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Formation and Evolution of Wetland and Landform in the Yangtze River Estuary Over the Past 50 Years Based on Digitized Sea Maps and Multi-Temporal Satellite Images

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1. Introduction

The Yangtze River originates in the Qinghai-Tibet Plateau and extends more than 6300 km eastward to the East China Sea, a tectonic subsidence belt (Li & Wang, 1991). It is one of the largest rivers in the world, in terms of suspended sediment load, water discharge, length, and drainage area. The Yangtze River Estuary is located in the east China. There are three main islands including Chongming Island, Changxing Island, and Hengsha Island as well as several shoals in the Yangtze River Estuary (Fig. 1). These islands once are shoals emerged from the water and merged to the north bank or coalesced together. In the Yangtze River Estuary, most of the sediments from the drainage basin are suspended. The spatial and temporal variations of the suspended sediment concentration in the estuarine field survey indicate that the sediment is suspended, transported, and deposited under riverine and marine processes, such as river flow, waves, tidal currents, and local topography (Cao et al., 1989; Chen, 2001; Gao, 1998; Li et al., 1995; Huang and Chen, 1995; Xu et al., 2002; Pan and Sun, 1996). In longitudinal section, these islands and shoals stand out on the link between the -10 m isobathic line (the zero elevation means the 1956 Yellow Sea Water Surface in Qingdao Tidal Station, Qingdao, Shandong Province, China) from the upper reach section to the lower reach section, it is a convex geomorphic unit in the Yangtze River Estuary (Fig.2 A-A' and Fig. 3), in transverse section, these shoals and islands sit in between the channels and distributaries (Fig.2 B-B' and Fig. 4). In order to analyze the formation and evolution of the wetland and landform of the Yangtze River Estuary, related sea maps from 1945 to 2001 and satellite images from 1975 to 2001 are collected and analyzed. Water and sediment discharge from 1950 to 2003 at the Datong Hydrologic Station 640 km upstream from the estuary mouth are also collected. Datong Hydrologic Station is the most downstream hydrologic station on the free-flowing Yangtze River, where the tidal influence can affect flows hundreds of kilometers upstream. All related sea maps are digitized using Mapinfo7.0, and the sediment volume deposited in this area is calculated from a series of processes dealt in Surfer7.0. The relation between formation and evolution of the wetland and landform of the Yangtze Estuary over the past 50 years were analyzed via Geographical Information System technology and a Digital Elevation Model.

