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Variations in tidal flats of the Changjiang (Yangtze) estuary during 1950s–2010s: Future crisis and policy implication

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ABSTRACT

Tidal flat, is a critical natural resource for coastal ecosystem and plays a tremendous role in coastal sustainable development. However, most tidal flats in the world are facing serious challenges from both natural change and anthropogenic activities. Based on the multi-year monitoring records of tidal flats in the Changjiang (Yangtze) Estuary, the temporal-spatial changes of tidal flats and possible driving factors were statistically examined. The results indicate that the increased rate of the majority of tidal flats in the Changjiang Estuary has become slow since 2000s. Tidal flats of both Hengsha and Jiuduan Shoal showed minor enlarged trends from 2004 to 2009. However, Tidal flat areas of Nanhui Shoal above 0 m had greatly decreased by 80.8% from 1958 to 2012. Even though estuarine hydraulic engineering structures can mitigate tidal flats decreased trends, the tidal flats of the Changjiang Estuary will still suffer significant losses due to the decreasing sediment flux from upstream, ground subsidence, sea level rise and recent intensive reclamation. Thereafter, the adaptive management strategies for sustainable tidal flat resources of the Changjiang Estuary are as follows: (1) Proceeding comprehensive adjustment involving watershed and estuary; (2) keeping balance between reclamation and rebirth of tidal flats; (3) coping with sea level rise; (4) scientifically promoting aggradation of tidal flats.

1. Introduction

Tidal flats, found between mean high-water and mean low-water spring tide datums (Dyer et al., 2000), are natural transitions from terrestrial ecosystems to ocean ecosystems, with tremendous values in coastal sustainable development (Kline and Swallow, 1998; Mulder et al., 2011; Oost, 2012; Yao, 2013). Tidal flats have functioned as "land factory" ungrudgingly or reluctantly since time immemorial (Feng et al., 2012), from which humans reclaimed land and expanded their living space. The Dutch had created 1/6th of their territory by tidal flat reclamation by 1980s (Hoeksema, 2007). In Japan, about 1/3rd of the coastal cities were established with land converted from tidal flats (Elgamal et al., 1996). With rapid population growth and intensive land development in the coastal areas, tidal flats are unavoidably viewed as an important potential land resource (Tang, 2008). The "factory" is becoming a significant way for people to gain land to live on. Meanwhile, tidal flats also serve as buffer zones to defend the coastal zones against storms and other natural hazards (Kirby, 2000).

However, tidal flats distributed over the world are facing serious crisis of degradation resulting from both natural impacts and anthropogenic activities (Joseph et al., 2000; Mitsch et al., 2009; Beusekom et al., 2012; Durigon et al., 2012; Dias et al., 2013; Saengsupavanich, 2013). Global sea level has risen during the 20th century and will accelerate rising through the 21st century, along with ground subsidence aggravating regional sea level rise (Nicholls and Cazenave, 2010; Kolker et al., 2011; Bi et al., 2013). Sea level rise has resulted in tidal flats submergence around the world (Morris et al., 2002; Blum and Roberts, 2009; Craft et al., 2009; Kolker et al., 2011; Bi et al., 2013; Leorri et al., 2013). Meanwhile, over the past century, anthropogenic activities including river damming, river diverting, irrigation, and urbanization, have decreased sediment loads of rivers all over the world (Milliman et al., 1987; Syvitski et al., 2005). Chinese rivers deliver only 0.4 Gt/yr of sediment to the Pacific Ocean, just 20% of sediment delivered in 1950s (Chu et al., 2009). Due to decreasing sediments into the estuary, aggradation of tidal flats has slowed down or even recess worldwide: The shoreline of the Nile Delta began to experience erosion in several areas at the beginning of this century as a consequence of Aswan Dam construction (Fanos, 1995). The

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human-induced decreasing sediment flux to the sea has lowered down land accretion of the Yellow River Delta (Xu, 2008). As a result of decreased sediment supply by almost 50%, large amounts of Mississippi deltaic wetlands have been lost to the ocean (Blum and Roberts, 2009). Moreover, anthropogenic activities, especially reclamation, have cut down tidal flat areas adequately by converting tidal flats to available land resources. Approximately 401 km^2 of tidal wetlands were lost as a result of the Saemangeum Reclamation Project embarked by South Korea in 1991 (Son and Wang, 2009). Similarly, the Isahaya Reclamation Project initiated in Japan in the early 1990s destroyed tidal flats of 16 km^2 in the Ariake Bay (Hodoki and Murakami, 2006). In China, reclamation of tidal flats has been intensified since 1950. 12 000 km^2 of tidal flats had disappeared in China by 2002. Due to increase in land demand, reclamation rates are consistently accelerating and reclamation areas are moving to the intertidal zone, which has resulted in a sharp decrease of intertidal flats (Chung et al., 2004). Therefore, there is a critical need to understand the temporal-spatial variations of tidal flats and their driving factors which can essentially help us develop more adaptive management strategies for future challenges (Zahran et al., 2006).

