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Morphological evolution of the South Passage in the Changjiang (Yangtze River) estuary, China

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ABSTRACT

Estuarine morphology of the world's major large rivers have experienced great changes due to intensive anthropogenic activities and natural forcings, especially in the Changjiang Estuary located at the end of the longest river in Asia. This study focuses on morphological changes of the South Passage (SP), which is one of the 4 channels in the branching estuary at the mouth of the Changjiang (Yangtze River), China. A multivariate analysis technique of Empirical Orthogonal/Eigen Function (EOF) method was used to examine the major modes of change in the long-term (over 26 years) water-depth data. The results show that the morphological changes at the SP could be divided into two stages: between 1987 and 1997, the SP had a single stable channel with closure of a cross-channel. Between 1997 and 2012, SP displayed southeastward elongation of a spit into the main channel, and westward shoal incision by a cross-channel. The opening of the SP developed a two-channel morphology, which stabilized and showed infilling during 2003–2012. The average deposition rate was 10 cm/yr. In the past 30 years, the most dominant morphological changes of SP included the deposition around the upstream opening of the channel. The second most important pattern of morphological change was related to the downstream elongation, retreat, and lateral migration of the spit of the Jiangyanan Shoal, which resulted in the two-channel configuration of the SP. Additionally, these morphological changes were not triggered by the decline of the distal sediment source from the upstream, but due to the input of proximal sources of the shoal at the upstream opening of the SP and spill-over sediment from the North Passage via a short-cut-channel.

1. Introduction

Estuaries are located in the narrow zone of the land-sea boundary, which are valuable areas of both local and global importance. The morphology of estuaries is closely linked to estuarine assets such as natural location to ports (Van der Wegen and Roelvink, 2008). The morphological formation and evolution of estuaries is relatively gradual and has a typical decadal timescale. Small-scale sea-level fluctuations may trigger drastic changes (Dyer, 1997). However, in the last century the gradual development of many estuaries and adjacent area has been interrupted by human activities (Lane, 2004; Kao and Milliman, 2008; Evans, 2012; Gong et al., 2012; Li et al., 2012). Such practices include for example, damming of the river, construction of dikes and groins in the river mouth, and land reclamation (Chu et al., 2009; Syvitski et al., 2009; Dai and Lu, 2010; Evans, 2012).

The reduction of river load due to damming is the cause for risks of erosion and inundation in many estuaries and deltas in the world (Walling and Fang, 2003; Syvitski et al., 2005). A well-known example is the Nile delta. Because of the Aswan Dam, the erosion rate for the area around Rosetta Promontory was 10×10^6 m^3/y (Inman and Jenkins, 1984). Because of the construction of the dam at Adana, the nearby Seyhan delta in Turkey has the erosion rate of 1×10^6 m^3/y Gagliano et al. (1981) estimated the land loss around the mouth of the Mississippi was 102.1 km^2 in 1980, which was higher than those of 1987, 1946, and 1913 at 72.8, 40.9, and 17.4 km^2/y, respectively. Compared to the previous century, the Ebro River in Spain lost 99% of its load due to the constructions of dams and reservoirs (Gullén and Palanques, 1997). The Danube lost 35% of its load due to dam construction that led to the erosion at the river mouth (Milliman and Farnsworth, 2011). Since 1941, the sediment load in the Colorado River declined by almost 100%,

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which caused irreversible damages to its delta (Pitt, 2001). Because of the sediment load reduction, the Niger delta suffered a recession rate of 10 m/y (Ibe, 1996). All of the examples above point to the link between reduction in the river sediment load and the erosion in the estuary, and shoreline recession of the delta at the river mouth.

However, due to the various physiographic characteristics of the river catchment (such as the nature of topography and river bed, spatial scale of the catchment, and degree of human disturbance), the change of suspended sediment load in the upper reaches of a river might not be directly reflected by the load in the lower reaches (Brizga and Finlayson, 1994; Phillips et al., 2004). For example, no dam-related changes in alluvial sedimentation are noticeable in the lower river reaches of southeast Texas, despite large reservoirs control 75–95% of the drainage area, and retention of massive amounts of water behind dams (Phillips, 2003; Phillips et al., 2004). Channel dredging and jetty construction caused the Mersey Estuary lost 0.1% of its volume in the past 150 years (Lane, 2004). Conversely, because of the retaining walls, a large amount of sediment has accumulated in the middle of the Lune Estuary (Spearman et al., 1998). Furthermore, morphological changes of a river mouth and its adjacent coast could also be caused by land reclamation, dredging of navigational channels, relative sea-level rise, and littoral drift (Phillips and Slattery, 2006; Van Landeghem et al., 2009; Evans, 2012). Under multiple influences of the changes in the river runoff and sediment load, changes in the local environment, engineering practices, and changes in the estuarine hydrodynamics, the morphological evolution of an estuarine is complex, and needs a comprehensive approach in the analysis.

