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Local human activities overwhelm decreased sediment supply from the Changjiang River: Continued rapid accumulation in the Hangzhou Bay-Qiantang Estuary system

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ABSTRACT

We investigate the morphological responses of the Hangzhou Bay, China, located immediately south of the Changjiang Estuary, to the drastic reduction of the sediment load from the Changjiang River and the large-scale coastal embankment schemes over past decades. The spatial patterns of deposition and erosion, sediment volume changes, and the hydrodynamic and sediment dynamic feedback were analyzed, on the basis of historical bathymetric and hydrographic data. The results show that the sedimentation rates in the bay have generally increased rather than decreased over the past decades, despite bed erosion having occurred in the northern bay-mouth. This observation reveals that the influence of the reduction in the Changjiang River sediment supply on the morphological evolution of Hangzhou Bay has to date been insignificant, mainly due to the buffering effect of existing sediment in the outer Changjiang Estuary. The morphological change is mainly related to the implementation process of the coastal embankment. Sediment accumulation induced by progressive seaward coastal embankment has resulted in seaward aggradation from the Qiantang Estuary towards Hangzhou Bay. Analysis of the annually-averaged high and low tidal levels, and durations of rising and falling tides reveals that flood dominance in the inner bay has been increased, due to the coastal embankment and sediment accumulation. The ratio between annually-averaged rising tide and falling tide durations have decreased from 0.85 to 0.63. The tidal prism at the interface between the inner and outer bay has decreased by about 25% since the 1980s, while the net landward sediment flux has been intensified to a certain extent, which is responsible for the intensifying sedimentation in the inner bay. The local human activities have overwhelm the decreased sediment from the Changjiang River. Although the coastal embankment will cease in the near future, the morphological response to human activities is expected to continue on for a longer time.

1. Introduction

Estuaries are defined as semi-enclosed coastal bodies of water which have free connection with the open sea (Fairbridge, 1980). They are unique ecosystems and are often located in densely populated areas (e.g. Kennedy, 1984; Dyer, 1997; Trenhaile, 1997; Wang et al., 2015). River discharge, tidal currents, waves and sediment supply are generally the major natural factors controlling the morphological evolution of estuarine environments. On the other hand, morphodynamic development of an estuary is also influenced by human activities such as flood protection, navigation channel dredging, land reclamation, dam construction, or sand extraction. Such human activities frequently cause substantial changes in the configuration of estuaries, their hydrodynamic regime, sediment transport, deposition and erosion patterns (e.g. Van der Wal et al., 2002; Blott et al., 2006; Wang et al., 2002, 2015; Winterwerp and Wang, 2013). In many cases the effects of human activities have exceeded changes induced by natural forcing factors. From the coastal management point of view, it is of major importance to understand the processes and mechanisms of morphological responses to human activities and to predict the trends of their future evolution.

Worldwide, the transport rate of river-borne sediments into most estuaries has apparently decreased in recent decades (Syvitski et al., 2005; Milliman and Farnsworth, 2011). With the sediment supply reduction, rapid changes have taken place, among them sediment transport adjustments, coastal retreat, slowdown of accumulation, and even

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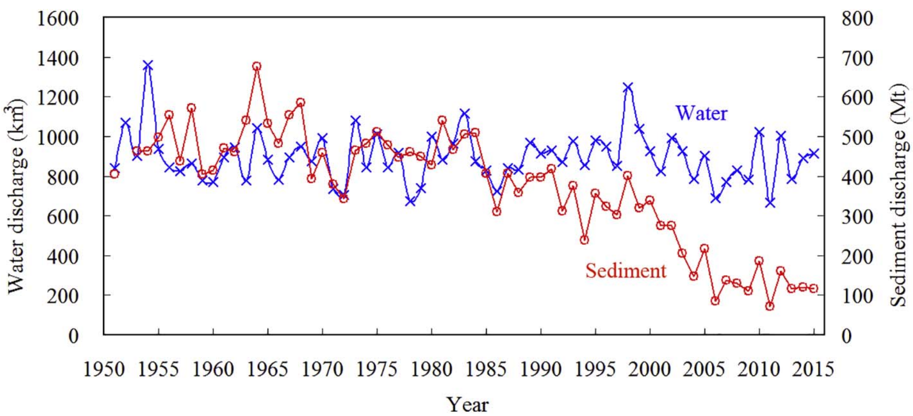

Fig. 1. Temporal variations of annual water and sediment discharges measured at the Datong gauging station located at the tidal limit 640 km upstream from the Changjiang River mouth (data from the Changjiang River Hydraulic Engineering Committee).

onset of erosion (e.g. Milliman, 1997; Syvitski et al., 2005; Yang et al., 2005, 2011; Gao and Wang, 2008). The Changjiang River is one of the largest rivers in the world, ranking 3rd in length (6400 km), 5th in runoff (925 km^3/y) and 4th in sediment load (486 Mt/y) (Eisma, 1998). In the last 30 years, and especially since 2003 when the Three Gorges Dam was constructed and operated, the sediment load at the Datong measuring station located about 640 km upstream of the Changjiang River mouth (the approximate limit of tidal penetration), has decreased drastically from more than 450 Mt/y before the1980s to less than 150 Mt./y, in some dry years (e.g. 2006 and 2011) falling below 100 Mt. (Fig. 1). As a result, the subaqueous delta of the Changjiang Estuary (CE) has switched from deposition to erosion, and the progradation rates of the fringing tidal flats have slowed down and locally even turned to degradation (Gao and Wang, 2008; Yang et al., 2011; Wang et al., 2015).