The Changjiang Estuary receives plentiful fluvial materials from the Changjiang (Yangtze) River, which is the largest river in the Eurasian continent, with a length of 6300 km, a catchment area of 1.8×106 km^2 and a human population of over 4×10^8 (Dai, 2011a). Being the terminal part of the Changjiang River, this 'golden zone' is the axis of economic development in China (Dai, 2008), holding the most prosperous metropolis – Shanghai. However, this economic center is congenitally deficient in available land resources. Thus generating land from tidal flats is the only way out and 62% of stacking area in Shanghai was converted from tidal flats reclamation (Chen, 1985). Unfortunately, anthropogenic activities including water diversions and land use changes such as soil and water conservation policies and the buildings of dams, especially the Three Gorges Dam (TGD) – the largest dam in the world, have led to a dramatic decrease in sediment flux delivering to the Changjiang Estuary, from the original 4.8×10^8 t/yr in the 1950s to less than 1×10^8 t/yr in the new century (Dai, 2008, 2010, 2011b, 2013a). Pitiful tidal flats with less food supplement could not maintain rapid growth with accreted velocity slowing down (Yang et al., 2005, 2011). Recent research has improved our understanding on the dynamics of tidal flats in the Changjiang Estuary, including the scouring mechanism of tidal flats (Yun, 1983), the channel evolution, great changes in sediment delivery (Dai et al., 2011a, 2013b), and the effects of reclamation on tidal flat evolution (Li, 2006; Mao, 2008). However, little research has been focused on long-term tidal flat changes, interference of anthropogenic activities and natural impacts, and associated advice on how to manage and maintain harmonic development of tidal flat resources of the Changjiang Estuary.

The tidal flats in the Changjiang Estuary are the ideal study area to empirically examine the temporal-spatial changes by considering their vulnerable natural conditions, highly intensive urbanization, dramatic infrastructure constructions, and systemically changing hydrology system. Four major shoals – Chong Eastern Shoal, Hengsha Shoal, Jiuduan Shoal and Nanhui Shoal, account for over ninety percentage of the total tidal flat area of the Changjiang Estuary (Fig. 1). Owing to the limited observation records of the Chongming Eastern Shoal, it was not included in this study. Three shoals – Hengsha Shoal, Jiuduan Shoal and Nanhui Shoal, are used to examine the temporal-spatial changes of tidal flats in the Changjiang Estuary. The purpose of this paper is to examine temporal-spatial changes of tidal flat areas in the Changjiang Estuary in the past sixty years. Moreover, this paper further identifies the possible driving factors from both nature and anthropogenic forces, and eventually proposes related advice on sustainable utilization and management of tidal flats using an adaptive management framework.

2. Data collection and methods

The collected data on tidal flat areas include above 0 m isobaths, 2 m isobaths and 5 m isobaths in Hengsha Shoal and Jiuduan Shoal from 1958 to 2009, and Nanhui from 1958 to 1996 from the official published Sea Maps of Navigation Guarantee Department of the Chinese Navy headquarters and the previous references (Yun, 2010). The records of Nanhui Shoal areas during 1997–2012 were obtained from the Shanghai Geological Environmental Bulletin (SGEB), 2013 (http://www.shgtj.gov.cn). The long-term water discharge and suspended sediment concentration data were recorded at Datong Station (the tidal limit of the Changjiang estuary) from 1953 to 2011 and were acquired from the Bulletin of China River Sediment (BCRS), 2003–2011 (2003–2011, available at: www.cjh.com.cn), and the sediment flux was subsequently estimated relying on these two observed parameters. Monthly mean sea level data from 1965 to 2012 at Lusi (32.08°N, 121.37°E), the nearest site to the Changjiang Estuary, was collected from the Permanent Service for Mean Sea Level (PSMSL), 2012 (PSMSL, available at: http://www.psmsl.org). Further, data on yearly subsidence rate of Shanghai from 1920 to 2006 was gathered from the Shanghai City Planning and Land Resources Bureau, 2013 (http://www.shgtj.gov.cn) for illustrating contribution of subsidence to regional sea level rise. Data on yearly reclamation area of Shanghai from 1953 to 2010 was gathered from the Shanghai Water Authority (http://www.shanghaiwater.gov.cn/indexZh.html).

Navigational charts of different years provide suitable data for studying the depositional and erosional rates in the delta and estuarine regions (van der Wal and Pye, 2003; Lane, 2004; Blott et al., 2006). Therefore, in this study, we collected charts associated to tidal flats as the source of data to quantify areas of tidal flats over different isobaths. Depth measurements for these charts were taken by the DESO-17 echo-sounder with the vertical error of 0.1 m, and a GPS device by Trimble, USA was used to calculate the positioning with error within 1 m. All surveys were carried out between early May and early June, prior to peak discharge. Based on the digitizing procedure by Blott et al., (2006), the depth data from charts were digitized and analyzed using ArcGIS 9.3 software. The data were georeferenced using twenty fixed landmarks that had related errors smaller than 0.01 cm and then all the digitized data were transferred from their original projections into Beijing 54 coordinates in ArcGIS 9.3. Thereafter, digital terrain model (DTM) for each digitized chart of the tidal flats of Changjiang Estuary was established. Based on DTM, tidal flat areas between different isobaths of the Hengsha Shoal, Jiuduan Shoal, and Nanhui Shoal were obtained. The area change ratios between two adjacent years were further calculated subsequently with the '3D Analyst' tool based on platform of ArcGIS 9.3. To diagnose the linkage between the changes in sediment flux from upstream and variations in tidal flats, a linear regression analysis was undertaken with significant level test.

