Estuarine, Coastal and Shelf Science 177 (2016) 8–19

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Sediment trapping in the Changjiang Estuary: Observations in the North Passage over a spring-neap tidal cycle

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ARTICLE INFO

Article history:
Received 24 January 2016
Received in revised form
3 May 2016
Accepted 3 May 2016
Available online 6 May 2016

Keywords:
Changjiang Estuary
Deepwater navigation channel
Field observation
Residual sediment transport
Sediment trapping

ABSTRACT

Water current, salinity, and suspended sediment concentration (SSC) were measured at three anchored boat sites along the North Passage (NP) of the Changjiang Estuary over a spring-neap tidal cycle, in order to study sediment trapping and siltation in the estuary. Pronounced stratification was observed during the late flood tide and the following early ebb tide, along with an advancing and retreating salt wedge, whereas strong vertical mixing occurred during the late ebb when the effect of the salt wedge faded. Therefore, the SSC in the flood-ebb tidal cycle tended to be asymmetric. In the upper reach of the NP, the seaward advective near-bed sediment transport dominated the total near-bed sediment transport, whereas in the middle reach of the NP, the landward tidal pumping component dominated. Accordingly, a notable convergent near-bed residual sediment transport was generated near the middle reach. Because the convergence of residual sediment transport in the region of a salt wedge is generally recognized as sediment trapping, convergent near-bed residual sediment transport is the cause of the high sedimentation rate in the NP.

1. Introduction

The transport and trapping of fine-grained sediments in estuaries is controlled by various factors, such as river discharge, tidal dynamics, flow patterns, salinity stratification, and particle dynamics (Blake et al., 2001; Shi, 2004; He et al., 2008). The residual sediment transport is strongly affected by the estuarine circulation due to the movement of salt fronts (Schubel, 1968) and turbulent mixing due to the variations in intertidal stratification (Geyer, 1993).

The turbidity maximum (TM) is a prominent feature of suspended sediment transport, in which the suspended sediment concentration (SSC) is much higher than the concentration in the adjacent water upstream or downstream (Schubel, 1968; Geyer, 1993). The TM is closely related to sediment trapping in many estuaries, especially in those that are partially mixed (i.e., the salinity exhibits moderate variations with depth). The transport of fine suspended sediment is controlled by residual flux and flood-ebb tidal asymmetry, which ultimately generate a TM (Jay and Smith, 1990). In mesotidal estuaries, sediment trapping and convergence are mostly formed at the landward limit of the saltwater wedge, which develops when riverine freshwater and landward bottom saline water meet (Dyer, 1986). Based on observations in the Weser Estuary, Wellershaus (1981) noted that the TM moves up and down the estuary with the salt wedge. The dominant factor affecting the formation and maintenance of the TM varies in different estuaries depending on tidal dynamics, topography and stratification conditions (Dyer, 1986; Uncles, 2002), such as waves and freshwater inflow in the Tweed Estuary (Uncles and Stephens, 1997), tidal current in the Ouse Estuary during the summer months (Uncles et al., 2006a), and the interaction of antecedent freshwater flow with tidal range in the Trent Estuary (Mitchell et al., 2003).

Despite the complexity of sediment transport, much research on suspended sediment transport and the TM has been conducted in the Changjiang Estuary. Using the mechanism decomposition method, Liu et al. (2011) found that the near-bed landward residual transport of sediment in the North Passage (NP) is not only controlled by density-driven estuarine circulation but also by tidal asymmetry (i.e., the tidal pumping). Based on field observations, Wu et al. (2012) determined that high SSC events tend to occur in the NP at the early or late stages of the ebb tide. These authors also

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http://dx.doi.org/10.1016/j.ecss.2016.05.004
0272-7714/

demonstrated that the out-of-phase phenomenon is induced by the growth or degradation of flow spirals instead of the traditional assumptions implicating indirect processes such as sediment advection for maximum flow or a phase lag between the current and sediment transport. Song et al. (2013) suggested that gravitational circulation in an estuary resulted in spring-neap asymmetry during low-flow conditions, whereas the semidiurnal tidal movement of a salt front induced flood-ebb asymmetric stratification. Li et al. (2014) focused on residual sediment transport near a moving salt wedge and demonstrated that landward bottom sediment transport might be responsible for sediment trapping in estuaries in which the advection of a salt wedge dominates the stratification.

Saltwater intrusion is pronounced in the Changjiang Estuary in the dry season. When the salt wedge is present, the water column is strongly stratified (Shen et al., 2003). Because it controls chemical and physical processes such as flocculation and stratification, the salinity distribution is one important factor affecting suspended sediment transport. The location of the TM is related to the geographical position of the freshwater-saltwater interface (FSI), and the separation of the TM and FSI varies under different runoff and tidal forcing conditions (Uncles et al., 2006b). As a bifurcated estuary, the peak salinity in the Changjiang Estuary can be observed not only during the spring tide but also during the middle tide after spring tide (MTAS) in the South Passage (Wu et al., 2010) and the middle tide after neap tide (MTAN) in the North Channel (Li et al., 2014). Although numerous field observations have been conducted to study the sediment transport during spring and neap tides in the Changjiang Estuary (Chen et al., 2006; Liu et al., 2011), few have been deployed during the MTAS or MTAN. A comprehensive understanding of the variation of sediment transport in the NP necessitates field observations during all four stages of a spring-neap tidal cycle.

