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.

Keywords: Turbidity Maximum Zone; Sediment Discharge; Landsat Imagery; the Changjiang Estuary; China

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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 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 to 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 Changxing 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.

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.

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 that the mean SSC value varied from 0.30 kg/m³ during ebb tide to 0.45 kg/m³ during flood tide; the maximum value reached 4.2 kg/m³ (Yun, 2004). The SSC value in the inner estuary is higher in summer than in winter, whereas the SSC value in the outer estuary is lower in summer than in winter. The demarcation line between the inner and the outer estuary is around the upper port of Changxing Island (Chen et al., 2004).

The tidal prism in Changjiang Estuary is large: the spring tidal prism is 5.3×10^9 m³ during flood season and 3.9×10^9 m³ during dry season, and the neap tidal prism is 1.6×10^9 m³ during flood season and 1.3×10^9 m³ during dry season. These tidal prisms are generally greater than the river fluxes in the corresponding periods (Chen et al., 1988). The average tidal range is 2.60 m at Hengsha Tidal Station. The saline wedge

(salinity value 5‰) can reach to the middle of Changxing Island near the riverbed at the end of a flood tide (Yun, 2004).

3. Materials and Methods

3.1. Water and Sediment Flux

The water and sediment flux data from 1965 to 2008 were recorded at Datong Hydrographical Station (30°52'N, 117°44'E) by the Bureau of Hydrology, Changjiang Water Resources Commission (CWRC). Datong Hydrographical Station is located at the dry season tidal limit of the river mouth; it is the control station for the measurements of water and sediment discharge from the river to the sea. According to the data, no obvious trend was found in the annual water fluxes from the river basin to the estuary from 1965 to 2008; the average value over the period was $8.88 \times 10^{11} \text{ m}^3/\text{yr}$. However, sediment discharge decreased greatly, the annual sediment discharge to the estuary declined gradually from $5.31 \times 10^8 \text{ T}$ in 1965 to $0.85 \times 10^8 \text{ T}$ in 2006 (CMWR, 2006). The average value was $4.53 \times 10^8 \text{ T/yr}$ over the first 15 years (from 1965 to 1980), $3.98 \times 10^8 \text{ T/yr}$ over the next 14 years (from 1981 to 1995) and $2.42 \times 10^8 \text{ T/yr}$ over the last 14 years (1996-2008) of the study period (CMWR, 2009).

3.2. Landsat Imagery Acquisition and Pre-processing

Thirty-two Landsat images from various sensors were collected for the period from 1979 to 2008 (Table 1). The Landsat series of satellites provides the longest continuous record of satellite-based earth observations; the launch of the first satellite in the series was in 1972 (Chander et al., 2009). The Landsat series consisted of seven satellites from 1972 to 1999; these seven satellites can be grouped into three generations according to their technological capabilities. The first generation included Landsat 1, Landsat 2, and Landsat 3, with the Multispectral Scanner (MSS) sensor. The second generation consisted of Landsat 4 and Landsat 5, which carried the Thematic Mapper (TM) sensor. The third generation included Landsat 6 and Landsat 7, which were equipped with the Enhanced Thematic Mapper (ETM) and the Enhanced Thematic Mapper Plus (ETM+) sensors, respectively. The Landsat data archive at the U.S. Geological Survey Earth Resources Observation and Science Center holds an unequalled 36-year record of the Earth's surface and is available to users via the Internet (Woodcock et al., 2008).

The Landsat images in this study were purchased or downloaded at no cost from the U.S. Geological Survey and the Computer Network Information Centre of the Chinese Academy of Sciences. The images were selected based on availability, quality and coverage of different seasons and tides. The images were grouped into five time series: (a) 1979-1982, (b) 1987-1995, (c) 1997-2001, (d) 2002-2005, and (e) 2006-2008. Each series included a flood season and a dry season, and each season included a spring, a moderate, and a neap tide. Some tides were absent in the dry seasons of series (a) and (b). The tidal information at the mapping moment was referenced to the Hengsha Tidal Station of the local Shanghai Water Authority. The mean wind velocity on the date was recorded by the Wusong Meteorological Station

and the Longhua Meteorological Station, provided by China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>) (Fig. 1). The wind velocity was lower than 5.3 m/s and the effects of wind and waves on SSC were not considered.

All images were geo-corrected by an image-to-map method referenced to local 1:50000 topographic maps. The radiometric correction of Chander et al. (2009) was followed. Atmospheric correction was based on the dark object subtraction (DOS) method (Chavez, 1996; Song et al., 2001; Lu et al., 2002).

