ARTICLE IN PRESS

Journal of Marine Systems xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Marine Systems

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

An analysis on half century morphological changes in the Changjiang Estuary: Spatial variability under natural processes and human intervention

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ARTICLE INFO

Keywords:
Changjiang Estuary
Morphological evolution
Sediment supply

ABSTRACT

Examination of large scale, alluvial estuarine morphology and associated time evolution is of particular importance regarding management of channel navigability, ecosystem, etc. In this work, we analyze morphological evolution and changes of the channel-shoal system in the Changjiang Estuary, a river- and tide-controlled coastal plain estuary, based on bathymetric data between 1958 and 2016. We see that its channel-shoal pattern is featured by meandering and bifurcated channels persisting over decades. In the vertical direction, hypsometry curves show that the sand bars and shoals are continuously accreted while the deep channels are eroded, leading to narrower and deeper estuarine channels. Intensive human activities in terms of reclamation, embankment, and dredging play a profound role in controlling the decadal morphological evolution by stabilizing coastlines and narrowing channels. Even though, the present Changjiang Estuary is still a pretty wide and shallow system with channel width-to-depth ratios > 1000, much larger than usual fluvial rivers and small estuaries. In-depth analysis suggests that the Changjiang Estuary as a whole exhibited an overall deposition trend over 59 years, i.e., a net deposition volume of $8.3 \times 10^8\,m^3$. Spatially, the pan-South Branch was net eroded by $9.7 \times 10^8\,m^3$ whereas the mouth bar zone was net deposited by $18 \times 10^8\,m^3$, suggesting that the mouth bar zone is a major sediment sink. Over time there is no directional deposition or erosion trend in the interval though riverine sediment supply has decreased by 2/3 since the mid-1980s. We infer that the pan-South Branch is more fluvial-controlled therefore its morphology responds to riverine sediment load reduction fast while the mouth bar zone is more controlled by both river and tides that its morphological response lags to riverine sediment supply changes at a time scale > 10 years, which is an issue largely ignored in previous studies. We argue that the time lag effect needs particular consideration in projecting future estuarine morphological changes under a low sediment supply regime and sea-level rise. Overall, the findings in this work can have implications on management of estuarine ecosystem, navigation channel and coastal flooding in general.

1. Introduction

Morphological evolutions are critical for socio-economic and ecological environmental development, especially in estuaries where most of the world's famous mega cities and harbors locate. The combined action of fluvial discharge, tidal flows, and waves generally controls the long-term estuarine morphological changes, resulting in a feedback loop between estuarine morphology and hydrodynamics through sediment transport (Cowell and Thom, 1994; Freire et al., 2011; Wang et al., 2013). Morphological evolution of large estuaries influenced by more than one primary forcing are insufficiently understood owing to inherent complexity in terms of large space scale and strong spatial and temporal variations. In addition, anthropogenic activities, such as waterway regulation project, dredging, embankment, reclamation, and dam construction, have profound effects on estuaries and human interventions play an increasingly important role in driving estuarine morphological changes (Milliman et al., 1985; Syvitski et al., 2005; Wang et al., 2013). Centennial bathymetric data of estuaries are rare while data at decadal time scales are readily more available, enabling quantitative examinations of medium- to long-term (decades to centuries) estuarine morphological evolution in response to natural forcing and human influences.

Morphological evolution and channel pattern changes in rivers, tidal basins, estuaries, and coasts have been broadly discussed at varying time scales. The depositional and morphologic patterns can be quite different under varying single or multiple primary forcing

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https://doi.org/10.1016/j.jmarsys.2018.01.007
Received 4 May 2017; Received in revised form 17 January 2018; Accepted 19 January 2018