The Hangzhou Bay, located immediately south of the CE, is one of the largest embayment along the coast of the East China Sea, covering an area of about 4800 km^2 (Fig. 2). The Hangzhou Bay is typical funnel-shaped embayment and dominated by tidal currents. The west of Hangzhou Bay, from Ganpu to Zakou, is the Qiantang Estuary (QE), which is controlled by the combination of river discharge and tides (cf. Fig. 2). Hangzhou Bay is an area of extensive material exchange with the Changjiang Estuary, on one hand, and the Qiantang Estuary, on the other (e.g. Chen et al., 1990; Han et al., 2003).

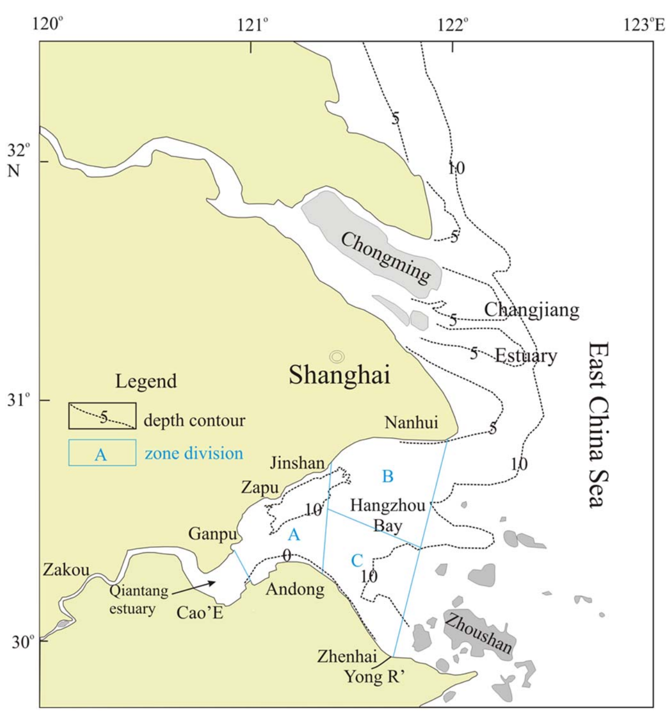

Fig. 2. Locations in the Hangzhou Bay referred to in the text. The dashed lines depict water depths. The definitions of the three zones referred to in the statistics of Tables 1 are also given.

The recent drastic reduction of sediment discharge from the Changjiang River and its effect on the morphological evolution of Hangzhou Bay have been a matter of great concern to marine scientists, coastal engineers and the regional management. In recent years, the northern bay mouth has evolved from an accumulating area to an eroding area, and thought to be related to reduction of sediment discharge from Changjiang River (e.g. Dai et al., 2014b). However, little quantitative work has been done on the large-scale morphological response in Hangzhou Bay to such sediment reduction, in particular, on assessing whether the sediment input into Hangzhou Bay has decreased by taking the sediment exchange with the QE into account.

On the other hand, a large-scale coastal embankment program has been implemented in the QE since the 1960s (Fig. 3), aiming at improving flood protection and navigation (Li and Dai, 1986; Han et al., 2003; Pan et al., 2010). So far, more than 1000 km^2 of tidal flats have been reclaimed, substantially changing the configuration of the estuary. Li and Dai (1986) reported that sedimentation in the QE before the 1980s was mainly caused by the reduction of the tidal prism. They predicted qualitatively that, with the downstream constriction of the QE, accumulation would shift seaward and thereby cause the tidal prism to decrease further. Yu and Cao (2006) documented that sedimentation in the QE from the 1960s to 2000 amounted to about 250×10^6 m^3. The morphological response of the Hangzhou Bay to the embankments is expected to be slower than that of the QE. Recently, Yu et al. (2012) modeled the formation of the large longitudinal sand bar in the QE which elongated 130 km upward of Zapu and occupied the whole QE, using an idealized long-term 2-D model. Their model results showed the sandbar would shift seawards with the increasing convergence of the estuary, and erosion would occur first at the mouth area with the sediment supply decreasing at the sea side. However, their model results were not fully verified due to the lack of detailed information on the temporal evolution of the QE. Although numerous human activities take place concurrently in estuaries, morphologic responses have often been observed to be slow (Wang et al., 2015). To capture the morphological evolution of the Hangzhou Bay, it is therefore necessary to base investigations on more and updated data.

Short-term changes on more local scales can often be satisfactorily predicted using the so-called 'bottom-up' models, which are based on hydrodynamic models and other process-based computer models, but they have limited capabilities for the prediction of longer-term geomorphological evolution (e.g. Whitehouse, 2002; Townend and Whitehead, 2003). Hence, so-called 'top-down' models, which are based on historical trend analysis, are more frequently used (e.g. Wang et al., 2002; Van der Wal et al., 2002; Lane, 2004; Blott et al., 2006; Yang et al., 2011).