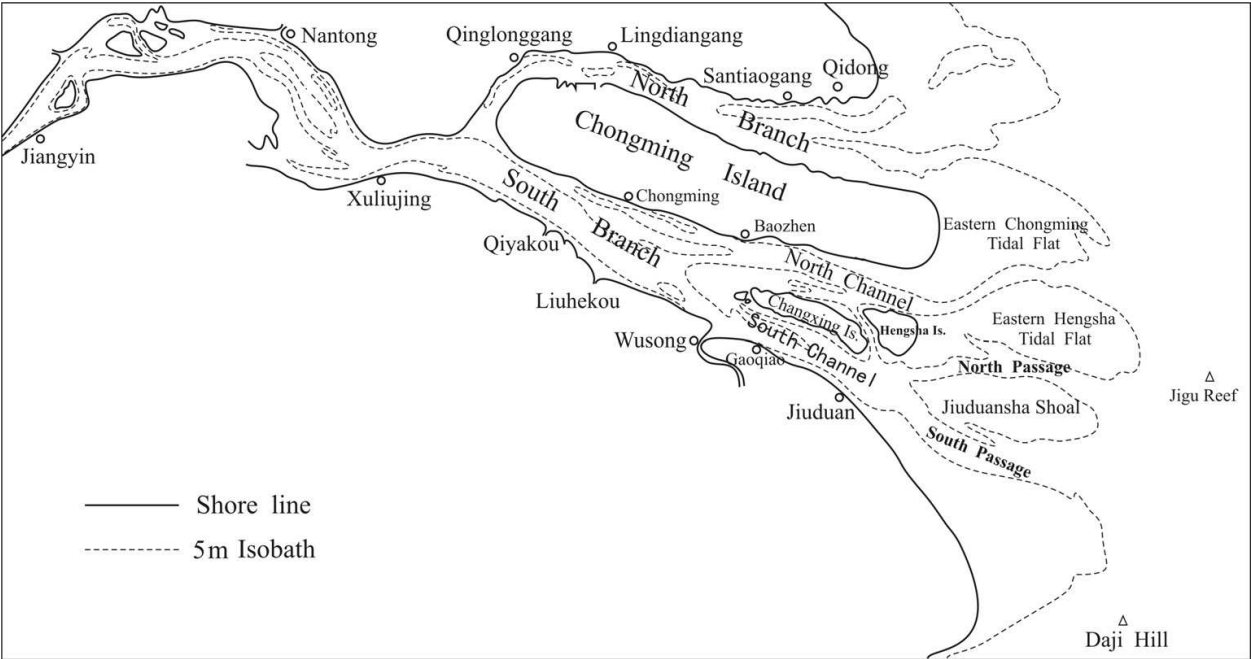


Fig. 1. The sketch map of the Yangtze River Estuary

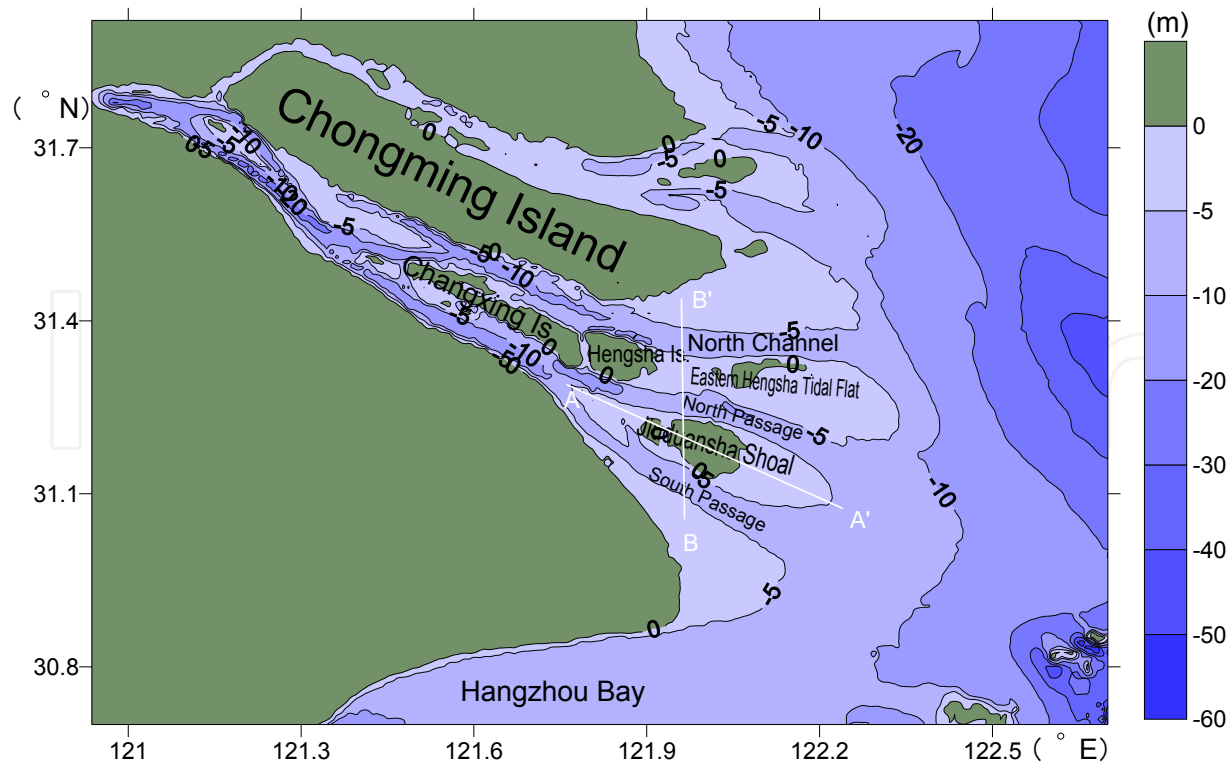


Fig. 2. Location of the Jiuduansha Shoal in Yangtze River Estuary

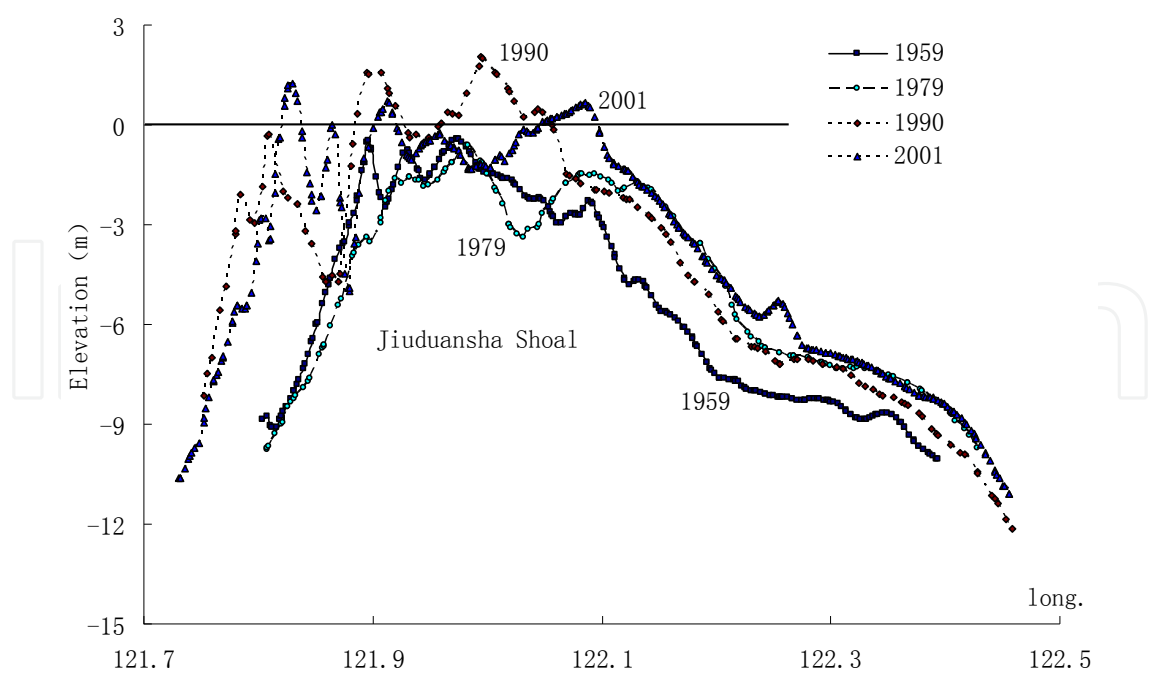


Fig. 3. Longitudinal section at 121°35'E, 31°16'N-122°25'E, 31°5'N (shown on Fig. 2 as A-A') of the Jiuduansha Shoal from 1959 to 2001

