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Decadal changes in bathymetry of the Yangtze River Estuary: Human impacts and potential saltwater intrusion

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A B S T R A C T

This study analyzed bathymetric changes of the 77-km Yangtze River Estuary in China over the past ten years in order to understand the impacts of recent human activities on the estuary of a large alluvial river. Morphological changes were assessed by analyzing digitized bathymetric data of the estuarine channels from 2002 to 2013. Additionally, multi-beam bathymetric measurements made in 2012, 2014 and 2015 were utilized to investigate microtophographic bedforms of the lower reach of the estuary. Our results showed that the middle and upper reaches of the Yangtze River Estuary experienced substantial channel bed erosion in the past 10 years, and that the recent human activities have contributed to the change. These included the construction of a 70 km^2 reservoir along the Yangtze River Estuary, the Qingcaosha Reservoir, for drinking water supply for the City of Shanghai, which has caused progressive bed erosion in the North Channel. The net volume of channel erosion in the Hengsha Passage from 2002 to 2013 was 0.86×10^8 m^3. A large amount of the eroded sediment was trapped downstream, causing overall accretion in the upper reach of the North Passage. The middle and upper reaches of the South Passage also experienced intense erosion (0.45×10^8 m^3) in the past ten years, while high accretion occurred in the lower reach because of the Deepening Waterway Project. The channel dredging left a large range of dredging marks and hollows in the North Passage. The increasing saltwater intrusion found in the Yangtze River Estuary may have been a consequence of either dredging or erosion, or both combined.

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1. Introduction

Many estuaries in the world have been interrupted by human activities, such as the damming of the river, building of reservoir and dredging for waterway (Blott et al., 2006; Benedet and List., 2008; Talke et al., 2009; Day et al., 1989). Remarkable consequences of these human activities in estuaries include morphological changes of the channel beds and saltwater intrusion; they have therefore been the foci of several scientific enquiries (Thomas et al., 2002; Nichols and Howard-Strobel., 1991; Gong et al., 2012).

Several studies have indicated that human activities could have pronounced effects on estuarine hydrodynamics and morphology. For instance, in the Ems Estuary in Germany, the estuarine dynamics and the erosion and sedimentation process were affected, pushing the position of the turbidity maximum zone upstream because of channel dredging (De Jonege et al., 2014). Due to the construction of the Aswan Dam, annual erosion rate for the area around Rosetta Promontory was reported to be 10×10^6 m^3 in the Nile delta (Inman and Jenkins., 1984). Lane (2004) reported that the volume of the Mersey Estuary in UK decreased by 0.1% in the past 150 years because of channels dredging and construction of retaining walls.

Seawater intrusion has been found to have intensified across the world in the recent decades due to human activities (Savenije, 2005; Barlow and Reichard., 2010). For instance, Yuan and Zhu (2015) found that dredging in the Pearl River estuary in China has strongly affected saltwater instruction. Omar et al. (2016) reported that over-pumpage of aquifers in the Mediterranean region has led to intensified seawater intrusion. However, few studies have investigated human effects on channel morphology of large alluvial river estuaries, such as the Yangtze River Estuary in China.

The Yangtze River Estuary is a continental-scale alluvial estuary, which has gone through many physical alterations for flood control, navigation, port construction, and urban development of the City of

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Shanghai, the most vibrant and largest economy in China. Shanghai is located near the Yangtze River Estuary and the Yangtze River is the major source of freshwater supply for the city. There are four large drinking water reservoirs within the estuary area that provide freshwater for about 50 million people living on the Yangtze River Delta. Like other tidal-controlled estuaries, the Yangtze River Estuary has been found to be affected by saltwater intrusion in recent years (Cheng and Zhu., 2013). This has raised serious concerns over freshwater supply (Wu and Zhu., 2010; Li et al., 2012a; Mao et al., 2001) and future economic development in the region (Chen et al., 2016).

Human interventions in the Yangtze River basin, e.g., the construction of the Three Gorge Dam (TGD) in the middle reach of the Yangtze River, have changed flow conditions in the river's lower reach and estuary (Zhang et al., 2009). In the recent decade, two large engineering projects - the Yangtze estuarine Deepening Waterway project and the Qingcaosha Reservoir project - may have particularly affected the morphology of the Yangtze River Estuary. Several studies (Jiang et al., 2012; Li et al., 2008; Liu et al., 2005; Dai et al., 2013) reported a morphological change of several sand bars of the Yangtze River mouth. However, very few studies have investigated changes across the entire lower estuary reach. Little is known for other parts of the large Yangtze River Estuary impacted by human interventions. In general, there is a knowledge gap as to how the Yangtze River Estuary channel has changed in the recent decade and whether these changes have played a role in saltwater intrusion. A study focusing on such a nature-human coupled complex system has important significance for improving our knowledge of human effects not only on the Yangtze River Estuary but also on other alluvial river estuaries in the world. Such knowledge can be crucial for developing effective management plans for coastal protection against sea level rise, erosion and land loss.