3. Results

3.1. Variations of water discharge and sediment flux into the Changjiang Estuary

Summary statistics of long-term time series of water discharge and sediment flux are shown in Fig 2, including yearly mean data, corresponding ten-year running mean series and decadal mean data. During the past half century, water discharge has remained

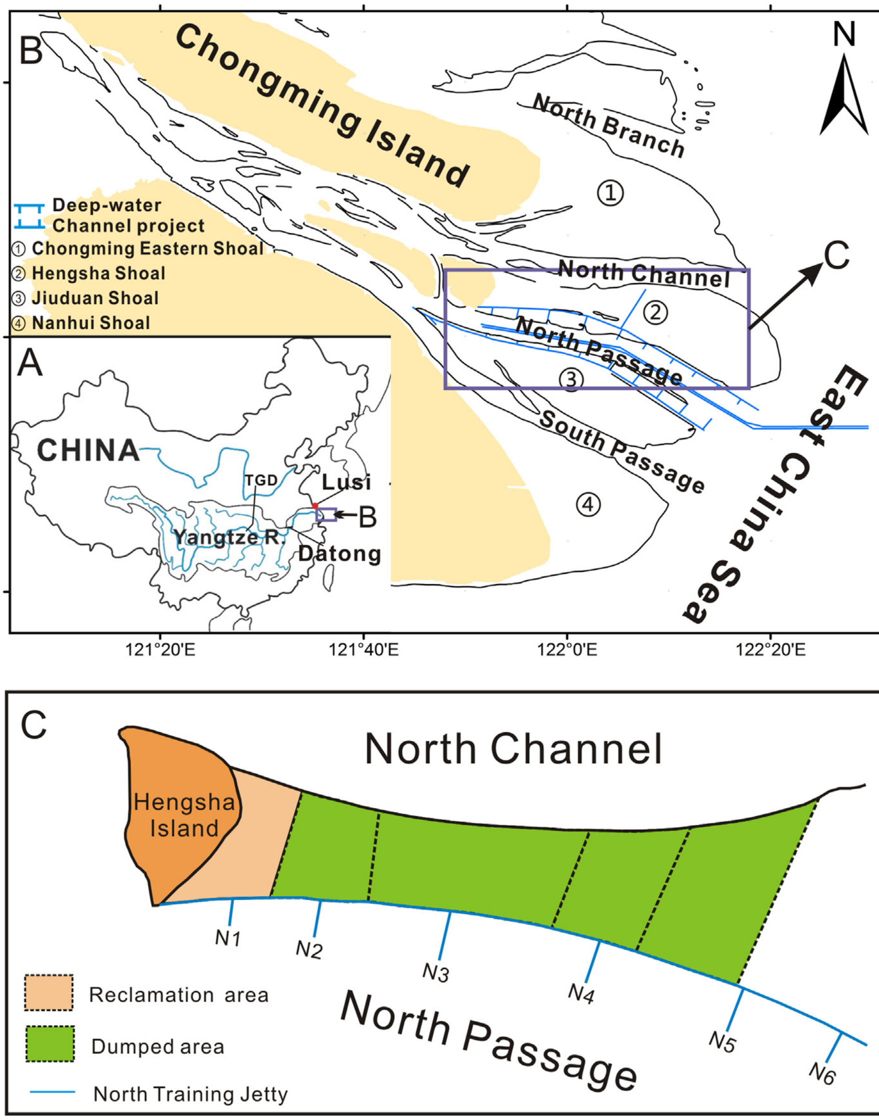

Fig. 1. Maps of (A) China shows the drainage basin of the Changjiang River, locations of TGD, Datong station and Lusi Station, (B) the detailed geographic setting of the study area, (C) the diagram showing reclamation and dumped area of Hengsha Shoal.

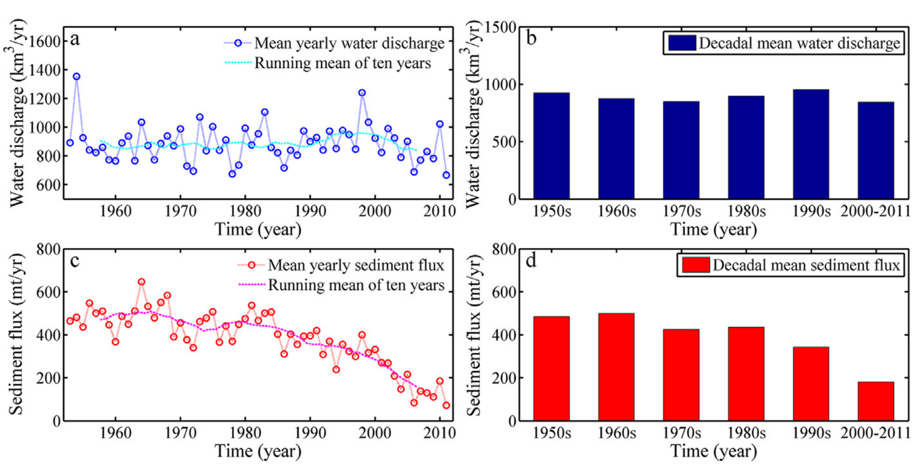

Fig. 2. Water discharge and sediment flux observed at Datong.

relative stable, fluctuating around the mean of 900 km^3/yr, though a slight increase starts from 1990. The decadal water discharge shows similar tendency, with no significant fluctuation through the whole time period.