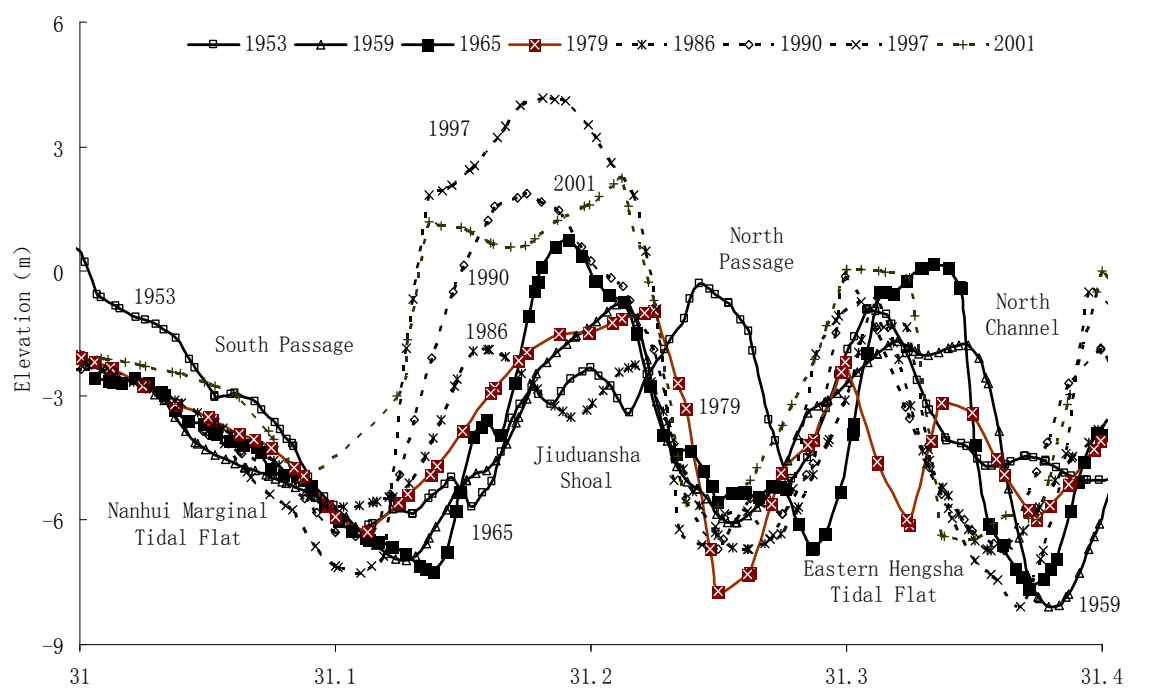


Fig. 4. Sketch map of the cross section at 122°E (shown on Fig. 2 as B-B') of the Yangtze River Estuary from 1953 to 2001

2. Data and methodology

In order to analyze the formation and evolution of the Yangtze River Estuary in past 50 years, related sea maps from 1945 to 2001 and satellite images from 1975 to 2001 are collected and analyzed. Landsat MSS (multi-spectral scanner) data acquired on 1975 and 1979, Landsat TM (Thematic Mapper) and Landsat ETM+ (Enhanced Thematic Mapper Plus) from 1990 to 2001, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data from 2002 to 2005 were collected and analysed. All these remote sensing data were corrected geometrically. Image processing of these satellites remote sensing data were used ENVI4.6 and Erdas9.0. And formation and evolution of the landform over the past 50 years are analyzed in detail.

3. Formation and evolution of wetland and landform

3.1 Formation mechanism of the Yangtze River Estuary

The Yangtze River Estuary is nearly 90 km wide at the mouth from the Southern cape to the Northern cape. Coriolis force and centrifugal force are strong enough to cause a horizontal separation of the flow, forming an ebb tide dominated channel and a flood tide dominated channel, respectively. Because of the river bed friction, tidal currents and wave power decreased during the tidal currents flow into the mouth and wave form began to change, and the flood tidal range in the northern part is larger than that in the southern part of the same cross section, while in the ebb tide period, the longitudinal water surface gradient and the transverse water surface slope increase (Zhang and Wang, 1987). The transverse water surface slope caused by curve bend circulation is J_B ,

$$J_B = \left(1 + 5.75 \frac{g}{C^2} \right) \frac{V_{cp}^2}{gr} \quad (1)$$

where C is the Chézy roughness coefficient, V_{cp} is the vertical mean velocity, r is the river bend radius of curvature, and g is the acceleration of gravity. For example, when $V_{cp} = 2$ m/s, $r = 10,000$ m, $C = 90$ m^{1/2}/s, and $g = 9.81$ m/s², then $J_B = 4.1 \times 10^{-5}$.

Another factor that might affect transverse water surface slope in the Yangtze River Estuary is the Coriolis force. The transverse water surface slope caused by the Coriolis force was studied by Zou (1990), in this case the transverse water surface slope is J_C ,

$$J_C = \frac{2\omega V_{cp} \sin \varphi}{g} \quad (2)$$

where ω is the rotational angular velocity of the earth, $\omega = 7.27 \times 10^{-5}$ (s⁻¹); φ is the stream section latitude, φ is 32°. If V_{cp} is equal to 2.0 m/s in the calculation like in curve bend circulation, and g is 9.81 m/s², then $J_C = 1.57 \times 10^{-5}$.

Comparing J_C and J_B , shows that for similar condition, the slope caused by the Coriolis force is smaller than that caused by curve bend circulation. However, due to the long term action of the Coriolis force, the thalweg of the ebb current and river flow is directed to the right bank and formed the Ebb Channel, while the thalweg of the flood current is directed to the left and formed the Flood Channel, the main tide direction is nearly 305° progressing from the East China Sea toward the river mouth area while the ebb tide current direction is nearly

90°-115°. The ebb tide current is not in a direction opposite to the flood tide direction; there is a 10°-35° angle between the extension line of the flood and ebb tidal currents because of the Coriolis force(Shen et al., 1995). Ebb tidal current is obviously diverted to the south, while the flood current is diverted to the north. Thus, between the flood and ebb tidal currents in the river mouth area there is a slack water region where sediment rapidly deposited to form shoals, and eventually coalesced to form estuarine islands (Chen et al., 1979). This is the evolutionary history of the three larger islands (Chongming Island, Changxing Island and Hengsha Island, respectively) in the estuary. These islands form three orders of bifurcation and four outlets in the Yangtze River Estuary. The first order of the bifurcation is the North Branch and the South Branch separated by Chongming Island. The South Branch is further divided into the North Channel and the South Channel by Changxing Island and Hengsha Island. The South Channel is further divided into the North Passage and the South Passage by the Jiuduansha Shoal (Fig. 1). Therefore, the Yangtze River Estuary has North Branch, North Channel, North Passage and South Passage four outlets through which the water and sediment from the Yangtze River discharge into the East China Sea.

