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South Flank of the Yangtze Delta: Past, present, and future

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ABSTRACT

Chenier plain and mudflat development in the South Flank of the Yangtze Delta are examined by multi-disciplinary methods over different spatiotemporal scales and changing human-earth interactions. The study site contains a narrow belt of elongated ridge complexes that formed along the sediment-deficient open coast from 6500 to 4000 yr BP. Since then and until the past two decades, shoreline progradation has accelerated due to increasing sediment supply, fueling rapid deltaic expansion. Superimposed on this trend are a series of discrete sand-dominated ridges deposited during several stormy intervals. Tidal flat development is regulated by complex estuarine processes. Short-term morphodynamic variations at the site are caused by the alternations of tides and waves, while intermediate morphodynamic variations are controlled by the multi-decadal shifting of river stem channel and stormy climates. The ongoing rapid accretion on the tidal flats is predicted to continue into the near future because the estuarine buffer effect is expected to balance the adverse impacts of decreasing riverine sediment discharge and rising sea level. Technological developments during the last ~2000 years are exemplified by seawall construction against sea flooding, marking a transition from passive to active. Dike construction has been used more frequently and intensively to reclaim land since the 1970s, in support of the booming socioeconomic development in the region. Lessons from complex morphodynamic change and human-earth interactions in the Southern Yangtze Delta admonish us to not reclaim coastal wetland by lower-flat enclosures (constructing new dikes near the low waterline), while an optimal alternative would be to implement upper-flat enclosures (constructing new dikes around the high waterline) on the continuously accretionary tidal flats, with auxiliary biological restoration engineering, to satisfy both socioeconomic development and sustainable wetland conservancy.

1. Introduction

Deltas are extremely fertile lowlands and have attracted human settlement and farming since their initial development in the Mid-Holocene. They are the cradle of Neolithic civilization, a testing ground of early agriculture and the birthplace of hydraulic engineering (Stanley and Warne, 1994, 1997; Zong et al., 2007; Chen et al., 2008; Vörösmarty et al., 2009; Liu et al., 2016). Due to easy transport, deltas have developed into worldwide socioeconomic hubs, housing > 500 million people, with continued growth expected in the near future (Syvitski et al., 2009; Vörösmarty et al., 2009; Foufoula-Georgiou et al., 2011; Brondizio et al., 2016). Humans have long contended with changing deltaic environments and a change from passive to active adaption occurred along the Yangtze Delta roughly 2000 years ago. Human-earth interactions since then were generally harmonious until the last few decades when humans began to over-exploit deltaic natural resources. Adverse impacts include ground subsidence by oil/groundwater extraction, and construction of tall and dense buildings in city centers, and loss of healthy wetlands by land reclamation, waterway management and waste disposal. The situations has been further worsened by synchronous acceleration of sea-level rise and a sharp decrease in sediment discharge by river impoundments, causing the deltas become the world's most vulnerable regions in response to changes imposed by climate and human activities (Li et al., 2004a; Syvitski et al., 2009; Foufoula-Georgiou et al., 2011; Switzer et al., 2012; Brondizio et al., 2016). Sinking and shrinking (erosion) deltas have recently attracted the widespread concern of scientists, decision-makers and coastal communities, especially in Asian mega-deltas with huge populations (Chen et al., 2005; Saito et al., 2007; Blum and Roberts, 2009; Syvitski et al., 2009; Foufoula-Georgiou et al., 2011; Shearman et al., 2013; Anthony et al., 2015; Zhang et al., 2015).