Sediment flux during this period decreases with highest values in the 1950s and 1960s, lower in the 1970s and 1980s, much lower in the 1990s, and the lowest after 2000. This decrease from around 500 Mt to lower than 100 Mt is significant and abrupt, which mainly happens after 1980. Moreover, due to the Three Gorges Dam operation in 2003, the amount of sediment decreased from 208.8 Mt in 2003 to 84.8 Mt in 2006 (Fig. 2c). While, it has been focused on tidal flats in the Changjiang Estuary, sharply decrease in sediment flux resulting from dam construction could show a distal implication to tidal flats evolution.

3.2. Changes of tidal flats in the Changjiang Estuary

3.2.1. Changes in Hengsha Shoal

It can be seen in Fig. 3 that changes of tidal flat areas of the Hengsha Shoal above 0 m, 0~−2 m and −2~−5 m isobaths have been irregular undulation with some tracks of erosion in areas between different isobaths (Fig. 3a). From 1958 to 1997, areas above 0 m showed decreased changes from 81.6 km^2 in 1958 to 39.4 km^2 in 1997. However, areas ranging 0~−2 m had minor oscillation with a decreased trend of 1.4 km^2/yr from 1958 to 1985 and remained almost unchanged from 1985 to 1997. Areas ranging −2~−5 m of Hengsha Shoal showed obvious increased trends from 18.3 km^2 in 1958 to 235.4 km^2 in 1997. Meanwhile, during 1997–2009, tidal flat areas increased by 89.1% of above 0 m, 39.5% of 0~−2 m, and remained unchanged of −2~−5 m, respectively (Fig. 3a).

Although tidal flat areas between different isobaths have minor changes, the area change ratio above −5 m between adjacent years shows abnormal characteristics. There has been an obvious decreased trend from 1958 to 1997 resulting in negative values between 1985 and 1997. This means that the tidal areas increase at a slower pace and even starts to decrease after 1985. There were large fluctuations between 1997 and 2009, which reflected rapid erosion and accretion in tidal flat areas (Fig. 3b).

3.2.2. Changes in Jiuduan Shoal

Jiuduan Shoal, the largest natural preservation zone in the Changjiang Estuary, has been formed since 1954. It can be seen from Fig. 4 that tidal flats of Jiuduan Shoal above 0 m kept increasing trends from 38.2 km^2 in 1965 to 177.1 km^2 in 2009 (Fig. 4a). When compared to those above 0 m, tidal flats between

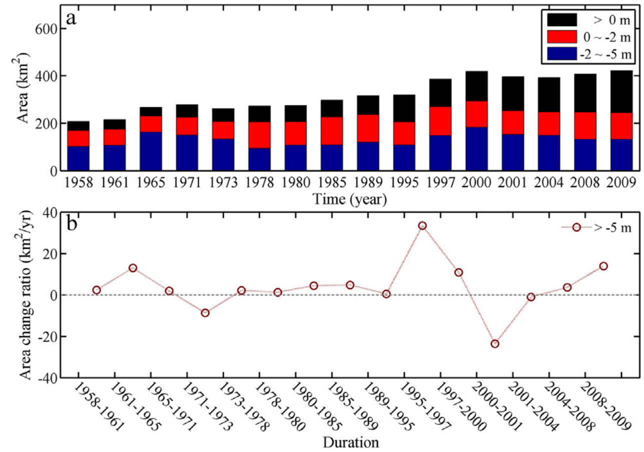

Fig. 4. Tidal area changes of the Jiuduan Shoal.

0 and −2 m had slightly increased by 0.87 km^2/yr. Although tidal flat areas between −2 and −5 m had obvious increase from 102.4 km^2 in 1958 to 183.3 km^2 in 2000, it is almost constant with about 150 km^2 from 2001 to 2009.

Tidal flats above −5 m of the Jiuduan Shoal increased by 103% from 1958 to 2009. However, the area change ratio between adjacent years clearly shows decreased trends with negative values of −23.6 km^2/yr during 2000–2001 and −1.0 km^2/yr during 2001–2004, and minor increase by 6.8% from 2004 to 2009, indicating that the tidal flat areas occurred decreased between 2000 and 2004 and slightly increased from 2004 to 2009 (Fig. 4b). This shows that the increasing rate of the tidal flats of the Jiuduan Shoal appeared much more slowly compared to those before 2000.

