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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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A B S T R A C T

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