Because of construction and operation of the world's largest reservoir – the Three Gorges Dam (TGD), the fate of the Yangtze Delta has become a focal point of public concern (Gao, 2007; Dai et al., 2014;

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Yang et al., 2014). The essential questions are whether and when the delta will change from accretionary into erosional, and what critical value of riverine sediment discharge (CVSD) is necessary to balance delta development. The projected CVSD ranges from 184 to 395 mt (million tons) yr^{-1} on the basis of different data and reasoning (Chen, 1998; Chen and Zong, 1998; Yang et al., 2003; Li et al., 2004b; Yang et al., 2006; Gao, 2007; Gao et al., 2011; Wang et al., 2011). After the dam completion in 2003, annual average sediment discharge into the river-mouth has decreased to 140 mt yr^{-1} over the period 2003–2014, less than one third of the discharge in the 1950–60s (497 mt yr^{-1}). The present sediment discharge is already below the lowest projected CVSD of 184 mt yr^{-1} (Li et al., 2003, 2004b), but most intertidal and subtidal flats (above 5-m isobath) are still accretional, except that the delta front between the 10-m and 20-m isobaths is undergoing increasing erosion (Yang et al., 2003; Zou et al., 2007; Huo et al., 2010; Chu et al., 2013; Dai et al., 2014). Recent hydrological data shows that the suspended sediment concentration (SSC) in the Yangtze river-mouth, especially in the turbidity maximum zones, has changed slightly after the dam completion (Song et al., 2007; Dai et al., 2013). This indicates that a time lag is buffering estuarine SSC in response to the decreasing riverine sediment flux. Abundant fine-gained sediments can be generated through a tidal pumping mechanism in the estuary, mitigating potential erosion on tidal flats. Continuous growth of tidal flats is a major concern of scientists and coastal stakeholders, but how long the present accretional pattern will continue under a decreasing sediment discharge scenario is not well known. Additional field and modeling analyses are needed to better understand sediment- and morpho-dynamics in tide-dominated deltas (Huo et al., 2010; Gao et al., 2011; Dai et al., 2013; Chu et al., 2013). Several large-scale engineering projects in the Yangtze river-mouth have exerted significant impacts on the erosion-deposition patterns of the delta, further complicating the development trend of tidal flats (Fan et al., 2013; Kuang et al., 2013; Dai et al., 2016; Li et al., 2016).

Holocene shoreline change provides insights into various behaviors of different coastal and estuarine units in response to sea-level change and sediment availability, so an understanding of Holocene evolution is needed for comprehensive coastal management (Woodroffe and Murray-Wallace, 2012; Switzer et al., 2012). Chenier ridges have long been recognized as a good indicator of paleo-shorelines and sea-level changes, and chenier plains consisting of at least two chenier ridges record variations in depositional modes along muddy coasts. The formation of chenier plains has been linked to a single or combined factors of secular variations in sediment supply (in response to changes in drainage and climate), delta-lobe switching or main-channel shifting, sea-level change, and storm frequency (Byrne et al., 1959; Otvos and Price, 1979; Wang and Ke, 1989; Lees, 1992; Augustinus, 2004; McBride et al., 2007; Fan, 2012b; Horne et al., 2015). Studies of chenier ridges and associated plains peaked in the late 1980s (Augustinus, 1989; Penland and Suter, 1989; Short, 1989; Zhao, 1989), and has significantly declined since then. Fortunately, this research has recently been revived using new dating methods for more accurate ridge chronology (e.g., optically-stimulated luminescence (OSL) dating technique) (Horne et al., 2015), and new field detecting methods to reveal the ridge internal architectures (e.g., ground-penetrating radar) (Weill et al., 2012). The South Flank of the Yangtze Delta is a chenier plain with a maximum width of 55 km (Figs. 1 and 2), presumed to have developed since the delta initiation ~7500 yr BP (Li et al., 1979, 2002; Liu and Walker, 1989; Yan et al., 1989). Uncovering secular shoreline evolution and landform development in the South Flank will undoubtedly shed light on future shoreline change (Woodroffe and Murray-Wallace, 2012; Horne et al., 2015).