From 1950 to 2003, the annual water discharge at the Datong Hydrologic Station did not substantially change. The total annual discharge is about 9481×10^8 cubic meters per year and the sediment load is about 3.52×10^8 tons/yr. The sediment discharge during the flood season (from May to October) constituted 87.2% of the annual sediment load before the 1990s, but decreased in the 1990s (Fig. 5). Most of the suspended sediment are silt and clay, which are transported to the East China Sea where they are carried away from the delta by the longshore currents. Part of the suspended load is deposited in mouth bars and a subaqueous delta area to form the tidal flats and mouth bars in the Yangtze Estuary. A broad mouth bar system and tidal flats were formed. The runoff and the sediment discharge

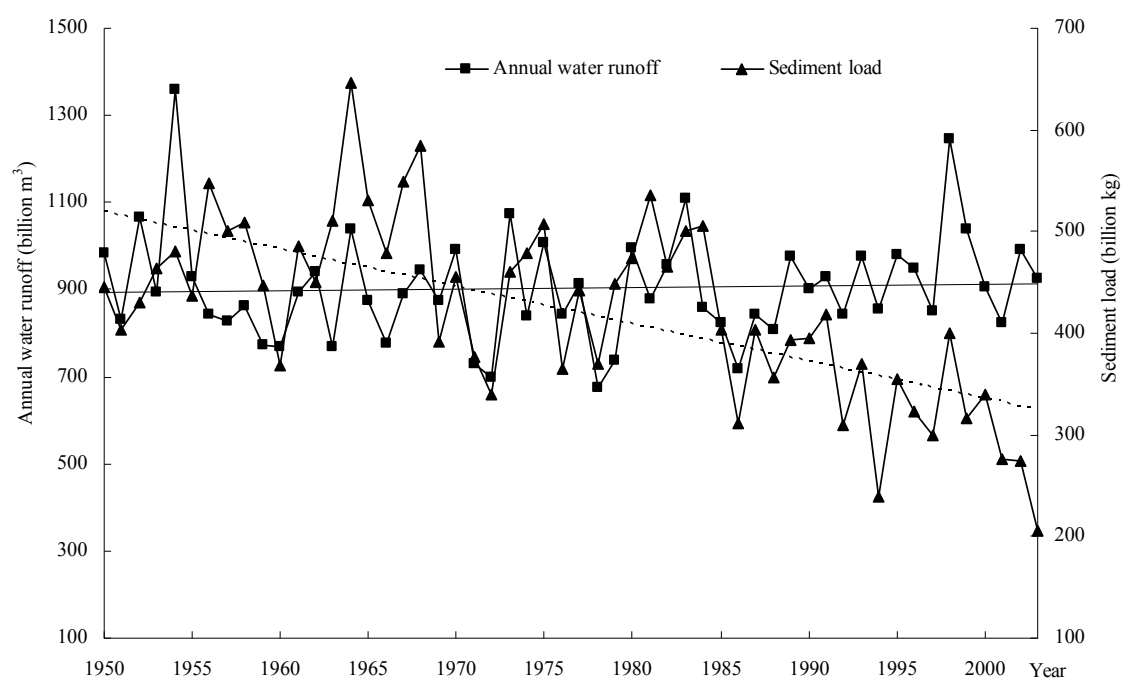


Fig. 5. Water and Sediment discharge from 1950 to 2003 at Datong Hydrologic Station.

during the flood season vary between 71.7 and 87.2 % of the annual total value based on data from the Datong Hydrologic Station. According to previous research (Gong and Yun, 2002; Niu et al., 2005), at discharges greater than 60,000 m³/s at the Datong Hydrologic Station, the estuarine riverbed has obviously changed due to erosion and deposition; when the flood water discharge greater than 70,000 m³/s, can form new branches on the river and cluster ditches because of the floodplain flows, these changes affect the estuary and new navigation channel development. In 1954 (from June 18th to October 2nd), the average water discharge at the Datong Hydrologic Station was about 60,000 m³/s, and the highest discharge was about 92,600 m³/s. Water discharge greater than 60,000 m³/s, increase the water surface gradient and the sediment carrying capacity in the estuary (Yang et al., 1999). Estuarine sedimentation and landform features have been observed and studied in various settings around the world, including the Thames Estuary, Cobequid Bay, and the Bay of Fundy (Dalrymple and Rhodes, 1995; Knight, 1980; Dalrymple et al., 1990), as well as Chesapeake Bay (Ludwick, 1974) and Moreton Bay (Harris et al., 1992). These studies found that tidal bars in all these estuarine settings are important sedimentary features. Because estuaries are areas where freshwater and seawater mix, the systems react very sensitively to small changes in geomorphology of the estuary, and the results can reveal the changes of the estuarine environment.

According to the evolution history of the Yangtze River Estuary (Wang et al., 1981; Li et al., 1983; Qin and Zhao, 1987; Qin et al., 1996; Chen et al., 1985, 1991; Chen and Stanley 1993, 1995; Stanley and Chen, 1993; Hori, K. et al., 2001a, 2001b, 2002; Saito, Y. et al., 2001), the main delta was formed by the step-like seaward migration of the river mouth bars from Zhenjiang and Yangzhou area, the apex of the delta, to the present river mouth (Fig. 6).

The newer generation island is Jiuduansha Shoal, it was once the southern part of the Tongsha Tidal Flat. In 1945, under the processes of ebb and flood tidal currents, one pair of a