3.2.3. Changes in Nanhui Shoal

It's obvious that tidal flat areas of Nanhui Shoal above 0 m had greatly decreased by 80.8% from 1958 to 2012, even though it remained unchanged for tidal flats between 0 and −2 m and −2~−5 m (Fig. 5a). This indicates that the total tidal flat areas over −5 m were decreasing, as a result of large reduction result in the tidal flat area above 0 m. Meanwhile, it was found that the area change ratio between adjacent years indicates a gradual decreased trend with negative values that occurred from 1978 to 2012 (Fig. 5b). When compared to those of Hengsha and Jiuduan Shoal, Nanhui Shoal not only had obvious reduction, but the eroded rate was also increased.

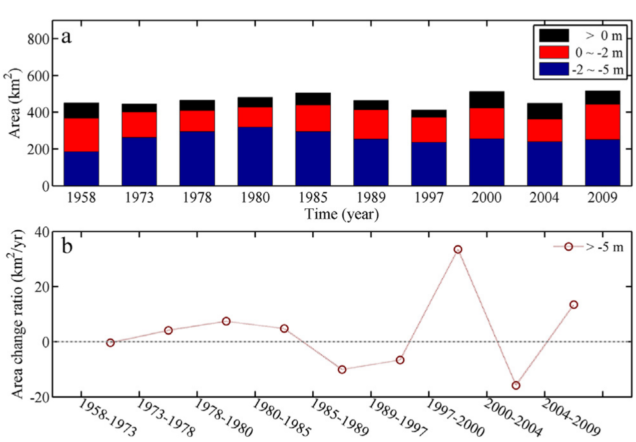

Fig. 3. Tidal flat changes of the Hengsha Shoal.

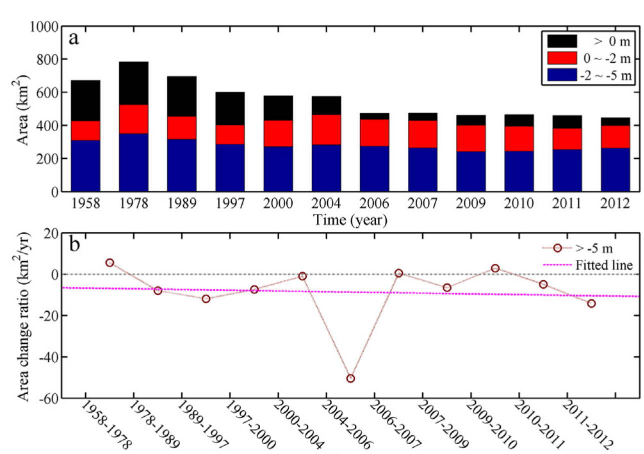

Fig. 5. Tidal area changes of the Nanhui Shoal.

4. Discussions

4.1. Impacted factors

4.1.1. Impact of sediment flux on tidal flat changes

To study the response of tidal flats to sediment supply from the Changjiang Basin, a linear regression analysis was done to analyze the possible linkage between decreased sediment flux and variation in tidal flat area change ratios of the different shoals.

A statistically significant positive relation was observed between decreased sediment flux and tidal flat area change ratios over −5 m of the Hengsha Shoal ($p < 0.005$) from 1958 to 1997 (Fig. 6). Meanwhile, relations between decreased sediment flux from upstream and area change ratios of tidal flats over −5 m of Jiuduan Shoal show a close positive correlation during 1958–1995 (Fig. 7). This means that variations of the tidal flats of both the Jiuduan Shoal and Hengsha Shoal should be determined by the amount of sediment flux from upstream.

Moreover, it can also be seen from Fig. 8 that there is a close positive relation between tidal flat areas over 0 m of Nanhui Shoal and sediment flux from upstream from 1958 to 2012. This indicates that changes of Nanhui Shoal are also controlled by sediment flux from upstream. However, relations between decreased sediment flux and corresponding variations in tidal flats of Hengsha Shoal and Jiuduan Shoal from 1997 to 2012 present distinct changes. This should be attributed to the operation of the deep-water channel project of the Changjiang Estuary between 1998 and 2008 (Dai et al., 2013b).

The results from this study further confirm the previous findings that decrease in sediment flux from rivers will slow down aggregation of tidal flats in estuaries and even lead to degradation of tidal flats (Yang et al., 2005, 2011).

4.1.2. Impact of local estuarine engineering on tidal flat changes

Operation of the deep-water channel project of the Changjiang Estuary produced large-scale dumped sediments. The mean yearly dredging and dumping volumes of the deep-water channel project of the Changjiang Estuary were 20×10^6 m^3 during 1999–2003, 34×10^6 m^3 during 2004–2006, and 81×10^6 m^3 from 2010 to 2012, respectively. These dredging sediments were partly put in the location of Hengsha Shoal in order to rapidly force shoal accretion (Fig. 1c). Therefore, although variations in tidal flat of the Hengsha Shoal could be likely controlled by upstream sediment changes before 1997, tidal flats could also be influenced by local estuarine hydraulic engineering with different changes after 1997 compared to those before 1997. However, because the amount of the decreased sediments from upstream was more than the dumped sediment in the Hengsha Shoal, tidal flats of the Hengsha Shoal were slowly deposited.