In comparison with long-term (multi-centennial to millennial) coastal development and short-term (seconds to multiple years) coastal processes, the intermediate (decadal to centennial) timescale of coastal behavior has been less studied. However, the latter timescale has been considered more important for planning and managing coastal systems in the future (Woodroffe and Murray-Wallace, 2012). Long-term coastal development can be studied through core strata analysis, chenier-ridge series, and related sedimentological and morphological approaches (e.g., Augustinus, 1989; Goodbred and Kuehl, 2000; Li et al., 2002; McBride et al., 2007; Zong et al., 2012a, 2012b; Horne et al., 2015). Contemporary coastal processes can be investigated by in situ hydrodynamic and sediment-dynamic surveys, time-series analyses of satellite images and nautical charts (Fan, 2012b; Woodroffe and Murray-Wallace, 2012; Chu et al., 2013; Shearman et al., 2013). However there is an apparent gap in our understanding of coastal morphodynamics between long-term and short-term scales due to a lack of a valid methodology (Kuehl et al., 1996). We are able to fill this gap in China, due to the long histories of the South Channel and South/North Passage as primary waterways in central China. Their bathymetries have long been surveyed and the first published chart dates back to 1842 (Shen, 2001; Huo et al., 2010). This allows for a quantitative assessment of multi-decadal variations in the tidal-flat-channel system along the South Flank, which can be studied through time-series comparisons of different-aged charts.

The South Flank of the Yangtze Delta is located within the Shanghai municipality which houses roughly 24 million people in a 5000 km^2 area (Fan et al., 2013). Secular (centennial and longer) evolution of the South Flank is studied by comparison of shoreline indicators including chenier ridges in the western part, and seawalls in the eastern part (Fig. 1). Intermediate-timescale development of the Nanhui tidal flats is examined by a detailed comparison of different-aged nautical charts from 1842 to 2004 with a DEM (digital elevation modeling) method. Present tidal-flat processes and morphodynamic change are investigated by hydrodynamic and bathymetric surveying data. We aim to better understand coastal processes and morphodynamic change in response to natural and human forcings in this tide-dominated mega-river delta, and offer insights for coastal planning and management.

2. Study area

The modern Yangtze Delta first formed ~7500 yr BP when the post-glacial transgression reached its maximum at an apex near the Zhejiang-Yangzhou transect (Li et al., 2002; Hori et al., 2001). The delta plain has an area of > 23,000 km^2 and contains two dominant Flanks (North and South), with bars and islands at the river-mouth. North Flank development is characterized by successive annexing of river-mouth bars to the mainland. Seven river-mouth bars have been formed, and four of them have been merged into the North Flank (Fig. 1a; Li et al., 2002). The Chongming Island is the biggest river-mouth bar at present, rapidly amalgamating with the North Flank by persistent silting of the North Branch under estuarine processes and human activities (Dai et al., 2016). The Jiuduansha Island is the newest river-mouth bar, with the first emergence in the middle of 20th century (Li et al., 2016). The South Flank is a chenier plain, demarcated by a series of chenier ridges of different ages (Liu and Walker, 1989; Fan, 2012a). The oldest and newest chenier ridges were formed around 6500 yr BP and 600 yr BP, respectively (Liu and Walker, 1989; Zhang, 1998).

The Yangtze Delta is influenced by semidiurnal tides with an apparent diurnal inequality. The semidiurnal tidal ranges reach their maximum at the river mouth and decrease landward and seaward from there, except in the North Branch, where tidal ranges increase landward because of a funnel-shape effect (Fig. 1b; Fan et al., 2004; Dai et al., 2016). The average and maximum tidal ranges at the river mouth are usually taken as 2.6 m and 4.6 m, respectively (Li et al., 2002; Fan et al., 2004), while they reach 3.3 m and 5.9 m at Luchaogang station near the outlet of the South Passage (Zou et al., 2007). The average and maximum tidal ranges decrease to 2.67 m and 4.62 m at Zhongjun station (middle South Passage), and then 2.45 m and 4.49 m at Changxin Island. Tidal flows are usually ebb dominated in the main channels of distributaries but flood dominated over the broad tidal flats. The delta is subject to monsoon climate, with southeast winds