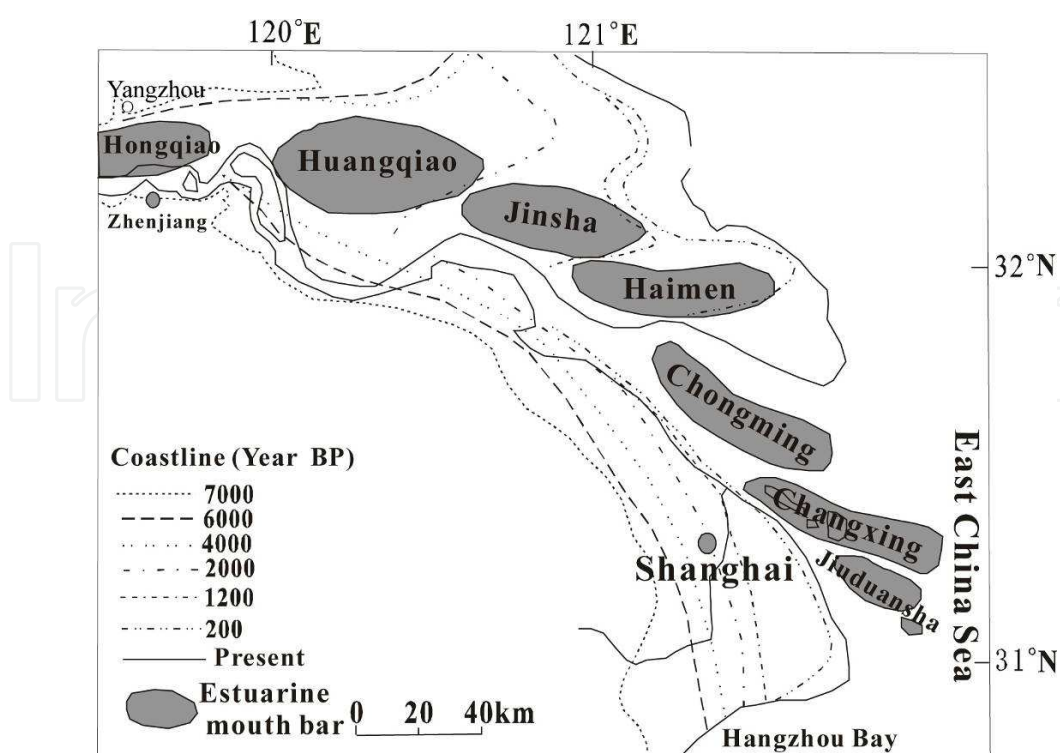


Fig. 6. Evolution history of the Yangtze River Estuary (after Chen et al., 2000)

flood channel and an ebb channel developed on the southern part of the Tongsha Tidal Flat, but the Jiuduansha Shoal had not formed as an isolated shoal (Fig.7). In 1954, the ebb channel and flood channel on the Tongsha Tidal Flat linked up, the linked ebb and flood channel formed the North Passage under the Flood from the drainage basin. While the -2 m isobath line linked up the ebb channel and the flood channel, the Jiuduansha Shoal was isolated, and the Jiuduansha Shoal formed as a new island in the Yangtze River Estuary (Fig.8).

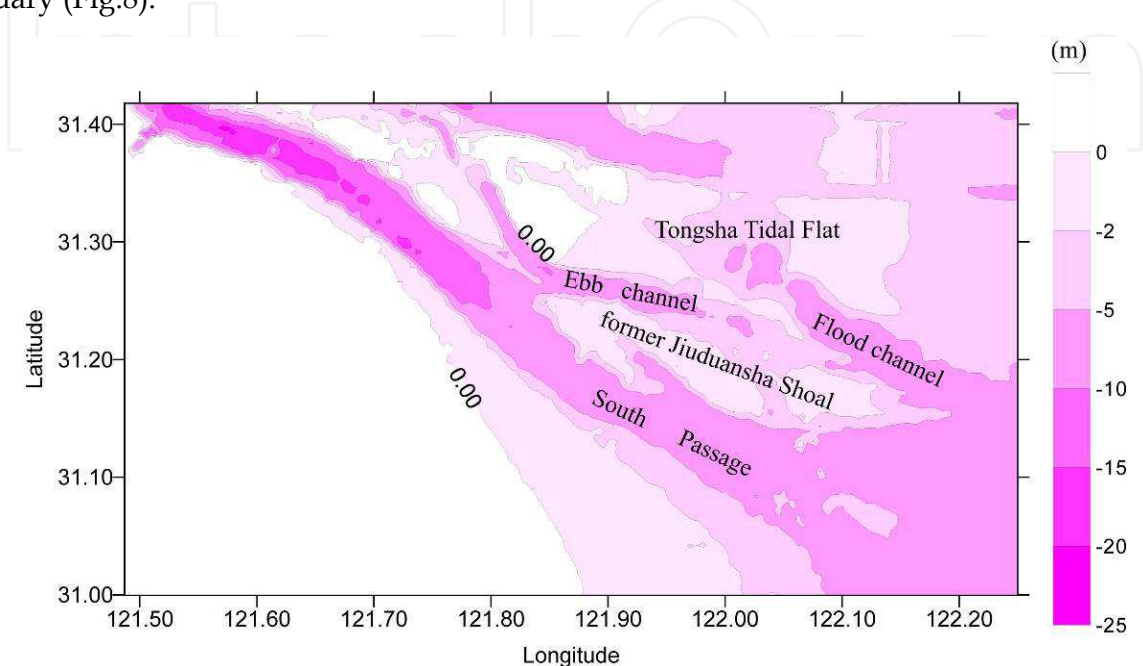


Fig. 7. Former Jiuduansha Shoal in 1945

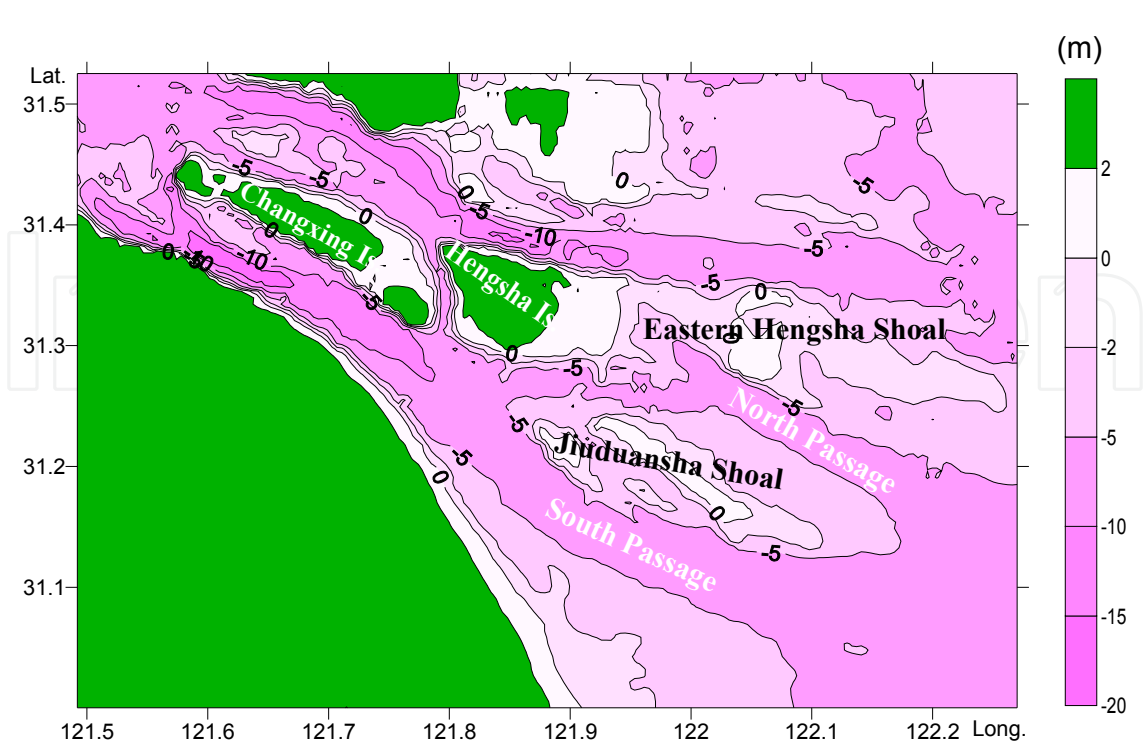


Fig. 8. The Jiuduansha Shoal and the North and South Passage in 1959.