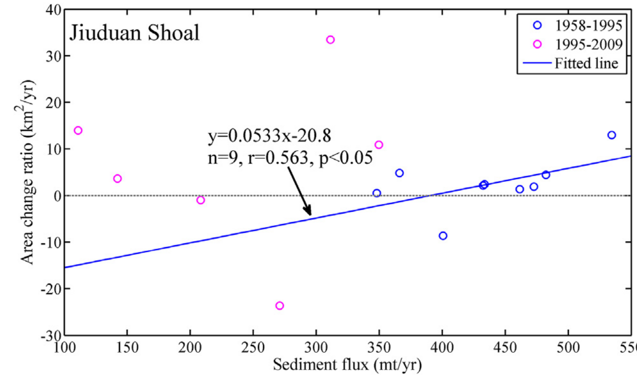

Fig. 7. Relations between sediment flux and area change ratio above −5 m isobaths in Jiuduan Shoal.

Meanwhile, construction of dikes and groins of the deep-water channel project in the North Passage mouth in 1998 has limited and destructed the previous sediment transportation paths with advantage to store more sediment in the Jiuduan Shoal. Therefore, construction of dikes and groins of the deep-water channel project could lead to continued accretion of Jiuduan Shoal (Jiang et al., 2012), even though there is an obvious decrease in upstream sediment flux. The combined results show similar slow accretion of tidal flats to the Hengsha Shoal. In the light of this information, it can be expected that both Jiuduan Shoal and Hengsha Shoal are subjected to possible erosion if sediment flux from upstream has been reduced. The effects of the deep-water channel project of the North Passage on the tidal flats of both shoals are weaker than that of the decreased sediment from upstream.

4.1.3. Impacts of reclamation on tidal flat changes

Reclamation has the most direct impacts on tidal flats evolution by converting tidal flats to available land. Tidal flats of the Changjiang Estuary have been suffering from intensive reclamation since 1950s (Fig. 9). Recorded reclamation in Shanghai started from 1953 with a total of 1259 km^2 tidal flats in 2010 being reclaimed, which enlarged land area of Shanghai City by 20%. This means that tidal flats of the Changjiang Estuary had lost over 1000 km^2 due to reclamation, which accounts for 50% of the whole tidal flats of the Changjiang Estuary. It can be seen from Fig. 9 that there is extremely reclamation rate of 34.7 km^2/yr occurred from 1996 to 2010, except for high reclaimed years in 1959, 1960, 1968 and 1973.

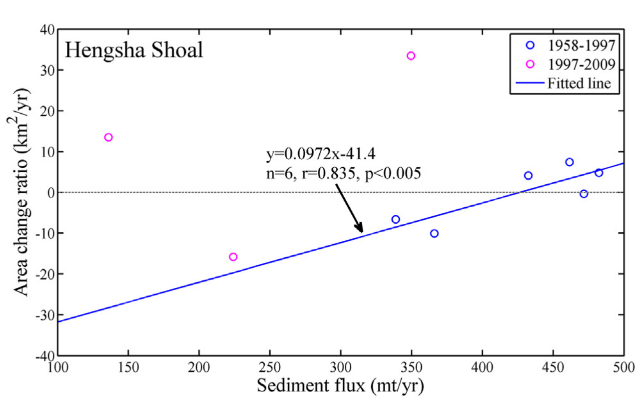

Fig. 6. Relations between sediment flux and area change ratio above −5 m isobaths in Hengsha Shoal.

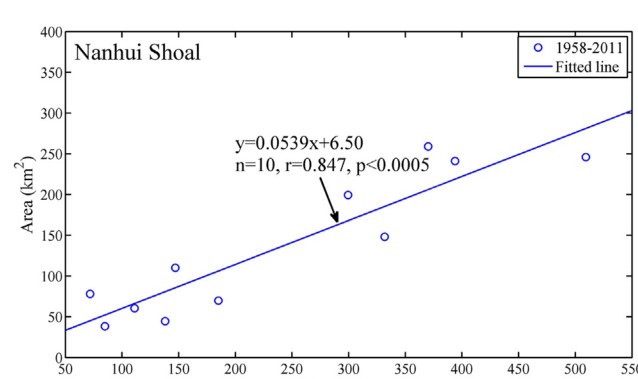

Fig. 8. Relations between sediment flux and tidal flat area above 0 m isobaths in Nanhui Shoal.

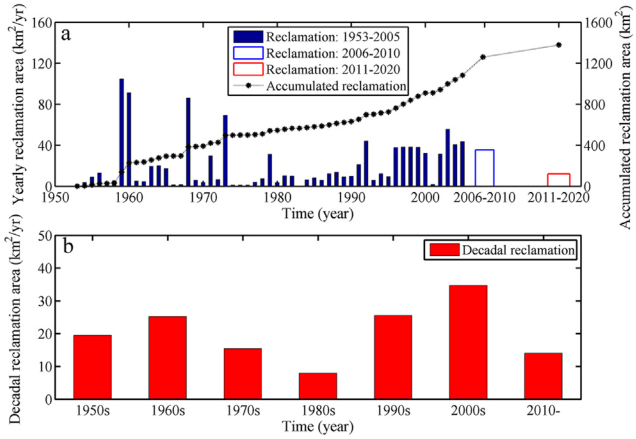

Fig. 9. Reclamation of tidal flats in Shanghai.