Table 1. Thirty-two Landsat images were collected and grouped into five series from 1979 to 2008 according to different season and tide type.

Series	Imaging date	Sensor	Mapping time (GMT)	Season	Tide type	Flood/Ebb	Wind velocity (m/s)
(a)	4 Aug 1979	MSS	1:46	Flood	Neap	Ebb 2 h	4.8
	27 Oct 1980	MSS	1:33		Spring	Flood 33 min	1.3
	15 Jul 1981	MSS	1:42		Moderate	Flood 4 h 3 min	2.3
	4 Mar 1979	MSS	1:36	Dry	Moderate	Ebb 6 h 19 min	2.8
	24 Nov 1981	MSS	1:44		Moderate	Flood 4 h 44 min	4.5
	28 Dec 1982	MSS	1:50		Spring	Ebb 4 min	1.0
	18 May 1987	TM	1:48		Moderate	Ebb 7 h 20 min	3.8
(b)	11 Aug 1989	TM	1:51	Flood	Neap	Ebb 5 h 14 min	2.5
	3 Jun 1993	TM	1:47		Spring	Flood 4 h 4 min	3.3
	12 Aug 1995	TM	1:28	Dry	Spring	Flood 1 h 31 min	1.8
	4 Dec 1990	TM	1:44		Spring	Flood 1 h 30 min	0.3
	6 Apr 1995	TM	1:34		Neap	Ebb 7 h	1.8
(c)	1 Aug 2000	ETM	2:16	Flood	Spring	Flood 3 h 7 min	2.8
	16 May 2001	ETM	2:15		Neap	Flood 1 h 29 min	3.0

Series	Imaging date	Sensor	Mapping time (GMT)	Season	Tide type	Flood/Ebb	Wind velocity (m/s)
(d)	3 Jul 2001	ETM	2:15	Dry	Moderate	Ebb 16 min	3.8
	9 Feb 1998	TM	2:01		Moderate	Flood 4 h 51 min	3.5
	27 Apr 2000	TM	2:17		Neap	Ebb 5 h 18 min	2.8
	5 Nov 2000	ETM	2:15		Neap	Flood 1 h 12 min	2.3
	11 Apr 1997	TM	1:52		Spring	Flood 33 min	3.8
	30 Jul 2002	TM	1:59	Flood	Moderate	Flood 13 min	3.0
	19 Jul 2004	TM	2:08		Spring	Flood 1 h 30 min	5.0
	15 Aug 2005	ETM	2:15		Neap	Ebb 4 h 12 min	3.4
	11 Jan 2002	ETM	2:14		Moderate	Ebb 8 min	1.8
	27 Nov 2002	ETM	2:13		Neap	Flood 8 min	1.8
	24 Dec 2003	TM	2:03	Dry	Spring	Flood 3 h	1.5
	2 Aug 2006	ETM	2:14		Neap	Flood 30 min	5.3
	17 May 2007	ETM	2:15		Spring	Flood 2 h 5 min	4.3
	28 Jul 2007	TM	2:18		Moderate	Flood 4 h 41 min	2.7
	20 Apr 2006	TM	2:16	Dry	Neap	Ebb 7 h 8 min	2.2
(e)	9 Jan 2007	ETM	2:14		Moderate	Flood 1 h	1.3
	24 Mar 2008	TM	2:15		Spring	Flood 45 min	2.3
	25 Apr 2008	TM	2:14		Moderate	Flood 50 min	3.8

3.3. The TMZ Area Estimation

A three-step process was used to estimate TMZ area:

1) Determining Landsat image bands that are highly correlated with the critical indicator of the TMZ: SSC values. Previous studies of TMZ in the South Passage demonstrated that the reflectance of TMZ water is highly correlated with SSC at the bands of 690 nm, 800 nm, 810 nm and 860 nm (Jiang et al., 2011). In addition, the Landsat MSS band 7 (central wavelength approximately 900 nm) and TM/ETM band 4 (central wavelength approximately 840 nm) have also been shown to have a high correlation with SSC (Ritchie and Cooper, 1988; Ritchie et al., 1990). Therefore, the reflectance of these two bands was chosen to delineate the TMZ.