The formation and landform evolution of the Yangtze River Estuary are related to the water and the sediment coming from the drainage basin and human activities, and also related to the riverine and marine processes. The Yangtze River Estuary is an irregular semidiurnal tidal estuary, there is a clearly different tidal range in a day, especially, the daily mean higher high tide is 1.47 m higher than lower high tide (Shen and Pan, 1988). In a tidal cycle, a flow diversion period exists, and this period differs throughout the year because of the different flood and dry seasons, and different spring and neap cycles. The channel bed changes easily and frequently under the actions of the runoff and the tidal current, while the human activities such as reclamation and navigation channel construction is also influence the landform features.

3.2 Field survey evaluation

In order to study the relation between the deposition and erosion of the tidal flat during the flood and dry season at spring and neap tides, field survey data for the middle section of the North Passage and the South Passage are analyzed. The velocity and sediment concentration in the North Passage and the South Passage during the spring tidal cycle obtained in the field survey use OBS 5 and DCDP and water and sediment samples which measured in the laboratory, part of the related results are shown in Fig. 9 and Fig. 10, and a summary of the collected data is listed in Table 1.

Data from this field survey show that the flow velocity and sediment concentration in the dry and flood seasons at spring and neap tidal cycles are different. In the dry season during spring tide in the South Passage, the flow velocity at the water surface (H is the relative water depth, the surface is $0H$, $1H$ is the bottom) in the ebb tide period is higher than that in the flood tide period (Table 1). At a relative depth of $0.4H$, the ebb tide velocity is lower than that the flood tide current. At $0.8H$ relative depth from the water surface, the flow velocity of the ebb tide is lower than that the flood tide current. In the neap tidal cycle in the South Passage, the ebb tide and river flow velocity at relative depth of $0H$ and $0.4H$ depth are higher than that flood tide velocity respectively, but the flood velocity at relative depth of $0.8H$ is higher than that ebb and river flow velocity.

In the dry season during spring tide in the North Passage, the velocity of ebb tide and river flow at relative depth of $0H$ is little lower than that flood velocity, but at relative depth of $0.4H$ and $0.8H$ are little higher than that flood velocity, respectively. While during the neap tide period, the ebb and river flow velocity at relative depth of $0H$, $0.4H$, and $0.8H$ are higher than that flood tide velocity respectively.

In the flood season during the spring and neap tidal cycle in the South and North Passage, the ebb tide and river flow velocity at relative depth of $0H$, $0.4H$, and $0.8H$ depth are correspondingly higher than that flood velocity, respectively.

In most cases, the mean sediment concentration during ebb tide period in the South and North Passage in the dry and flood season during the spring tidal cycle at relative depth of $0H$, $0.4H$, and $0.8H$ are higher than that flood tide period, respectively. But in some cases, the sediment concentration at relative depth of $0H$ and $0.4H$ are different because of the different riverine mechanics during the spring and neap tidal cycle.

Through the comparison of the velocity of ebb tide and river flow with flood tide velocity during the spring and neap tidal cycle in flood and dry season, in most cases, the ebb tide and river flow velocity at water surface is higher than the flood tide velocity, while at relative depth of $0.4H$ and $0.8H$, in some cases, the flood tide velocity is higher than that the ebb tide and river flow velocity. That is during the flood tide period, flood tide current start

