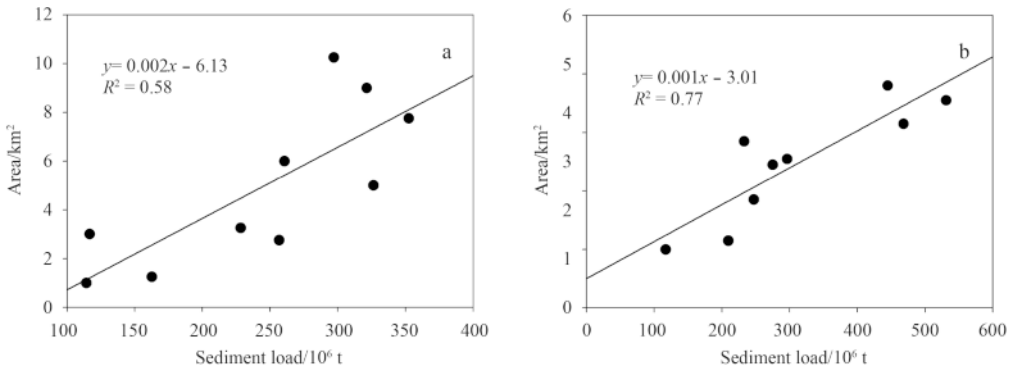



**Fig. 6.** The relationships between sediment load and the area change of CES and JDS. a. CES and b. JDS.

iment load, suggesting that sediment load has a significant effect on the evolution of CE. These findings further confirm the results in previous studies; a decrease in upstream sediment load will slow the accretion of a delta in estuary and even lead to the erosion of the delta (Yang et al., 2001, 2006; Gao, 2007).

4.2.2 *Changes of JDS and the relationship with sediment load*

The JDS has developed since 1954 and grown above the high water level in 1996, which is the largest region preserved under natural conditions in the CE. The area of JDS increased from 8.3 km² in 1996 to 71 km² in 2014 (Fig. 5c), with an average rate of ca. 4 km²/a. As shown in Fig. 4c, JDS consists of two parts and the coastline change is complicated with the coexistence of erosion and accretion. A previous study suggested that the construction of DWP affected the hydrodynamics of the CE, thereby preventing the natural trend of horizontal extension of JDS and enhancing the vertical progradation of the JDS (Jiang et al., 2012). Therefore, JDS is a fluvial island that is produced naturally by sediment supplied from upstream and that is influenced by coastal engineering in the CE.

We also performed linear regression analysis to understand the influences of sediment load and coastal engineering on the evolution of JDS, analyzing the possible linkage between decreased sediment load and variations in JDS area change. The datasets of sediment load and area were the mean value for every two years during the study period. Figure 6b illustrates that there is a clear positive relationship between JDS land increment and the amount of sediment discharged at Datong Station from 1996 to 2013. The relationship is described by Eq. (2):

$$y = 0.001x + 3.008 \quad \left(R^2 = 0.77, P = 0.002\right), \tag{2}$$

where $x$ is the total value of sediment discharge of every two years ($10^6$ t), and y is the total value of area change of every two years (km²). Figure 6b and Eq. (2) indicate that the land area increment increases with an increasing sediment load. However, an issue with this equation needs to be addressed: when $y$ is 0, $x$ is negative, and this does not make sense practically. We propose that the evolution of JDS is not controlled by the sediment load alone.

### 4.3 *Variation of CE and the relationship with costal engineering*

4.3.1 *Changes of NHS and the relationship with reclamation*

The changing pattern of NHS is divided into three stages: slow accretion stage (1974–1994), rapid accretion stage (1994–2006), and stable stage (2006–2014) (Fig. 5d). From 1974 to 1994, NHS increased by 41 km², with an average rate of 2 km²/a, and extended seaward balanced. In contrast, during 1994–2006, the coastline advanced drastically towards the water, and NHS increased by 141 km², with an average rate of 11.75 km²/a. In the last stage, the area of NHS increased by merely 4 km², and the coastline was nearly unchanged comparing with the second stage. The NHS area change patterns are distinct in different stages. In the first stage (1974–1994), NHS area change is slow, as sediment discharge dominates the deposition with few human interference. In the second stage (1994–2006), the area change of NHS is drastically under the predominant control of urban construction in Shanghai. During this stage, the Lingang New City of Shanghai was constructed and a massive tidal flat was reclaimed. In the final stage (2006–2014), there is little change in the NHS area as a consequence of the combining effects of the increasing sediment discharge and the reducing reclamation.

