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Sediment transport in response to changes in river discharge and tidal mixing in a funnel-shaped micro-tidal estuary

Wenping Gong[a,b,*], Liangwen Jia[a,b], Jian Shen[c], James T. Liu[d]

[a] Center for Coastal Ocean Science & Technology Research, School of Marine Sciences, Sun Yat-sen University, 135 Xingangxi Rd., Guangzhou 510275, China
[b] Guangdong Provincial Key Laboratory of Marine Resources and Coastal Engineering, Guangzhou 510275, China
[c] Virginia Institute of Marine Science, College of William& Mary, 1208 Greate Road, Gloucester Point, VA 23062, USA
[d] Department of Oceanography, National Sun Yat-sen University, Kaohsiung 80424, Taiwan

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ABSTRACT

Huangmaohai Estuary is a micro-tidal funnel-shaped estuary, located along the southwestern side of the Pearl River Delta complex. Variations of sediment transport patterns under different conditions of river discharge and tidal mixing are investigated by using field measurements and data analysis during both dry and wet seasons, respectively. The intratidal variation of sediment dynamics is largely controlled by the tidal asymmetry. The typical pattern of 25-hour mean sediment transport during the dry season is that the transport is landward in the channel and seaward on the shoals. A bifurcation pathway of sediment transport shows that sediments are imported from the East Opening and exported through the Middle Opening. However, this pattern can be altered by mixing processes and river discharge. Enhanced mixing or increased discharge can result in a predominantly seaward transport. Conversely, weak mixing can result in an emphatic landward transport. In general, the sediment transport is closely associated with the morphological evolution in the estuary.

1. Introduction

Sediment dynamics in an estuary is of great importance in many respects: siltation of the navigation channel, coastal embankment erosion, water quality and health of the ecosystem. Sediment transport in estuaries is largely affected by river discharge and its associated sediment load and tidal mixing. River discharge sets up a barotropic pressure gradient in the seaward direction and a baroclinic pressure gradient in the landward direction, thus creating a two-layered circulation with fresher outflow near the surface and saltier inflow at depth (e.g., Pritchard, 1952). As the suspended sediment is mostly concentrated near the bottom, this estuarine circulation favors the landward transport of sediment from the coastal sea to the estuary. The convergence of seaward transport from upstream and landward transport from downstream near the null point has been attributed as the major mechanism for the formation of the Estuary Turbidity Maximum (ETM) (Schubel, 1968). With an increase of river discharge, the river flow augments the seaward surface flow, and facilitates the seaward escape of the riverine sediment from the estuary. In the meantime, the increase of river discharge increases the baroclinic pressure gradient and enhances the gravitational circulation, which consequently strengthens the landward sediment transport at the bottom and prevents sediment from escaping to the coastal sea. The sediment transport pattern responding to changes in river discharge is, thus, a delicate balance between these two effects.

Sediment transport is also greatly modulated by the spring–neap tidal cycles. Strong mixing by spring tide generally destroys the stratification of the water column and decreases the two-layered exchange flow, and is advantageous for seaward sediment transport, whereas the neap tide enhances the estuarine circulation and favors the landward sediment transport. Apart from these tidally averaged processes, Mantovanelli et al. (2004) demonstrated that the tidal asymmetry in velocity and duration between ebb and flood can play a major role in determining the residual flow and the transport of waterborne substances. Moreover, the intratidal asymmetry of stratification and mixing (internal asymmetry) has been revealed to primarily control the sediment pumping in estuaries, which contributes to the formation and maintenance of the ETM (e.g., Scully and Friedrichs, 2007; Sommerfield and Wong, 2011). For a partially mixed estuary, the tidal straining effect results in a decreased stratification during flood and an increased stratification during ebb (Simpson et al., 1990). The enhanced stratification during ebb suppresses the bottom turbulence and confines the sediment near the bottom, while the enhanced mixing during flood reinforces the bottom turbulence and allows the bottom sediment to be entrained into

* Corresponding author at: Sun Yat-sen University, Center for Coastal Ocean Science & Technology Research, School of Marine Sciences, 135 of Xingangxi Road, Guangzhou, Guangdong 510275, China. Tel.: +86 20 8411 3729; fax: +86 20 8411 3678.
E-mail address: gongwp@mail.sysu.edu.cn (W. Gong).

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the upper water column (e.g., Geyer, 1993; Jay and Musiak, 1994; Scully and Friedrichs, 2003). This intratidal asymmetry results in a preferential landward sediment transport when averaged over a tidal cycle.

Along with the sediment dynamics, the change of sediment deposition is a key element in controlling the long-term morphological equilibrium of an estuary with sea level rise. Allen et al. (1980) found that the longitudinal position of sediment deposition varied as a function of freshwater in the Gironde estuary. During a high discharge period, the estuary is pushed toward the mouth, and sediment trapping is favored in the lower reaches of the estuary. After river discharge returns to the normal level, sediment initially deposited downstream is resuspended and transported back upstream by flood-dominated bottom currents to the ETM depositional zones. Woodruff et al. (2001) and Geyer et al. (2001) investigated the seasonal variation of sediment deposition in the Hudson River estuary. They noted that sediment was pushed downstream during a freshet, and was moved upstream afterwards. The timing between the freshet and spring–neap tidal cycle is critical in determining the location of deposition/erosion in the estuary. This conclusion is consistent with that found by Castaing and Allen (1981). Ganju and Schoellhamer (2009) noted that, in the Suisun Bay, the most landward embayment of San Francisco Bay, USA, episodic freshwater flows export sediment from Suisun Bay, while gravitational circulation during the dry season imports sediment from seaward sources.

