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Response of the turbidity maximum zone to fluctuations in sediment discharge from river to estuary in the Changjiang Estuary (China)

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ABSTRACT

In the Changjiang Estuary, interactions between the sea and the river result in the development of a turbidity maximum zone (TMZ). Riverine sediments are an important source for TMZ formation. Since the 1960s, sediment discharge from the river basin to the estuary has decreased due to dam construction, water and soil conservation, and water diversion projects. Thirty-two Landsat images of the estuary, covering the period from 1979 to 2008, were collected to identify the TMZ response to sediment decline. A threshold value of suspended sediment concentration (SSC) of 0.7 kg/m^3, corresponding to a spectrum reflectance of 5% of Landsat MSS band 7 and 7% of Landsat TM/ETM band 4, was used to identify the Changjiang Estuary TMZ. The TMZ area was then extracted from each image to investigate its temporal and spatial variations during the past 30 years. The images were grouped into five time series; the average TMZ area of each series was estimated. The results show that the TMZ area declined 23% from series (a) to series (e), responding to a 77% reduction in riverine sediment discharge. In addition, the TMZ had strong seasonal and tidal variations; it was generally larger during flood seasons than during dry seasons and during spring tides compared to neap tides. The spring/neap tidal cycle played a more important role in TMZ change than did the seasonal cycle. Due to the continued reduction of sediment discharge to the estuary resulting from dams already constructed and to those that will be constructed upstream in the Changjiang River, it is predicted that the TMZ area will continue decreasing and that the re-suspension of local sediments will play a more important role in the formation of the TMZ.

1. Introduction

A TMZ is the region in an estuary where the suspended sediment concentration (SSC) is greater than in the surrounding area (Schubel, 1968; Li and Zhang, 1998). The TMZ has been observed and studied in many estuaries, including Gironde Estuary in France (Doxaran et al., 2006), Chesapeake Bay and Hudson Estuary in the USA (Schubel, 1968; Bokuniewicz and Arnold, 1984), St. Lawrence Estuary in Canada (Lucotte and d'Anglejan, 1986), Fly River Estuary in Papua New Guinea (Wolanski and Eagle, 1991), Tamar Estuary in England (Uncles et al., 1985), and Changjiang Estuary in China (Shen et al., 1992). A TMZ is formed by the dynamic accumulation of suspended sediments caused by tidal movements, salinity gradients, estuarine circulation, re-suspension of the bottom sediments, etc. The causes of TMZ formation vary among estuaries and even among different parts of an estuary (Schubel, 1968; Festa and Hansen, 1978; Allen et al., 1980; Eisma, 1986; Uncles and Stephens, 1993; Brenon and Le Hir, 1999). The TMZ plays an important role in the transportation and deposition of fine sediments in estuarine areas and in shaping channel morphology. The TMZ also drives pollutant dispersal patterns by affecting the biogeochemical processing of heavy metals and organic material (Shen et al., 1992; Hollibaugh and Wong, 1999; Gao et al., 2008). As an example, the TMZ strongly affects ocean biological processes because it affects the depth of light penetration into the water column, a factor controlling primary production (May et al., 2003; de Swart et al., 2009). The TMZ also appears to act as an entrapment zone for zooplankton, thus providing a habitat for fish breeding grounds (Dodson et al., 1989; Roman et al., 2001).

The TMZ in the Changjiang Estuary is well developed and is primarily characterised by a high SSC compared with adjacent waters and by a high wash-load content. Tidal movements and saline flow form the TMZ in the Changjiang Estuary, and these two factors have varying influence in different parts of the estuary (Shen et al., 1992). Sediment is supplied to the TMZ from the

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drainage basin, the sea and estuarine re-suspension, but no research has determined which factor dominates TMZ dynamics.

Studies have come to differing conclusions about the response of estuarine SSC to decreased sediment load. He (2007) compared the temporal and spatial characteristics of SSC during flood seasons in 1982, 2003 and 2005 based on in-situ hydrological and sediment measurements in Changjiang Estuary and adjacent areas. The results indicated that the SSC was reduced during recent flood seasons compared to 1982, primarily due to decreased sediment flux. In contrast, Jin et al. (2006) observed that estuarine SSC did not decline greatly, based on daily SSC measurements from Aug 1998 to Aug 2001. A possible explanation is that the total amount of movable sediments in the estuarine area is larger than the total quantity of sediment from the river basin because of re-suspension. The average amount of sediment re-suspension was estimated at approximately 3–4 billion tons per year, but the annual sediment load from the river basin is only hundreds of millions of tons. The influence of decreased sediment on estuarine SSC may not be observed over such a short time.

The inconsistent responses of estuarine SSC to decreased sediment load may result from sparse and infrequent in situ measurements. This may also explain why no in situ study has yet delineated the size of the TMZ, despite the critical importance of this information. A long historical archive of remote sensing data provides an effective means to study the spatial and temporal changes in estuarine areas (Ruhl et al., 2001; Doxaran et al., 2009). Therefore, this study used thirty-two satellite images from 1979 to 2008 to detect TMZ variations in the Changjiang Estuary and to examine the TMZ response to the decrease in sediment load.