The results of the liner regression analysis also revealed that reclamation influenced CE coastline change the most owing to the change of tidal flat elevation and seawalls construction. According to Wei et al. (2014b), more than 1 200 km² of tidal flats were reclaimed during 1953–2010 in Shanghai, which accounts for 50% of the tidal flats in the CE. A large-scale reclamation project was also carried out in Jiangsu Province, more than 2 500 km² of tidal flats were reclaimed during 1949–2004. Thus, the effect of reclamation can be hardly ignored on the change of coastline. Figures 4d and 5d exhibit the changing pattern of NHS during 1974–2014, and the rate of area increment accelerated significantly in the period of 1996–2006 owing to the reclamation in NHS. Land acquired from the reclamation was used to build Lingang New City, 133 km² of which originated from reclamation (with a total area of more than 300 km²). In this period, the mean annual rate of area increment in NHS is more than 13 km²/a, which was only 2 km²/a during 1974–1996.

4.3.2 *Changes of Qidong and the relationship with reclamation*

The changing pattern of Qingdong during 1974–2014 is different from that of other study areas, given that it maintained a relatively stable state in the south coast near the CE and slowly extends seaward in the east coast (Figs 4e and 5e). Yet, as illustrated in Fig. 5e, the area change of Qidong is unstable, with three stages of rapid accretion and two stages of slow accretion. Only 62 km² of land was accreted in the study period, when the region was dominantly controlled by artificial reclamation. Previous studies proposed that water discharge to the ECS by the North Branch began to decrease in the eighteenth century, and the hydrodynamic environment gradually converted from mainly runoff into tidal control. With the reduction of water discharge, sedi-

ment load transported by the North Branch also decreased sharply. As a result, the south coastline of Qidong no longer extended. Nevertheless, the coastline near the ECS still extended seaward, resulting in the change in the coastline during the study period. Previous studies in this area showed that the reclamation of tidal flats was the controlling factor that led to the area increment. Sun (2012) studied the distribution and dynamic evolution of tidal flat resources along the Jiangsu coast during 1980 to 2011; the area change of Qidong caused by reclamation in this stage was 67.9 km$^2$, with an increment rate of 2.19 km$^2$/a. Zhang et al. (2013) also collected reclamation materials from Jiangsu Province and calculated that the reclaimed area in Qidong ran up to 66 km$^2$ during 1950–2013. Our results using remote sensing images are consistent with these previous studies that 62 km$^2$ of tidal flats were reclaimed during 1992–2014 in this study.

To quantify the effects of reclamation on the evolution of CE, we defined a contribution rate of area change. We assumed that the evolution of CE was controlled only by sediment load and coastal engineering (reclamation, and harbor construction), and ignored the influence of rising sea levels. The rate was calculated using the following Eq. (3):

$$R = S'/S, \tag{3}$$

where $R$ is the value of contribution rate, $S'$ is the area (km$^2$) increment of reclamation and $S$ is the area (km$^2$) increment of total Changjiang Subaerial Delta. We collected reclamation data from 2000 to 2014 and calculated the contribution rate during this period. The reclamation area in this period is 159 km$^2$, and the total area increment in this period was 351 km$^2$. According to Eq. (3), the contribution rate of reclamation during 2002–2014 is 45.3%. Thus, the reclamation has a great effect on the evolution of CE.

Table 3 allows us to understand the distribution of reclamation in the YRD area during 2000–2014. The tidal flat reclamation played a role during 2000–2008 with an average contribution rate of 67.1%. During this period, large-scale reclamation engineering was carried out in Qidong and NHS, e.g., the construction of Sea Venice and Lingang New City. Reclamation almost stopped afterwards, as reflected in the contributed reclamation rate after 2008, especially during 2008–2010. The contributed reclamation rate after 2008 was 8.2%, which contributing little to area increment during this period. Consequently, we divide the "reclamation influence" into two stages: rapid reclamation stage during 2000 to 2008 and slow reclamation stage during 2008 to 2014.