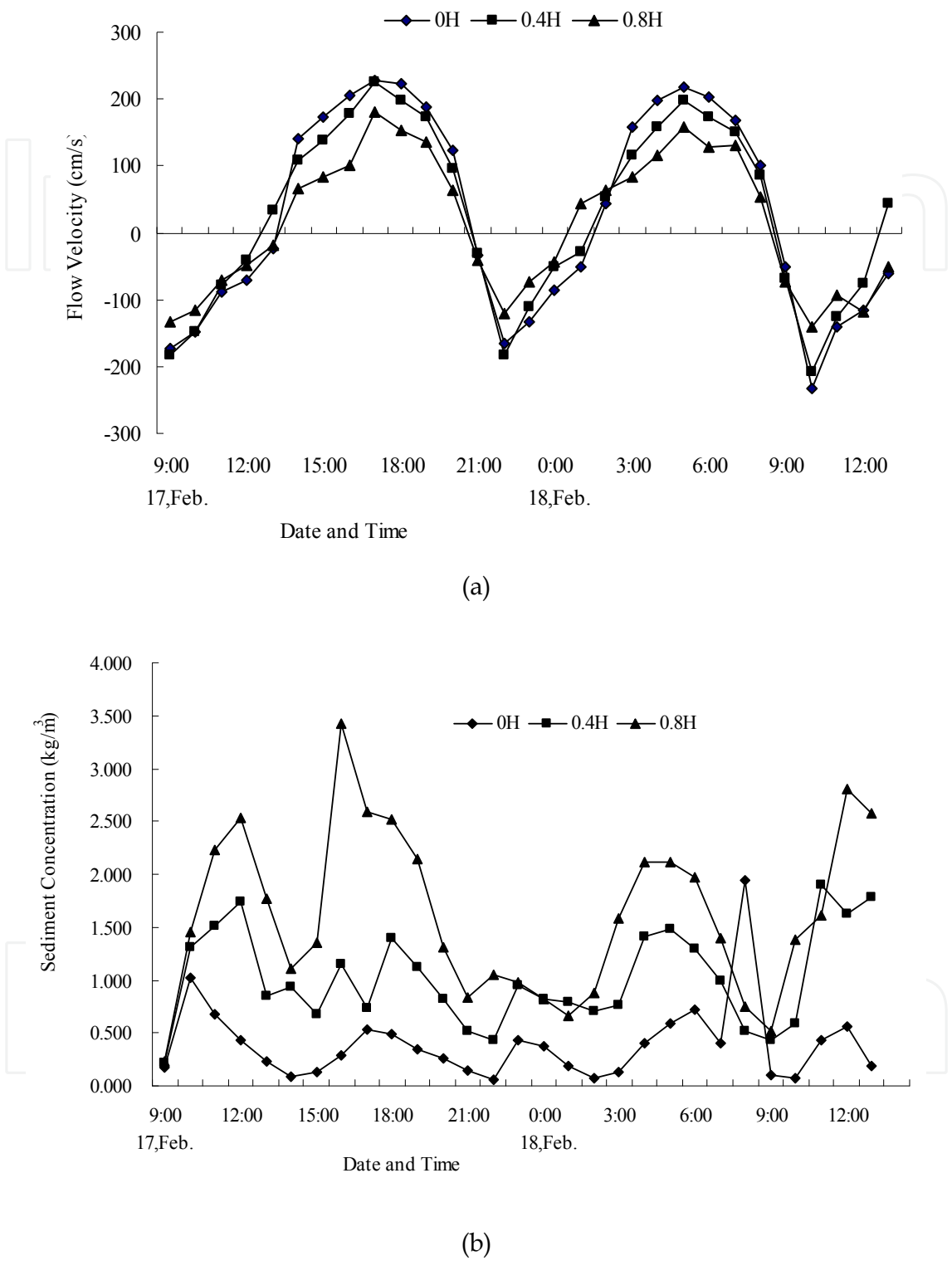


Fig. 9. Variation of the (a) flow velocity and (b) sediment concentration in the dry season at spring tide in the North Passage, where 0H means measured at the surface, 0.4H and 0.8H means measured at the 0.4 and 0.8 fractions of depth (H) from the surface, respectively.

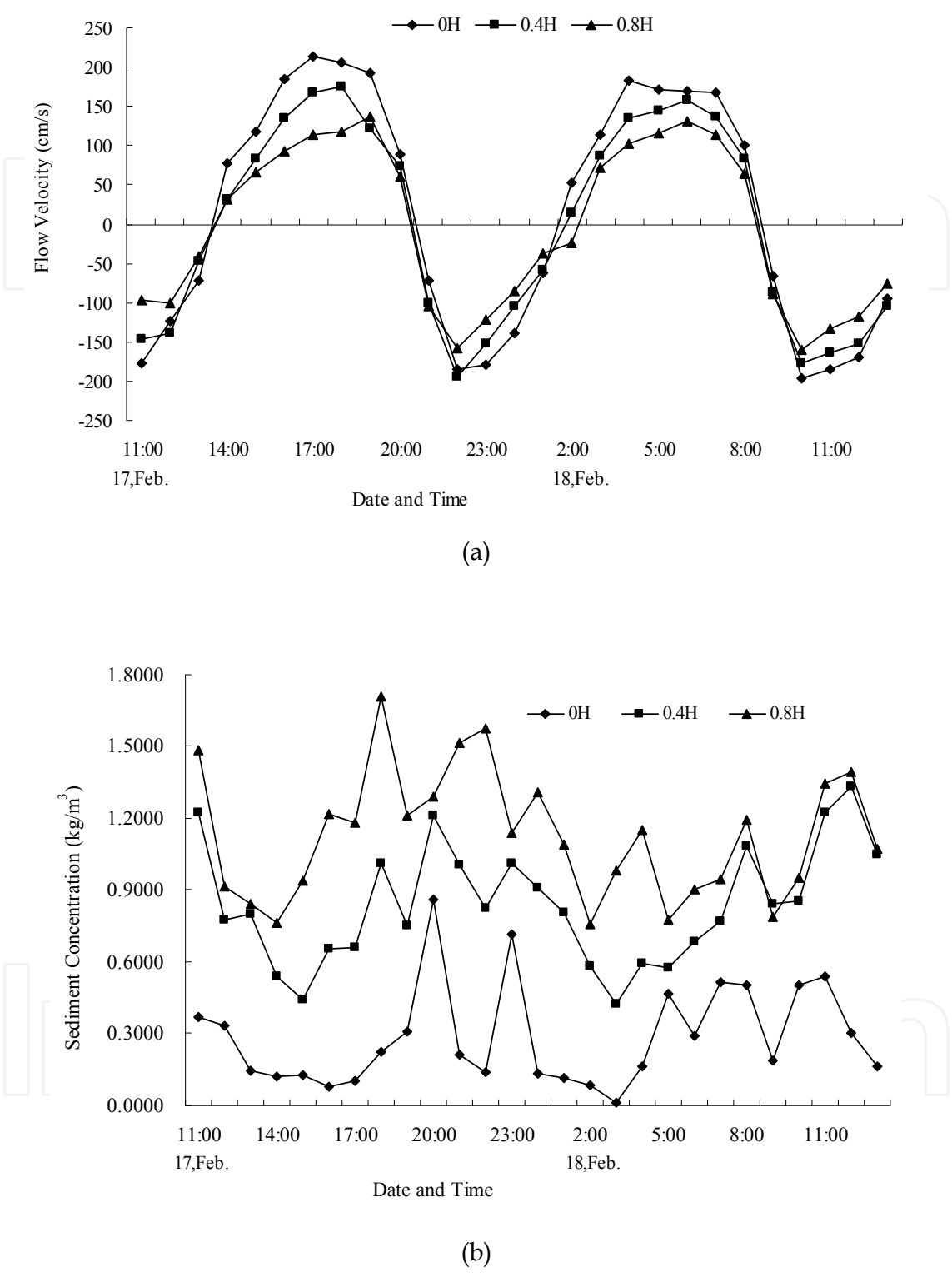


Fig. 10. Variation of the (a) flow velocity and (b) sediment concentration in the dry season at spring tide in the South Passage, where 0H means measured at the surface, 0.4H and 0.8H means measured at the 0.4 and 0.8 fractions of depth (H) from the surface, respectively.

