Estuarine, Coastal and Shelf Science 93 (2011) 192–201

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Tripod measured residual currents and sediment flux: Impacts on the silting of the Deepwater Navigation Channel in the Changjiang Estuary

Gaofeng Liu [a,b], Jianrong Zhu [a,*], Yuanye Wang [b], Hui Wu [a], Jiaxue Wu [c]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, North Zhongshan Rd. 3663, Shanghai 200062, P. R. China
[b] Shanghai Estuarine and Coastal Science Research Center, Xinsheng Road 1045#, Pudong District, Shanghai 201201, P. R. China
[c] Research Center of Coastal Ocean Science and Technology, Sun Yat-sen University, GuangZhou, Guangdong 510275, P. R. China

ARTICLE INFO

Article history:
Received 14 January 2010
Accepted 5 August 2010
Available online 13 August 2010

Keywords:
changjiang estuary
bottom-mounted tripod
residual currents
sediment trapping and resuspension
sedimentation
deepwater navigation channel

ABSTRACT

Four bottom-mounted instrument-equipped tripods were deployed at two sections spanning the region characterized by severe sedimentation rates in the Deepwater Navigation Channel (DNC) along the North Passage of Changjiang Estuary in order to observe currents, near-bed suspended sediment, and salinity. Seaward residual currents predominated in the up-estuary section. In contrast, a classical two-layered estuarine circulation pattern occurred in the down-estuary section. Flow moved seaward in the upper layer and a heavier inflow, driven by the salinity gradient, moved landward in the lower layer. The near-bed residual currents in the up-estuary section and the down-estuary section acted in opposing directions, which implies that the region is a convergence zone of near-bed residual currents that trap sediment at the bottom. The maximum salinity gradient at the maximum flood current indicates the presence of a strong front that induces sediment trapping and associated near-bottom convergence of sediment, which explains the high sedimentation rates in this section of the estuary.
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1. Introduction

An estuarine turbidity maximum (ETM), where the suspended sediment concentration (SSC) is very high, is observed in many estuaries of the world (Shen and Pan, 2001; Shi, 2004; Talke et al., 2009). Residual circulation and flood/ebb tidal asymmetry are the major mechanisms controlling the transport of fine suspended sediment and generating an ETM (Schubel, 1968; Officer, 1981; Jay and Smith, 1990). Residual currents can be produced by river discharge, wind drag on the sea surface, a nonlinear effect caused by flow separation of the tidal current due to a complicated coastline (Zimmerman, 1981), tidal asymmetries in stratification and mixing (Jay and Musiak, 1994; Scully and Friedrichs, 2007), horizontal density gradients due to non-uniform salinity or temperature distributions (Johns and Robinson, 1983; Wong, 1994; Friedrichs and Hamrich, 1996), turbidity gradients due to suspended sediment (Talke et al., 2009), and other mechanisms. When freshwater discharged from a river meets the heavier salty water at the sea, a saltwater wedge is developed near the river mouth, and a gravitational residual circulation usually occurs within this section (Li et al., 1994; Pan and Sun, 1995; Shen and Pan, 2001; Wu and Guo, 2004). A saltwater wedge can induce sediment trapping and convergence. Trapping of suspended sediment around the front at an ETM is a well-known phenomenon (Glangeaud, 1938; Meade, 1969).

A density gradient introduces small but significant tidally averaged residual velocities that involve counter-flowing down-estuary and up-estuary components in the lower and upper parts of the water column (Prandle, 2004). In general, the velocities of residual currents are one or two orders of magnitude less than those of the tidal streams (Johns and Robinson, 1983), but persistent advection of residual currents dominates net transport and they are partly responsible for long-term transport of materials, such as salt, pollutants, and sediment (Codiga and Aurin, 2007).

One of the most challenging problems occurring in the Changjiang Estuary is severe silting in the Deepwater Navigation Channel (DNC) in the North Passage (Fig. 1a). Since the completion of the DNC, the annual amount of dredging required to maintain the DNC from 2006 to 2008 was far greater than the original estimation of 30 million m^3 (Wu and Guo, 2004). Detailed descriptions of this estuary, engineering constructions, and the silting problems are introduced in Section 2. Qi et al. (2005) proposed some mechanisms to explain the causes of silting, but they did not consider the influences of residual current, sediment trapping, and thereby sediment flux. The residual characteristics and trapping processes in Changjiang Estuary have received little research attention to

* Corresponding author.
E-mail address: jrzhu@sklec.ecnu.edu.cn (J. Zhu).