2) Defining the critical surface SSC value that can be used to separate the TMZ from the surroundings. Previous studies have no specific value as the critical SSC value for the TMZ in the Changjiang Estuary. In this study, based on the range of surface SSC values in the TMZ (from 0.1 kg/m³ to 4.2 kg/m³ (Yun, 2004)) as well as SSC measurements in different parts of the Changjiang Estuary (Li and Zhang, 1998), an SSC value higher than 0.7 kg/m³ was empirically used to indicate the TMZ.

3) Determining the critical reflectance values for MSS band 7 and for TM/ETM band 4 to delineate the TMZ with a SSC value higher than 0.7 kg/m³. In situ measurements were taken in the Changjiang Estuary during 9 Aug 1978 (Yun, 2004) and 24 Mar 2008 (Jiang et al., 2011). Water samples were collected and transported back to the laboratory to calculate the SSC. Landsat images were available at these two times, from the MSS and TM sensors, respectively. In comparing the reflectance values with the synchronous field-measured SSC, we observed that an SSC value of approximately 0.7 kg/m³ corresponded with a MSS band 7 reflectance values of approximately 5% and a TM/ETM band 4 reflectance values of approximately 7%. Higher SSC values corresponded to higher reflectance values between bands 350 nm and 950 nm, thus reflectance values greater than 5% in MSS band 7 and greater than 7% in TM/ETM band 4 were used to delineate the region where SSC was higher than 0.7 kg/m³; this region was regarded as the TMZ. The area of the TMZ inside the AOI polygon (Fig. 1) was then calculated for each image, and the average value of each time series was used to determine the changes during the past 30 years.

The ENVI software from American ITT Visual Information Solutions Company and ArcGIS from American Environmental Systems Research Institute, Inc. (ESRI) were used for the above processing.

4. Results and Discussion

4.1. The TMZ Delineation Results

The TMZ area for each image was calculated, the area value varied dramatically from a minimum area of 987 km² (on 24 Nov 1981) to a maximum area of 2639 km² (on 4 Dec 1990), with an average area of 1570 km². The results extracted from images of spring/neap tide in the flood and dry seasons are shown in Fig. 2. The typical location of the TMZ was in the North Branch and along the mouth bar areas near the eastern edges of Chongming and Hengsha Islands, the surrounding regions of Jiuduansha Wetland. The mechanisms of formation differ for different parts of the

TMZ. The TMZ in the North Branch and South Passage is mainly formed by tidal action. The TMZ in the North Channel and North Passage, the main river channels, is mainly formed by residual circulation caused by saline flow (Shen et al., 1992).

Fig. 2. The TMZ extraction results, generally the area was larger in spring tide than in neap.

4.2. Variations in TMZ Areas

The difference in TMZ area between high discharge and low discharge seasons was also analysed (Fig. 2 and Table 2). The mean TMZ area is 1567 km² in the flood season and 1547 km² in the dry season. This is because sediment flow to the estuary is greater during the flood season and thus is a larger sediment source to the TMZ. This is confirmed by previous studies, which indicate that the flood season TMZ is larger than that in the dry season (Li and Zhang, 1998). However, the differences in average TMZ area between the dry season and the flood season are not dramatic. The enhanced tidal current caused by strong winter storms, which leads to intensive re-suspension during the dry season, may be a possible explanation (Gao et al., 2008).

The differences in TMZ areas among spring, moderate and neap tides are also shown in Table 2. The spring tide has much stronger effects on the TMZ than the neap

tide, corresponding to 2062 km² and 1328 km² in the flood season and 1962 km² and 1219 km² in the dry season, respectively. This result is consistent with other studies, in which the TMZ was observed to increase in area more during the spring tide than during the neap tide (Li and Zhang, 1998). The dramatic area difference between the spring and neap tides can be explained by greater re-suspension during spring tides.

The tidal phase contributed more to variation in TMZ area than did the season of the year. A similar conclusion can be drawn from the field-acquired SSC statistics of different locations: in the mouth bar area, the difference in average SSC between the flood and dry seasons is less than 0.18 kg/m³, but it is greater than 0.32 kg/m³ between the spring and neap tide (Li and Zhang, 1998).

Table 2. The TMZ area variations among different tides in the flood season and the dry season (km²).