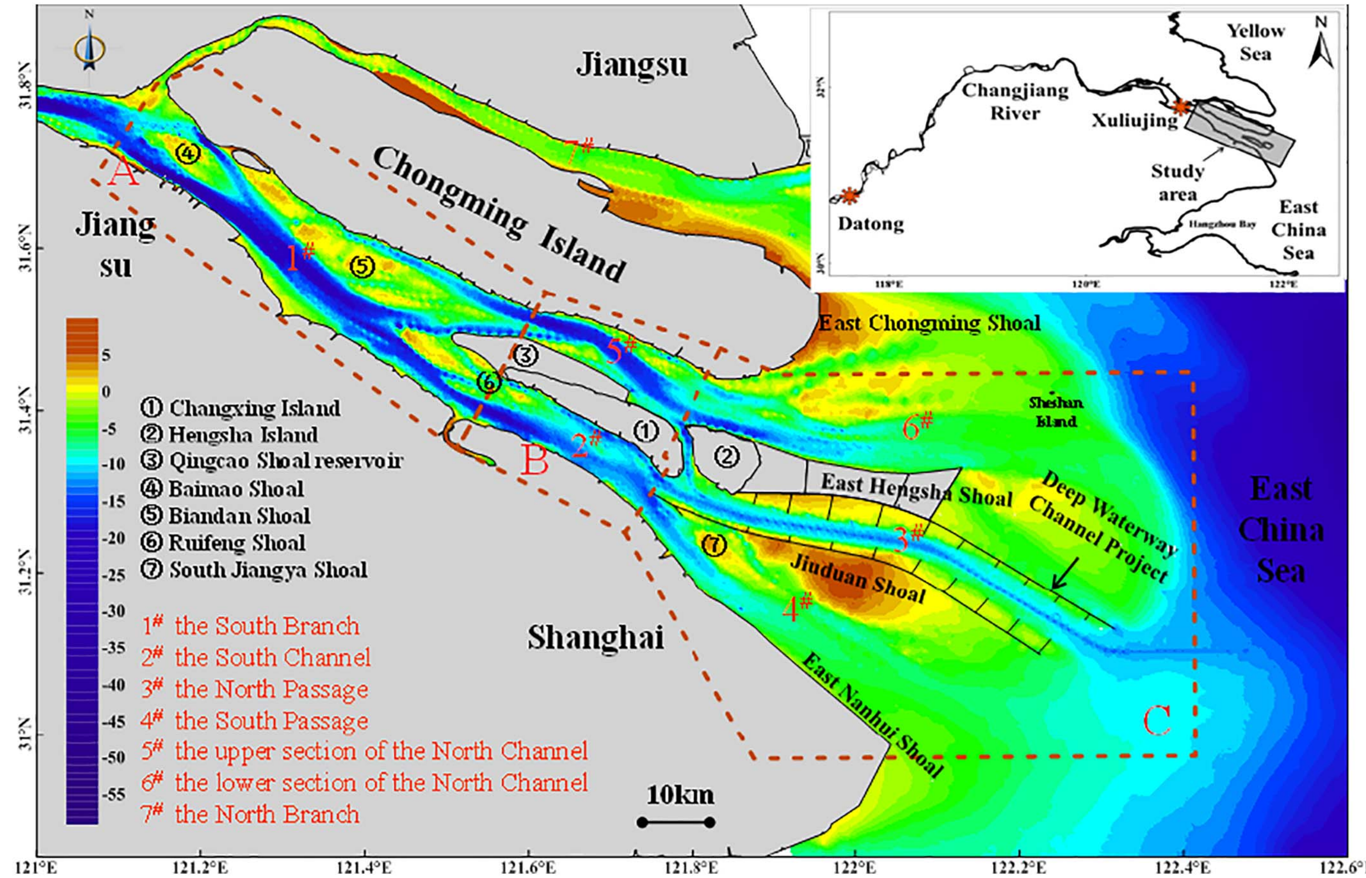

Fig. 1. A sketch map of the study area and division of different branches in the Changjiang Estuary with its bathymetry (depth in meters) in 2016. The whole study area is divided into three parts by brown solid lines, i.e., region A (the South Branch (1#)), region B (the South Channel (2#) and the upper section of the North Channel (5#)), and region C (the North Passage (3#), the South Passage (4#), and the lower section of the North Channel (6#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

including river, tides, waves, etc. (Wright, 1977). A meandering channel pattern with coexisting flood and ebb channels is observed in tide-dominated systems, such as the Dutch Western Scheldt Estuary (Van Veen et al., 2005; Van den Berg et al., 1996; Toffolon and Crosato, 2007) and the Chesapeake Bay in the USA (Ahnert, 1960). Distributary channels with multiple bifurcations are observed in river-controlled estuaries and/or delta systems (Andrén, 1994; Edmonds and Slingerland, 2007; Wang and Ding, 2012). Large scale morphodynamic behavior under combined river and tidal forcing, such as the Changjiang Estuary in China, is insufficiently examined (Guo et al., 2014, 2015).

Morphological evolution of the Changjiang Estuary has been examined by calculating erosion-deposition volumes and analyzing movements of isobaths, shorelines, and thalwegs (Chen et al. 1985 and 1999; Yun, 2004; Wang et al., 2013; Luan et al., 2016). Riverine sediment source availability and human activities are widely seen as two important factors in controlling morphological evolution in the Changjiang Estuary, which is also true in other estuaries and deltas such as Niles, Mississippi, and Colorado (Syvitski and Kettner, 2011). Note that previous examinations of the morphological changes in the Changjiang Estuary were mainly at regional scale without taking the estuary as a whole into consideration. For instance, owing to riverine sediment supply reduction, regional erosion was detected in the South Branch (Wang et al., 2013) and the delta front regions (10 m deep nearshore) (Yang et al., 2003, 2005, 2011) in the recent decades, whereas the examination of a larger region including the sand bars in the mouth bar zone indicates continued deposition (Dai et al., 2014). Moreover, the time scale of large scale estuarine morphodynamic adaptation in responding to external forcing changes is very much ignored in previous studies. The morphological impacts of human activities such as reclamations (Chu et al., 2013; Wei et al., 2015) and the Deep Waterway Channel Project along the North Passage (De Vriend et al., 2011; Jiang et al., 2012, 2013) can also vary in a large space and time scales depending on their location, implementation time, and scales. Sea-level rise is also another factor needs consideration (Wang et al., 2013; Wang et al., 2014; Wei et al., 2015). So far, a comprehensive and quantitative investigation of morphological evolution in the entire Changjiang Estuary is still very much needed.

This study analyzes the morphological changes in the Changjiang Estuary as a whole based on the bathymetric data collected in the period between 1958 and 2016. We will focus on the erosion-deposition processes, changes of hypsometry, and cross-section configuration of different branches in the estuary to elaborate the channel patterns and the spatial and temporal variability of the estuarine morphology. The controls of the morphological changes are discussed in terms of natural processes and human activities. The insights obtained from this study are helpful for management and restoration opportunities in the Changjiang Estuary.

2. Data and methods

2.1. Brief introduction to the Changjiang Estuary

The Changjiang River and its estuary is one of the biggest on earth with respect to its quantity such as river discharge, sediment load, and space scales. The annual mean river discharge is approximately $28.3 \times 10^3\ m^3/s$ (1950–2015) and annual sediment load is 3.7×10^8 tons (1953–2015) (CWRC, 2015). The river and sediment