The above documented sediment transport and depositional patterns are basically related to the processes in the longitudinal direction. In recent decades, lateral sediment transport has received more attention and has been revealed to play important roles in sediment dynamics (e.g., Huijts et al., 2006; Ralston et al., 2012). Along a cross-section with channel-shoal morphology, strong lateral variability exists. In the channel, the baroclinic circulation, stratification, and shear asymmetries are stronger and sediment is trapped more effectively than on adjacent shoals. On the shoals, the estuarine circulation and stratification are weaker and the river outflow has a greater influence on the near-bed mean flow. The net sediment fluxes tend to be seaward on the shoals and landward in deeper channels (Nichols, 1972). Lateral asymmetries in sediment flux, with landward transport in the channel and seaward transport on the shoals, have been observed in the lower Hudson (Panuzio, 1965) and York River estuaries (Scully and Friedrichs, 2007). In the Delaware estuary, channel fluxes are landward while transport on the shoals is variable (Sommerfield and Wong, 2011).

The Huangmaohai Estuary (HE) is located in the southwestern part of the Pearl River Delta complex (Fig. 1a), which is one of the fastest growing economic areas in China. It is composed of a bay proper and a tidal river (Fig. 1b). The bay proper is funnel-shaped, whose width increases exponentially from the head towards the mouth, where several island chains are located. The Pearl River Delta complex is a micro-tidal regime with mixed semi-diurnal tides. Pearl River has three major tributaries: the West River, North River, and East River. Being dominated by the East Asian monsoon, the Pearl River displays a large seasonal variation in discharge and sediment load. During the dry season from October to March, the river basin receives little precipitation and about 30% of the total annual river discharge occurs. The discharge in the wet season from April to September comprises 70% of the annual discharge. Additionally, 90% of the sediment load is transported from the watershed to the coastal sea in the wet season, while only 10% is transported in the dry season.

Compared to other extensively studied estuaries in the world, the process of sediment dynamics in the HE is relatively less investigated. Yang (1993) studied the sources and transport pathways of sediment in the estuary using heavy minerals as indicators. Yang et al. (1995) investigated dynamics at the mouth shoal (sandy doorsill) and discussed the feasibility of dredging and maintaining deep navigational channels in the estuary. Wu (1995) examined the small scale hydrodynamic units and linked them with the erosion/deposition pattern. Yang et al. (1997) further investigated the morphological system and seabed erosion/deposition in the estuary.

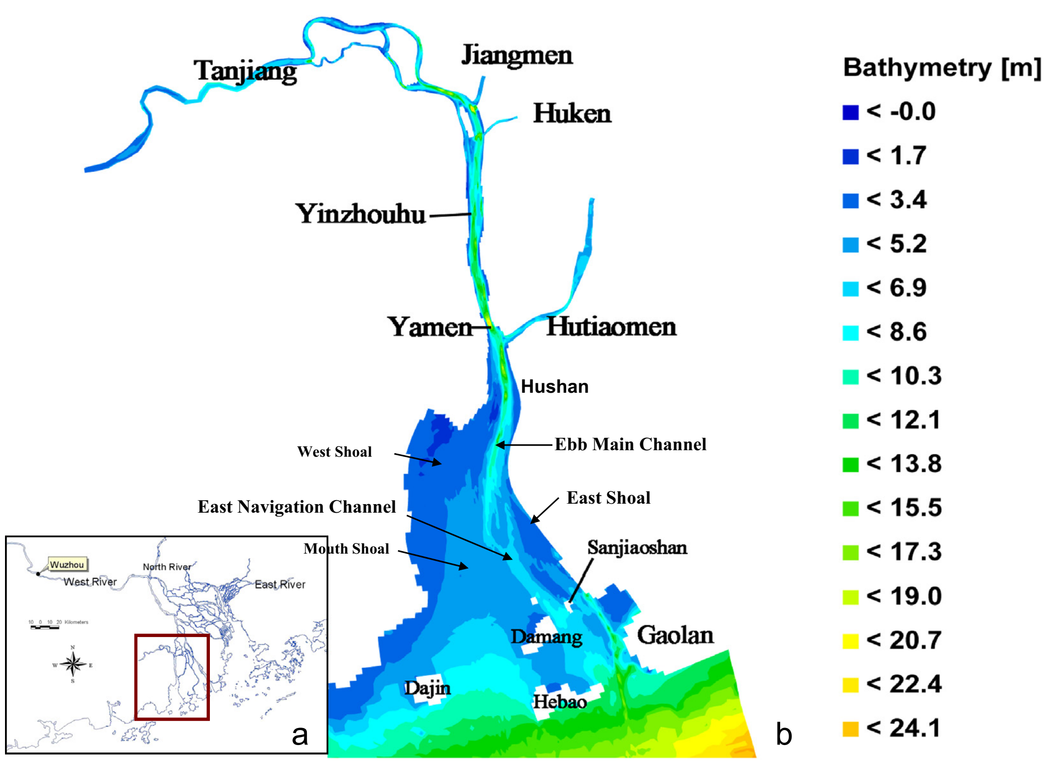

Fig. 1. The location of the Huangmaohai Estuary in relation to the Pearl River Delta (a), and the bathymetric features of the estuary (b).