The estuary of the Changjiang is located at the end of the longest river in China. The width of the river mouth is almost 100 km wide (Fig. 1). At the river mouth, the mean tidal range is 2.67 m, and the mean flow rate is 1 m/s (Dai et al., 2013a). Three islands, Chongming, Hengsha, and Jiuduan Shoal divide the mouth into 4 channels of North Branch, North Channel, North, and South Passages (Fig. 1b). In the past century, the river mouth has been prograding seaward (Chen et al., 1985). Because of extensive land reclamation, the North Branch has become a tidally dominated estuary (Yun, 2004). Due to the engineering project to maintain a deep navigational channel, the North Passage has become an artificially controlled estuarine channel (Dai et al., 2013a) (Fig. 1). The engineering project started in January 1998 (Fan and Gao, 2009), which consisted of four parts: the river diversion, construction of north and south jetties along the channel, and dredging of the thalweg. The first stage of the project completed in June 2001, which achieved the diversion of the river flow, partial completion of the jetties, and the navigational channel reached 8.5 m depth. The second stage began in May 2002 and lasted until March 2005, in which the jetties with the attached groins along the length of the N. Passage were completed and the navigational channel reached 10 m depth. The last stage commenced in September 2006 and was completed in March 2010, in which the dredging was the main focus and the navigational channel reached 12.5 m depth. Upon the completion of the channel improvement and maintenance project, the deep-water navigation channel was 92.2 km long, 350–400 m wide, having the thalweg depth of 12.5 m (Fan and Gao, 2009; Fan et al., 2012; Dai et al., 2013a) (Fig. 1).

The world's largest dam, the Three Gorges Dam (TGD), located in the upstream of the Changjiang, became operational in 2003. The measured suspended sediment discharge (SSD) at Datong (the upper limit of the tidal river) dropped sharply to 2.06×10^8 and 1.47×10^8 in 2003 and 2004, respectively, in comparison to over 4.2×10^8 t/y before the 1970s (BCRS, 2010, 2011). In 2006, and 2011, the sediment delivered to the sea declined further to be 0.84×10^8, 0.72×10^8 t/y (BCRS, 2010, 2011). Whether the drastic reduction of sediment load is going to trigger erosion or the progradation of the

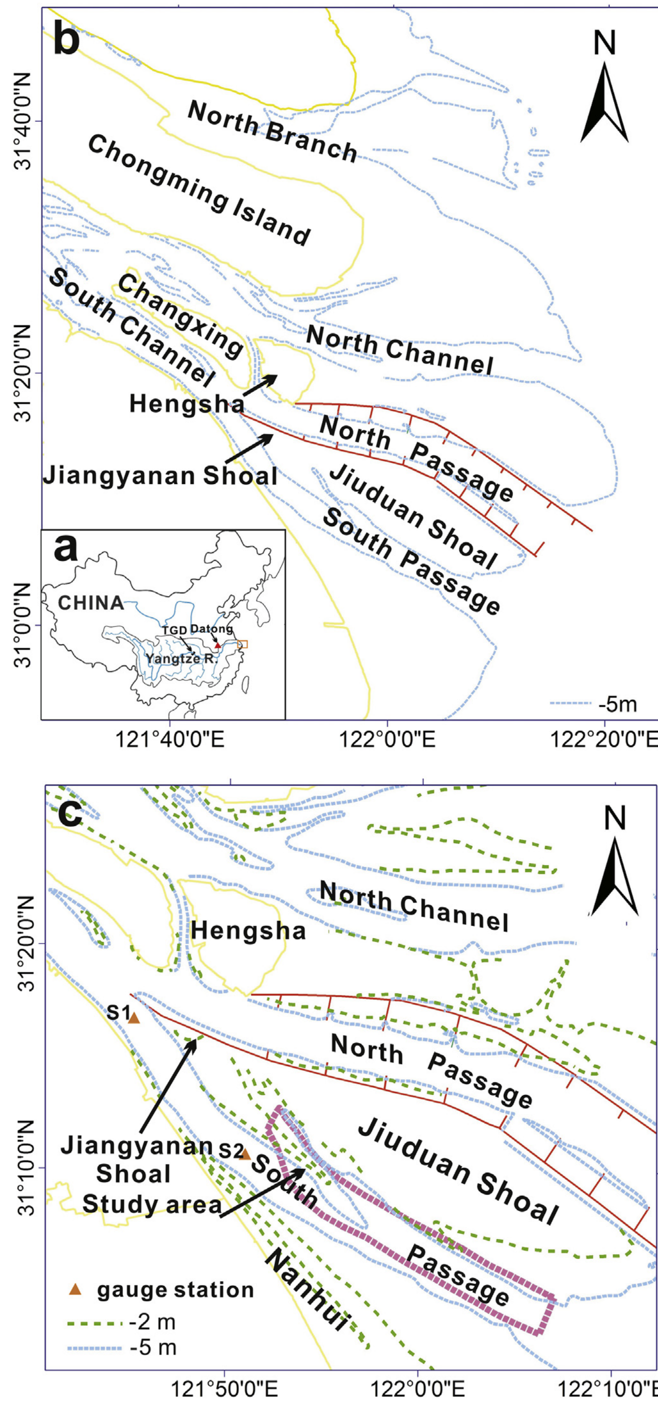

Fig. 1. Maps showing: a. the location of the study area in relation to the China; b. the morphological units at the mouth of the Changjiang based on the 2006 navigational chart; c. the location of the SP and the study area is marked by dashed lines.

Changjiang estuary delta will continue has been an international dispute (Liu et al., 2007; Yang et al., 2007, 2011; Syvitski et al., 2009; Wang et al., 2009; Chen et al., 2010; Dai et al., 2013b; Wang et al., 2013). Based on local cross-sectional changes in the estuary, Yang et al. (2007) found that the reduction of the river sediment load of the Changjiang is the reason for the erosion of estuarine wetlands. However, from the analysis of the morphological changes of the shipping channel along the North Passage, Dai et al. (2013a) found deposition in the peripheral groin fields along the shipping