Meanwhile, according to the Comprehensive Regulation and Development of the Changjiang Estuary planning, reclamation area between 2010 and 2020 will be 118.9 km^2. While it was concerned with the rapidly decreasing in sediment from the upstream, accretion rate of present tidal flats is also slowing down. Thereafter, a more slowly accreted rate and more intensive reclaimed behavior could have large influences on variations in tidal flats of the Changjiang Estuary. While the increased tidal flats cannot keep with the reclaimed rate, tidal flat areas have to gradually decrease in the Changjiang Estuary.

4.1.4. Impact of ground subsidence and sea level rise on tidal flat changes

One alarming consequence of global warming is sea level rise, studies suggest a mean rise rate of 1.8 mm/yr in the past century and more than 3 mm/yr after 2000 (Church et al., 2011). Due to relative low-lying topography of the Changjiang Delta, minor sea level rise could induce extreme risk in the Changjiang Estuary, especially for the variations in tidal flats. In Fig. 10, it can be clearly seen that the monthly mean sea level data from 1965 to 2012 measured at Lusi showed inter-annual fluctuation with long-term increased trend of 5.34 mm/yr, which is larger than the global mean sea level rise rate. Furthermore, the groundwater overdraft around the Shanghai city has led to significant ground subsidence. Since 1920, subsidence rate in Shanghai has increased rapidly, from 0.64 mm/yr to 112.15 mm/yr in 1960, reaching the crest. From 1958 to 1964, subsidence was severe with a mean subsidence rate of 95 mm/yr. In recent past, accumulated subsidence value increased from 1770 mm in 1965–2024 mm in 2006 with a mean subsidence rate of 4.3 mm/yr for the same time period. Although the mean subsidence rate of 4.3 mm/yr for 1965–2006 is relatively small compared to that during 1958–1964, it's close to the mean sea level rise rate of 5.34 mm/yr. Thus subsidence in Shanghai accelerates regional sea level rise of the Changjiang Estuary, which could accelerate tidal flats of the Changjiang Estuary submerged resulting in decreased tidal flats. It is our expectation that tidal flats of the Changjiang Estuary in subsequent decade could be likely to further decrease due to ground subsidence and sea level rise.

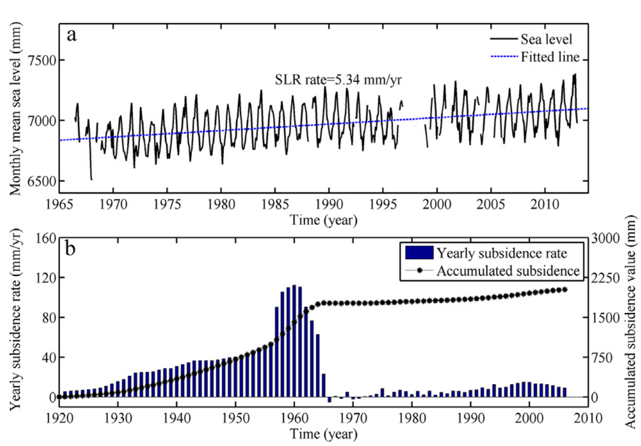

Fig. 10. Monthly sea level at Lusi and ground subsidence rate in Shanghai.

4.2. Policy implications

Tidal flats in the Changjiang Estuary are facing serious crisis of slower growth rate due to decreased sediment flux from upstream, even though there is some interference from deep-water channel project. Meanwhile, tidal flats are suffering from a series of consequences, including ground subsidence, sea level rise, and intensive reclamation (Milliman et al., 1987; Syvitski et al., 2005; Blum and Roberts, 2009; Mitsch et al., 2009; Son and Wang, 2009; Kolker et al., 2011; Durigon et al., 2012; Dias et al., 2013; Leorri et al., 2013). Thus, maintenance of growing of tidal flats and sustainable exploitation of tidal flat resources are of prime importance (Joseph et al., 2000; Beusekom et al., 2012; Saengsupavanich, 2013). Some proactive measures from adaptive management and policy advice must be proposed in advance to achieve the desired outcomes in the interface of complex multi-dimensional challenges.

4.2.1. Comprehensive adjustment involving watershed and estuary

The evolution of tidal flats in the Changjiang Estuary is closely related to sediment flux from the Changjiang River (Mao, 2008; Yang et al., 2011), which is an agreement with the present research. Watershed process gets linked with estuary morphological evolution: climate, geological conditions and anthropogenic activities in the river basin control sediment delivering to the estuary, in which anthropogenic activities, especially dam construction and land-use change play a tremendous role in this process. Moreover, the sediment delivered to the Changjiang Estuary is basic source for tidal flat growth. Thus, anthropogenic activities in catchment can influence the variations of tidal flats in the Changjiang Estuary by decreasing sediment into the estuary. This correlation is similar to many other rivers around the world, where deltas and estuarine tidal flats suffered from erosion induced by insufficient sediment supply, such as the Nile River, Mississippi River and Yellow River (Fanos, 1995; Xu, 2008; Blum and Roberts, 2009).