Although it can provide a large amount of land resources, reclamation affects the natural accretion of tidal flats. Since the 21st century, tidal flats in NHS and Qidong extended seaward very slowly as a result of the rapid reclamation and slow accretion. In other words, tidal flat areas have to gradually decrease in the CE as the rate of reclamation overweighs the deposition rate of the deposited tidal flats. To prevent the reduction of tidal flats and to improve accretion in tidal flats, the government has taken relevant actions.

**Table 3.** The contribution rate of reclamation at interval two years during 2000 to 2014

| Stages | Area of reclamation/km$^2$ | Area change of Changjiang Subaerial Delta/km$^2$ | Contribution rate of reclamation/% |
|---|---|---|---|
| 2000–2002 | 39 | 63 | 61.9 |
| 2002–2004 | 44 | 77 | 57.1 |
| 2004–2006 | 30 | 56 | 53.6 |
| 2006–2008 | 23 | 24 | 95.8 |
| 2008–2010 | 0 | 8 | 0 |
| 2010–2012 | 21 | 73 | 28.8 |
| 2012–2014 | 2 | 50 | 4 |
| 2000–2014 | 159 | 351 | 45.3 |

#### 4.3.3 *Changes of HES and the relationship with Deep Waterway Project*

With socio-economic development, more attention has been paid to harbor construction. In order to improve the navigability of the channel into Shanghai Harbor, a large scaled Deep Waterway Project (DWP) was carried out in the North Passage (NP) of the CE during 1998–2010, which increased waterway depth to 12.5 m. The project was executed in three stages with the construction of 2 widely spaced training walls, 19 long groins, and diversion works. With the construction of DWP, the reclamation of the HES was implemented on the basis of the construction of jetties, which results in the rapid accretion in HES (Fig. 7).

The construction of DWP directly changed the topographical features of the estuary, which inevitably influenced the hydrodynamics in the NP. Hu and Ding (2009) demonstrated that the flow pattern of NP was changed from a rotational current into rectilinear flow because of the DWP construction, which also affected the transportation of sediment and the geomorphology of CE. This agrees with the findings by Jiang et al. (2012), who claimed that the bar area of CE experienced substantial morphological changes as a result of the changes in hydrodynamics that are brought in by the large scale navigation project. Jiang et al. (2012) also found that the construction of DWP promoted the storage of more sediment in the JDS, and resulted in the continued progradation of JDS even though the upstream sediment load experienced a sharp decrease.

### 4.4 *Error analysis*

Coastline is the connection of land and water. Therefore, a coastline always changes with landform variations and sea level change. Errors are brought in when we extracted coastlines from remote sensing images are acquired at different times as the tide varies with time, despite that the effects of tide have been reduced greatly with the use of the mean high tide line in this study. Tide and landform variations have a significant influence on the extraction of coastline. Additionally, given their relatively low spatial resolution, remote sensing images only provide a rough evaluation of coastline changes. The researchers initially held the view that synthetical error is roughly one pixel (30 m×30 m), this is small and ignorable compared with the magnitude of the overall coast changes of the CE when delineating coastlines in a flat coastal zone with Landsat imagery (Huang et al., 2002).

## 5 Conclusions

In this study, mean high tide lines were extracted from multitemporal remote sensing images at intervals of two-year from 1974 to 2014 (21 images in total), and were subsequently utilized to examine the changing pattern of Changjiang Estuary with RS and GIS tools. In general, coastlines in the Changjiang Estuary eprogradated towards the ocean during the study period, and parts of the coastline showed inter-annual fluctuations and even degradation. Delta area increased by 871 km$^2$ with a mean net accretion rate of 21.8 km$^2$/a. The general change pattern of accretion-erosion in the Changjiang Estuary was divided into three stages: slow accretion stage (1974–1986), moderate accretion stage (1987–2002), and rapid accretion stage (2003–2014).