2. Study area

The Changjiang River is the longest river in Asia, the fifth largest in the world in terms of water discharge and, historically, the fourth largest in the world in terms of fluvial sediment load (Milliman and Syvitski, 1992; Chen et al., 2001; Stone, 2008). The Changjiang Estuary, located in the centre of the Chinese eastern coast, has a branching channel structure consisting of three bifurcations and four outlets into the East China Sea. The estuary is first divided into the South Branch and the North Branch by Chongming Island. The South Branch is then split into the South Channel and the North Channel by Changing Island and Hengsha Island. Farther downstream, the South Channel is finally divided into the South Passage and the North Passage by Jiuduansha Wetland. The Changjiang Estuary is a large estuary: the length from the first bifurcation to the mouth bar is approximately 110 km, while the width near the mouth bar is approximately 90 km. The depth varies spatially, from approximately 4 m to more than 20 m (Fig. 1).

There is a large annual flux of water and sediment from the Changjiang River basin into the sea. Approximately 50% of total river sediment is deposited in the estuary each year (Chen et al., 1985). Runoff volume and sediment flux vary seasonally. During the flood season between May and October, the discharge of runoff and sediments was approximately 71.7% and 87.0% of the annual amount, respectively (Chen et al., 2001); the rest was discharged in the dry season between November and April.

The Changjiang Estuary is characterised by high turbidity with large spatio-temporal variability. Daily SSC measurements from August 1998 to June 2001 at Hengsha Tidal Station (Fig. 1) showed

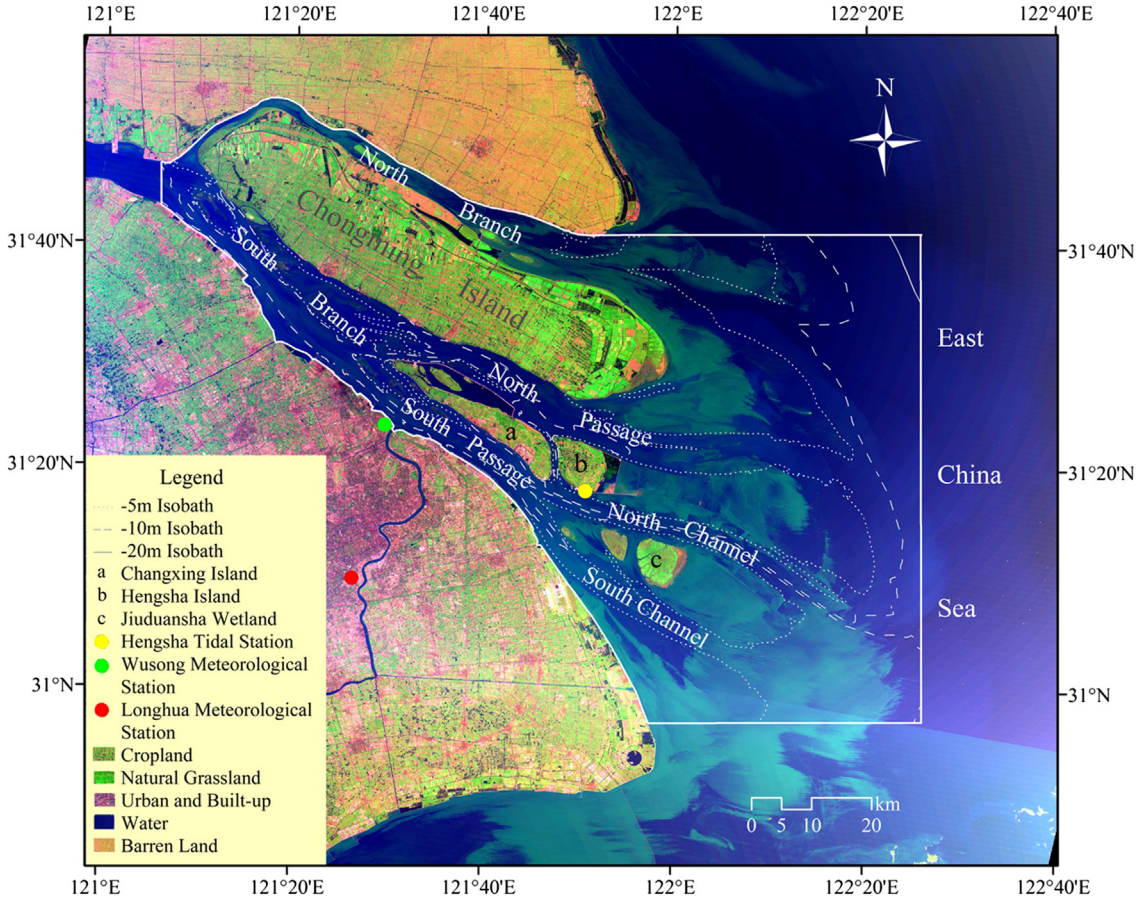

Fig. 1. Landsat ETM image (RGB: band 7, 4 and 2) acquired on 21 Sep 2009 showing the location of the Changjiang Estuary and this study's area of interest (AOI). The overlaid isobaths were digitised from the marine charts published in April 2011 by the Maritime Safety Administration of China.