When discussing management on tidal flats in the Changjiang Estuary, we shouldn't just limit our view to the estuary, but formulate policies regarding watershed and estuary as a whole. In the river basin, rational program on dam construction should be conducted to minimize undesirable side-effect of dams (Milliman, 1997). When it comes to the estuary, remedies facing to sharp decrease in sediment import and slower or negative aggradation rate of tidal flats should be proposed and carried out such as artificial silting and sand nourishment, the enlightenment from the Netherlands, who plans to upgrade protection by building its North Sea coast seaward using beach nourishment (Delta Commission, 2008).

4.2.2. Keeping balance between reclamation and rebirth of tidal flats

Tidal flats have their own natural aggradation rate, which is mainly attributed to sediment flux and corresponding dynamic environment. If reclamation operates at a lower rate than the natural aggradation rate, tidal flats could recover in several years. Decrease in areas of Nanhui Shoal was not only caused by sediment load changes from upstream, but also resulted from local reclamation with relative high intensity and frequency. Furthermore, in the Wadden Sea, reclamation is the key reason for the missing mud flats (Mai, 2000). Thus reasonable reclamation rate that can't exceed the natural aggradation rate of tidal flats should be conducted (Hodoki and Murakami, 2006).

However, due to the urgency of demand for land resource in Shanghai city, limitation of tidal flat reclamation of the Changjiang Estuary could fail. Therefore, it is argued that the local government should construct favorable conditions to rebirth the tidal flats and make reasonable use of present reclaimed tidal flats.

4.2.3. Coping strategy to sea level rise

Sea level rise (SLR) is a world concerning issue due to climate change and restrains accretion of tidal flats globally (Morris et al., 2002; Blum and Roberts, 2009; Craft et al., 2009; Kolker et al., 2011; Bi et al., 2013; Leorri et al., 2013). Efforts have been taken to improve tidal flats adaptation to SLR (Nicholls and Cazenave, 2010). In the Changjiang Estuary, together with the influence of human-induced ground subsidence, survival of tidal flats has been threatened seriously by regional sea level rise, which could be more serious in the future. Actions and countermeasures on how to reserve present tidal flats of the Changjiang Estuary should be rapidly taken. Firstly, it can be emphasized that the standard of dykes to resist threats brought from sea level rise should be increased. In Thailand, a combination of spaced low-crested revetments and low-crested detached breakwaters, with bamboo fencing, is acknowledged as an alternative effective coastal protection measure (Saengsupavanich, 2013). Secondly, protection of wetland ecosystems should be strengthened by together with artificial ecological restoration project undertaken where wetlands are destructed by SLR (Kim, 2010). However, appropriate restoration actions should be identified to work best for specific conditions (Meli et al., 2014). Thirdly, it's necessary to establish pre-warning system on impacts of SLR induced by global warming with particular attentions on effects of storm and typhoon actions due to their increased intensity with SLR (Craft et al., 2009; Katsman, 2011; Kolker et al., 2011; Leorri et al., 2013).

4.2.4. Scientifically promoting aggradation of tidal flats

Although the hydraulic engineering could facilitate sedimentation on tidal flats by alteration of the hydrodynamic environment around tidal flats, the ecosystems and intrinsic properties of the tidal flats were dramatically destroyed. Therefore, taking advantage of science-based management practices in promoting aggradation of tidal flats is an effective and harmless tool, which relies mainly on growing plants to accelerate siltation on tidal flats. For example, *phragmite communis* is one of the significant saltmarshes to quickly accumulate sediments in the tidal flat and oblige tidal flat seaward aggradation (Yang et al., 1998). Such findings are discovered in other parts of world, like in Netherlands (Bouma, 2005) and Australia (Erskine, 2009). Moreover, Shanghai government had undertaken green silting and wetland restoration project in 1997 by planting 40 hm^2 of *phragmite communis* and 50 hm^2 of *spartina alterniflora project*, which resulted in rapid increase in tidal flats of Jiuduan Shoal. To improve the efficiency of the green silting project, guidance by science is essential, relating to what plants to grow, plant density and area selection.

5. Conclusions

This study identifies the temporal-spatial changes of the tidal flats in the Changjiang Estuary during the past sixty years. The findings provide an empirical overview for the variations of tidal flats and discover the critical driving factors on these changes. The aggradation rate of tidal flats of the Changjiang Estuary was decreasing since 2000s when compared to that before 2000. The altered tidal flats pattern actually reflects the consequences of complex natural processes and anthropogenic disturbances, including upstream sediment input, ground subsidence, sea level rise, coastal reclamation, and hydrologic infrastructure. The findings show that estuarine hydraulic engineering has some positive effects to promoting tidal flats remaining increased trends. However, continuing ground subsidence, sea level rise, decreasing sediment flux from upstream, and intensive reclamation, can result in loss of tidal flats in the Changjiang Estuary. If the current trend continues, this study expects that tidal flats of the Changjiang Estuary could be in crisis of high loss in the future.

In order to face with the challenges of tidal flats in the Changjiang Estuary, adaptive management strategies should be adopted to future coastal zone management: (1) Proceeding comprehensive adjustment, involving watershed and estuary; (2) keeping balance between reclamation and rebirth of tidal flats; (3) coping with sea level rise; (4) scientifically promoting aggradation of tidal flats.

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