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doi:10.1016/j.ecss.2010.08.008

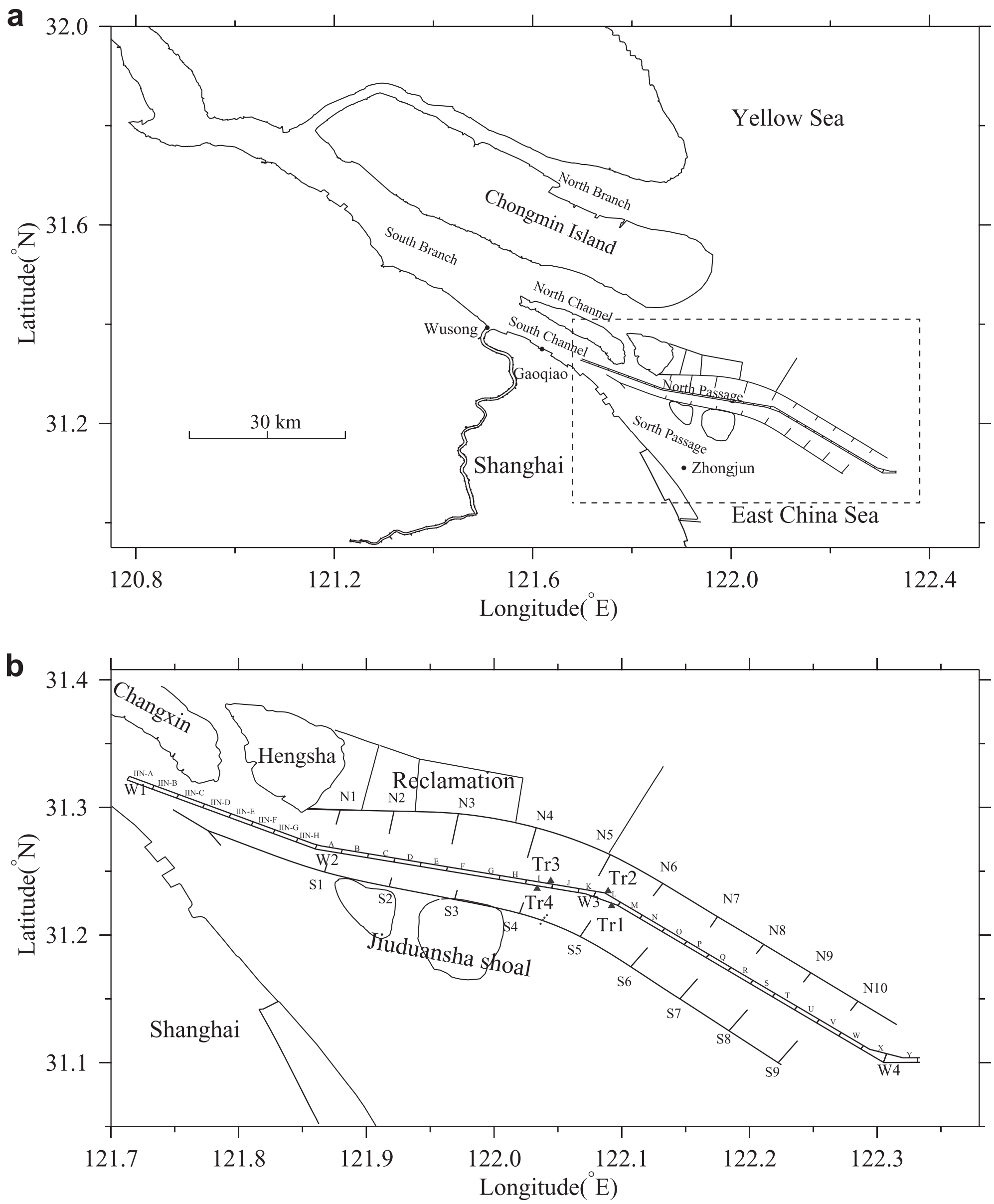

Fig. 1. The study area location showing (a) the Changjiang Estuary and the Deepwater Navigation Channel project and (b) four observation stations that are located near the node W3. Stas. Tr1 and Tr2 were located on the down-estuary side of node W3, while Stas. Tr3 and Tr4 were located on the up-estuary side of node W3.

date, but we propose that they play a key role in determining the sedimentation within the DNC.

2. Study area

The Changjiang River is the largest river in China and the fourth largest in the world in terms of water discharge and sediment load (Chen et al., 2001; Yang et al., 2007). The Changjiang Estuary is a multi-channel estuary with a three level bifurcation. Four outlets, which are separated by islands or shoals, are present at the river mouth (Fig. 1a). The Changjiang Estuary is characterized as a mesotidal estuary in terms of tidal range (Shen et al., 2003). The mean (and maximum) tidal range is 2.66 m (4.62 m) at Zhongjun near the river mouth (Fig. 1a) and decreases up-estuary to 2.43 m (3.96 m) at Gaoqiao and 2.21 m (4.48 m) at Wusong in the South Channel (Wu et al., 2009).

The Changjiang Estuary is partially mixed and has a significant freshwater discharge. Annually averaged river discharge is estimated to be $\sim$29,300 m^3/s at the Datong gauging station, which lies about 640 km up-estuary from the river mouth (Shen et al., 2003). Annually averaged SSC at the Datong station is estimated to be $\sim$0.48 kg/m^3, and the diameter of suspended sediment in the North Passage ranges from 0.006 to 0.4 mm, with an average of about 0.01 mm (Shen and Pan, 2001). The total sediment discharge is approximately 0.486 billion tons annually (Li et al., 1993), which is about 2.7% of the entire world's annual suspended sediment transport (Shen and Pan, 2001). About half of the fine-grained sediments from the Changjiang River Basin are deposited in the estuary and on the subaqueous delta (Chen et al., 1985). The latter forms a large area of sand bars with a minimum depth of 6 m below the mean lowest low water level (MLLWL) and seriously limits the access of large vessels into the Changjiang River (Wu et al., 2006). Sediment discharge has been reduced dramatically because of

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