	Spring tide	Moderate tide	Neap tide	Mean
Flood Season	2062	1310	1328	1567
Dry Season	1962	1462	1219	1547

4.3. The Distribution Change of TMZ

The decreased sediment flux from the river basin to the estuary also led to changes in the TMZ distributions, especially during the flood season. Comparing the flood season TMZ distribution under similar tidal conditions, we observed that the TMZ has moved seaward. In the earlier years, for example on 12 Aug 1995 and 15 Jul 1981, the TMZ was mostly in the inner estuary and the mouth bar area during flood seasons; In contrast, in flood seasons of later years, on 19 Jul 2004 and 28 Jul 2007, the TMZ region was mostly in the mouth bar area and the outer estuary (Fig. 3). The upper limit of the TMZ moved from upstream of Changxing Island to downstream of Hengsha Island; the lower limit moved seaward, but the change was not as great as that for the upper limit. These results indicated that the seaward shift of the upper limit of the TMZ is most likely the result of decreased sediment flux. The TMZ distribution was less variable among dry seasons than among flood seasons. The decrease of sediment flux likely had less influence on the TMZ in the dry seasons because the sediment source of the TMZ was mainly from local and adjacent areas during dry seasons.

Fig. 3. The distribution of the TMZ changed in the past decades.

The TMZ was observed to vary according to an interactive effect of the river flow and tidal currents. The general upper limit of the TMZ could reach approximately $121^{\circ}20'E$ (upstream of the Changxing Island). The general lower limit of the TMZ was reaching $122^{\circ}15'E$, while the lowest limit was near $122^{\circ}33'E$. The general range between the upper and lower limit was about 95 km, greater than the TMZ range of either the Gironde Estuary (approximately 70 km) (Doxaran et al., 2006) or the Chesapeake Bay (approximately 40 km) (Sanford et al., 2001). The distribution of the TMZ showed strong seasonal and tidal variations.

4.4. The Response of TMZ to the Sediment Decrease

The sediment discharge from the Changjiang River basin to the estuary has decreased greatly since the 1960s, primarily due to dam construction. In the past 50 years, more than 10,000 dams have been built in the drainage basin, including the Three Gorges Dam, trapping large amounts of sediment in reservoirs (Yang et al., 2005; Zhang et al., 2006). Decreasing sediment discharge has led to changes in the estuary. The TMZ area and its distribution change have shown the response to the sediment decrease. The average TMZ area of each time series decreased gradually as the sediment flux declined, there were 1848 km², 1554 km², 1586 km², 1456 km² and 1428 km², corresponding to series (a), (b), (c), (d) and (e), respectively (Fig. 4). The lower sediment discharge from the Changjiang River basin led to the reduction of the TMZ area and seaward shift of the upper limit of the TMZ in the estuary. However, the decline in average area was not as great as the decline in sediment flux. A possible explanation is that the TMZ depends upon sediments not only from the river basin but also from local sediments exchanged within the estuary and from adjacent waters. Thousands of years of sediments have been deposited in these areas, similar to a sediment reservoir (Liu et al., 2010), and these may provide sediment for the formation of the TMZ. The diminution of TMZ area was verified by the suspended sediment concentration measurements, which showed a 20-30% decrease in the lower estuary and adjacent coastal waters over the past 10-20 years (Li, 2012).

Fig. 4. Sediment loads and TMZ areas in the five periods. The sediment loads were averaged for each time series.

The TMZ areas are predicted to continue declining and to reach a new equilibrium eventually. Local sediment sources will play a more important role in the TMZ, as there will be less river-derived sediment in the estuary due to new project construction in the Changjiang river basin (Yang et al., 2003; Yang et al., 2006).

5 Conclusions

Thirty-two Landsat images from 1979 to 2008 were collected to examine the response of the TMZ to a decrease of sediment load and to study the TMZ variations within the Changjiang Estuary. The TMZ area for each image was calculated. When we grouped the images into five series according to different reasons and tide type, the average area value of each time series showed the trend of the TMZ changes and led to the following conclusions:

- From series (a) to series (e), the TMZ areas declined about 23% in response to a 77% reduction in sediment discharge from the Changjiang River basin to the estuary.
- Local sediment was an important source for the TMZ in the well-mixed Changjiang Estuary, which caused the reduction of the TMZ area to be less than the reduction of riverine sediment flux.
- The large variation in TMZ area was related to the season of the year and tidal stage. The spring / neap tidal cycle is a stronger determinant of TMZ area and spatial distribution than the seasonal cycle. In general, the TMZ was larger during flood seasons than during dry seasons and during spring tides compared to neap tides.
- During the last 30 years, the TMZ decreases were mainly in the inner portion of the estuary. The changes outside the river mouth were not as great because of strong local sediment re-suspension.
- A continued decrease in sediments from the river basin will likely cause a further

decline in the TMZ area. Local sediment supply will play a more important role in TMZ formation.

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