This study focused on the NP and the severe siltation in this area.

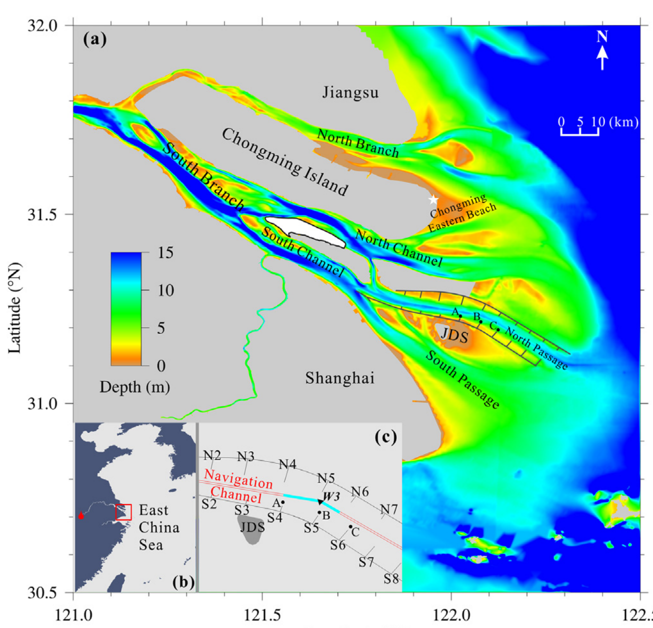

Fig. 1. (a): Topography of the Changjiang Estuary at three observation stations (A, B, and C) in the NP. The white star at the eastern beach of Chongming is the location of the weather station. (b): Location of the Changjiang Estuary. The Datong gauge station is represented by the red water drop. (c): The detailed structure of the DNC in which the red parallel lines indicate the 92 km long, deep channel. The most vulnerable silt area along the channel is the blue zone around node W3 (labeled with the black triangle).

Three boats (A, B, and C) were deployed to measure the currents, salinity and SSC near node W3 (Fig. 1). Our in situ observations were carried out during the spring tide, MTAS, neap tide, and MTAN in November 2013, with the objective to explore the process of sediment trapping in the NP. The temporal and spatial variations in sediment transport, as well as the associated residual transport, were examined using observational data.

The remainder of this paper is organized as follows. The observational method along with the analysis method is presented in Section 3. The observed results for the currents, salinity and SSC are described in Section 4. Section 5 discusses the importance of stratification and the subtidal sediment transport and is followed by the conclusion section.

2. Study area

The Changjiang Estuary is known for considerable river discharge, strong tides, and high SSCs. Four shallow waterways (i.e., North Branch, North Channel, NP and South Passage) are separated by intertidal flats at the 90 km-wide river mouth (Fig. 1). There is marked seasonal variation in the river discharge, with the lowest monthly mean value of 11,200 m^3/s in January and the highest monthly mean value of 49,700 m^3/s in July (Changjiang Water Resources Commission, data from 1950 to 2014). Normally, the ratio of high to low river discharge influences the extent of seasonal migration of the TM (Mitchell, 2013). It is a mesotidal estuary with a mean tidal range of 2.66 m and maximum of 4.62 m at the river mouth (Shen et al., 2003). The tide in the estuary exhibits semidiurnal, diurnal, and fortnightly spring-neap signals.

The Changjiang is the fourth largest river in the world in terms of sediment discharge (Milliman and Syvitski, 1992), with an annual mean sediment discharge of approximately 0.486 billion tons before the 1990s and 0.2 billion tons after the 1990s. Nearly half of the fine-grained sediments from the Changjiang basin are deposited in the estuary and on the subaqueous delta, resulting in massive sand bars with a minimum depth of 6 m below the mean lowest low water level that seriously limit the feasibility of navigation. To improve the navigation conditions in the sand bar area, the engineering project Deepwater Navigation Channel (DNC) along the NP began in 1998 and was completed in 2011. Two dikes (south dike: 48 km long, north dike: 49.2 km long) and 19 groins (total length: 30 km) were built to increase the current speed and decrease the sediment deposition in the main navigational channel, which was designed to be 92.2 km long, 350–400 m wide, and 12.5 m deep (Fig. 1c). As a consequence of this project, flow along the main navigational channel has increased, changing from a rotational current to an almost rectilinear current. Because of the dikes, the lateral sediment transport from the South Passage to the NP was reduced (Ge et al., 2012; Jiang et al., 2012). However, because the south dike was only 0.37 m above mean sea level, it was unable to block all south-to-north sediment transport from the Jiuduan Shoal (JDS in Fig. 1c). As a result of local terrain and bottom friction, flood waters tend to pass through the south dike between S6-S8 from the JDS during high tides, carrying concentrated benthic suspensions into the navigational channel via the shallow embayment. Overtopping sediment transport during flood tides across the south dike has been captured by many field observations (Xu et al., 2009; Liu et al., 2010).

The DNC project was planned and implemented in three phases. However, since the completion of the second phase in 2004, a siltation problem in the middle segment of the navigational channel began to draw attention. Much greater amounts of deposited material needed to be dredged in routine maintenance to safeguard navigation than the original estimate of 30 million m^3/year. The annual amount of deposited material dredged from the DNC