This study aimed to assess the recent morphological changes of the channel beds using bathymetric survey charts, high-resolution multi-beam data, river discharge and sediment load data. The primary goal was to document bathymetry change in the Yangtze River Estuary in order to understand the relationship between human activities and the channel morphology, as well as the potential risk of saltwater intrusion. Results gained from this work can be useful for river channel morphology research, river water management and coastal protection. It can also serve as an example for the remediation and development of other estuaries under similar natural and anthropogenic influences.

2. Methods

2.1. Study area

Draining a land mass of approximately 1.8 million km^2, the Yangtze River (Fig. 1) is the world's fourth largest river in terms of sediment load (Yang et al., 2005). There is a tidal influence in the Yangtze River extending 650 km upstream. The last 120 km section of the estuary below Xuliujing shows a three-consecutive bifurcations with four outlets. It is first divided into the South and North Branches by the Chongming Island (Fig. 1). The South Branch is then divided into the South and North Channels by the Changxing Island and the Hengsha Island. The South Channel is again divided by the Jiuduan Shoal into the South and North Passages. The mouth bar section is geographically located between 121°45′-122°30′ E and 30°45′-31°45′ N (Fig. 2A). The turbidity maximum zone exists in the river mouth-bar area all year round, with high solid concentrations due to the interaction of freshwater and tidal flows (Chao et al., 2015; Li and Wu., 2011).

Long-term discharge at Datong Hydrological Gauging Station, located about 600 km upstream from the river mouth, averaged

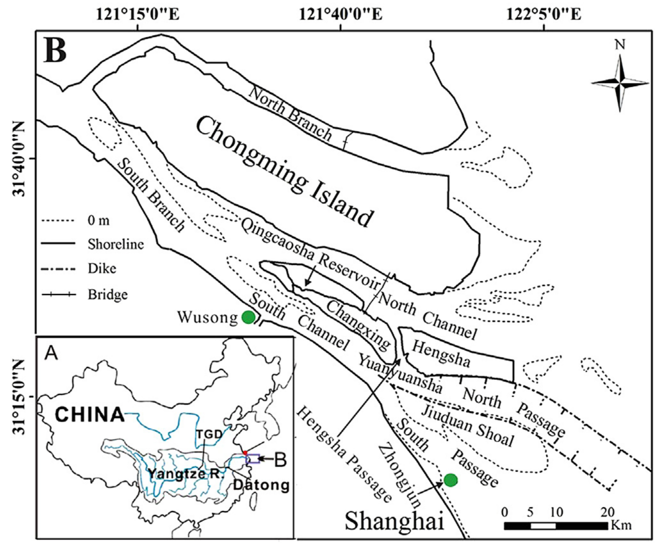

Fig. 1. Geographical location of the study area – the Yangtze River Estuary in China, with the Chongming, Changxing and Hengsha Islands, the Jiuduan Shoal, the South and North Branches, the South and North Channels, the South and North Passages, and the Hengsha Passage.

29 300 m^3/s (Cheng et al., 2004). The river flow fluctuates seasonally, generally low in January or February (dry season) and high during July or August (wet season) (Pu et al., 2015). The annual mean suspended sediment load from the Yangtze River from 1956 to 2009 was 388.6 million tons (Jiang et al., 2012). It has been estimated that 40% of the annual sediment load is deposited in the Yangtze River Estuary (Zhu et al., 2015). The sediment deposit in the Yangtze River Estuary is mainly composed of fine sand, silt and clay (Liu et al., 2010).

The Yangtze River Estuary is characterized as a mesotidal estuary in terms of tidal range (Wu et al., 2009). Tides are regular semi-diurnal out of the mouth, and non-regular semi-diurnal inside. The long-term mean tidal range at Zhongjun Station nearby the mouth is about 2.67 m, with a tidal velocity amplitude of approximately 1 m/s (Yang et al., 2015a).

2.2. Bathymetric data collection

Digitized bathymetry-derived Digital Elevation Model (DEM) has become a useful tool to study morphological changes of estuaries (Thomas et al., 2002; Lane, 2004; Blott et al., 2006; Jaffe et al., 2007). In order to investigate the morphological changes in the Yangtze River Estuary, the bathymetric surveys have been carried out by the Changjiang Estuary Waterway Administration Bureau (CJWAB), Ministry of Transportation. The digital survey charts of 2002 and 2007 were used in this study. The bathymetric survey charts for 2010 and 2013 in the South and North Channels, and the South and North Passages, provided by Shanghai Estuarine & Coastal Science Research Center, were also used in this study. The marine charts of 2012 in the North Channel and 2013 in the Hengsha Passage, provided by Maritime Safety Administration of the People's Republic of China (PRC), were also used to investigate the morphological changes. The marine charts (1:15 000 scales) were digitalized and used in our GIS analysis (Table 1).

The long-term discharge and sediment load monitored at the Datong station located at the landward limit of the tidal river between 2002 and 2013 published in the Yangtze River Sediment Bulletin, were used to interpret the cause of the morphological changes in the study area.

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