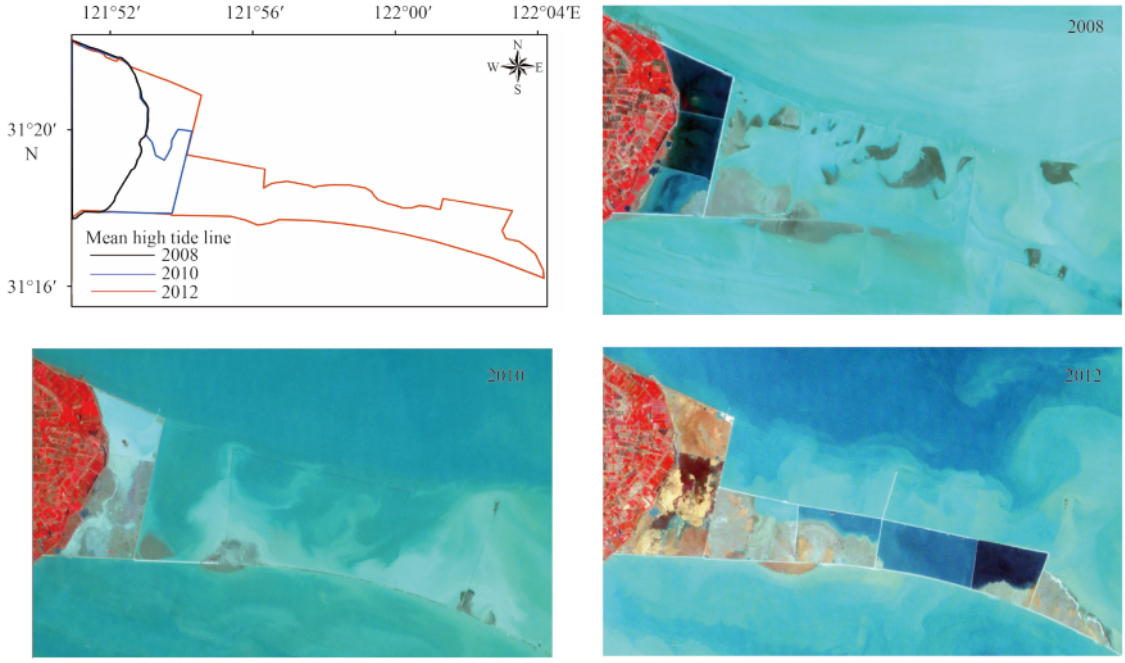



**Fig. 7.** The construction of DWP and the reclamation of HES.

We extracted the signals of water discharge and sediment load in order to analyze their influences on the evolution of Changjiang Estuary. The sediment load of Changjiang Estuary exhibited drastic downward trends during the period of 1974–2013, whereas the annual water discharge showed a slight decrease. Linear regression analysis was performed to identify the relationship between the accretion-erosion area of Chongming Eastern Shoal and Jiuduansha and the sediment load. The area of Chongming Eastern Shoal showed a good response to the sediment load. We proposed that when the amount of sediment load declines, delta degradation will occur correspondingly. The critical annual sediment load is $0.77\times10^8$ t/a in order to maintain the accretion balance in Chongming Eastern Shoal during 1974–2014. In this study, the analysis of Jiuduansha showed a positive correction between sediment load and Jiuduansha area change. However, this finding contradicts the common scene. When the sediment load is 0, the area increment is a positive, meaning that the area change of Jiuduansha is controlled by multiple factors. Studies have suggested that coastal engineering such as Deep Water Project will influence the evolution of Jiuduansha. Similar with Jiuduansha, the evolution of Nanhui Shoal is also impacted enormously by human activities such as reclamation. The study on the Hengsha Eastern Shoal indicated that Deep Water Project had a significant effect on the evolution of Changjiang Estuary, which changed the geomorphology of Changjiang Estuary magnificently. To quantify the influence of coastal engineering on the Changjiang Estuary, we defined a contribution rate of area change to evaluate the contribution of reclamation to the evolution of Changjiang Estuary. We calculated the rate of reclamation during 2004–2014 as 45.3%, implicating that more than 45.3% of the area increment of Changjiang Estuary was ascribed to reclamation. In conclusion, reclamation has a tremendous influence on the evolution of Changjiang Estuary.

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