In the flood season	North Passage											
	spring tide (15-16, July)						neap tide (20-21, July)					
	Max Flood Velocity (cm/s)	0H	122	Sediment Concentration (kg/m³)	0H	0.21	Max Flood Velocity (cm/s)	0H	74	Sediment Concentration (kg/m³)	0H	0.11
		0.4H	113		0.4H	0.34		0.4H	86		0.4H	0.22
		0.8H	111		0.8H	0.78		0.8H	76		0.8H	0.48
	Max Ebb Velocity (cm/s)	0H	195	Sediment Concentration (kg/m³)	0H	0.87	Max Ebb Velocity (cm/s)	0H	139	Sediment Concentration (kg/m³)	0H	0.51
		0.4H	193		0.4H	0.16		0.4H	129		0.4H	0.55
		0.8H	145		0.8H	1.53		0.8H	111		0.8H	0.56
	South Passage											
	spring tide (15-16, July)						neap tide (20-21, July)					
Max Flood Velocity (cm/s)	0H	198	Sediment Concentration (kg/m³)	0H	0.40	Max Flood Velocity (cm/s)	0H	79	Sediment Concentration (kg/m³)	0H	0.22	
	0.4H	191		0.4H	1.16		0.4H	77		0.4H	0.22	
	0.8H	159		0.8H	1.82		0.8H	61		0.8H	0.38	
Max Ebb Velocity (cm/s)	0H	246	Sediment Concentration (kg/m³)	0H	0.88	Max Ebb Velocity (cm/s)	0H	180	Sediment Concentration (kg/m³)	0H	0.29	
	0.4H	232		0.4H	1.97		0.4H	164		0.4H	0.28	
	0.8H	184		0.8H	1.97		0.8H	116		0.8H	1.09	
In the dry season	North Passage											
	spring tide (17-18, Feb.)						neap tide (23-24, Feb.)					
	Max Flood Velocity (cm/s)	0H	233	Sediment Concentration (kg/m³)	0H	0.07	Max Flood Velocity (cm/s)	0H	147	Sediment Concentration (kg/m³)	0H	1.02
		0.4H	207		0.4H	0.59		0.4H	125		0.4H	0.46
		0.8H	141		0.8H	1.37		0.8H	88		0.8H	2.30
	Max Ebb Velocity (cm/s)	0H	228	Sediment Concentration (kg/m³)	0H	0.53	Max Ebb Velocity (cm/s)	0H	220	Sediment Concentration (kg/m³)	0H	0.14
		0.4H	225		0.4H	0.74		0.4H	190		0.4H	0.70
		0.8H	180		0.8H	2.59		0.8H	117		0.8H	1.23
	South Passage											
	spring tide (17-18, Feb.)						neap tide (23-24, Feb.)					
Max Flood Velocity (cm/s)	0H	197	Sediment Concentration (kg/m³)	0H	0.51	Max Flood Velocity (cm/s)	0H	130	Sediment Concentration (kg/m³)	0H	0.70	
	0.4H	194		0.4H	0.83		0.4H	121		0.4H	0.88	
	0.8H	160		0.8H	0.95		0.8H	101		0.8H	1.53	
Max Ebb Velocity (cm/s)	0H	213	Sediment Concentration (kg/m³)	0H	0.10	Max Ebb Velocity (cm/s)	0H	188	Sediment Concentration (kg/m³)	0H	0.11	
	0.4H	175		0.4H	1.01		0.4H	143		0.4H	0.36	
	0.8H	137		0.8H	1.21		0.8H	93		0.8H	1.09	

Table 1.

from the bottom firstly, and during the ebb tide period, the ebb tide current start from the surface firstly. These different riverine and marine mechanics may cause the sediment deposited during the flood season because of the more longer slack water period, during the dry season, because of the lower water level and less water discharge from the drainage basin, Jiuduansha Shoal will be eroded. During the neap tidal cycle, the flow velocity is lower than that during the spring tidal cycle, and the sediment concentration is lower than

that the spring tidal cycle, that means the more sediment deposited on the tidal flat and estuarine river channel. During spring tidal cycle, because of the higher flow velocity and stronger tidal current, some of the deposited sediment in the channel and tidal flats maybe eroded and maximum turbidity formed.

3.3 Evolution of the Eastern Chongming Tidal Flat, Jiuduansha Shoal and Nanhui Marginal Tidal Flat

The Yangtze River transported a quantity of sediment into the estuarine region, and deposited sediment in estuary formed the tidal flats and shoals. About 2/3 of land area are expanded because of reclamation of the tidal flat, in nearly 50 years, about 800km² been reclaimed. From 1978 on, about 338.4km² tidal flat been reclaimed, especially in Eastern Chongming Tidal Flat and Nanhui Marginal Tidal Flat, and the reclamation still continued at present.

Eastern Chongming Tidal Flat, Jiuduansha Shoal and Nanhui Marginal Tidal Flat are the three very important wetlands in Yangtze Estuary. The Eastern Chongming Tidal Flat is an important wetland in the Yangtze River Estuary, from 1975 to 2005, the reclaimed area of the upper tidal flat is about 82 km², that means about all tidal flat over 0m isobathic line had been reclaimed under 1992, 1998 and 2001 levees construction (Fig. 11-14). Nanhui Marginal Tidal Flat is the main tidal flat in the south bank of the Yangtze River Estuary, but continued reclamation in past 30 years, about 140km² tidal flat had been reclaimed, and the tidal flat has lost the ecological significance because of the human actions (Fig. 15-16). After the formation of the Jiuduansha Shoal because of the Flood in 1954, the area, volume, and elevation of the Jiuduansha Shoal increased respectively. Figure 11 and figure 12 to 13 show a comparison of the Jiuduansha Shoal during 1975 to 2005. In 1975, the Jiuduansha shoal still formed by three shoals named Shangsha, Zhongsha and Xiasha respectively, there is only 9.5km² over 1m isobathic line (Yellow Sea Level) (Fig.17), under the riverine and marine processes, and human actions in the Yangtze Estuary, and Zhongsha and Xiasha coalesced in 2001 (Fig.18), and then three shoals of Jiuduansha Shoal coalesced in 2005 (Fig.19).

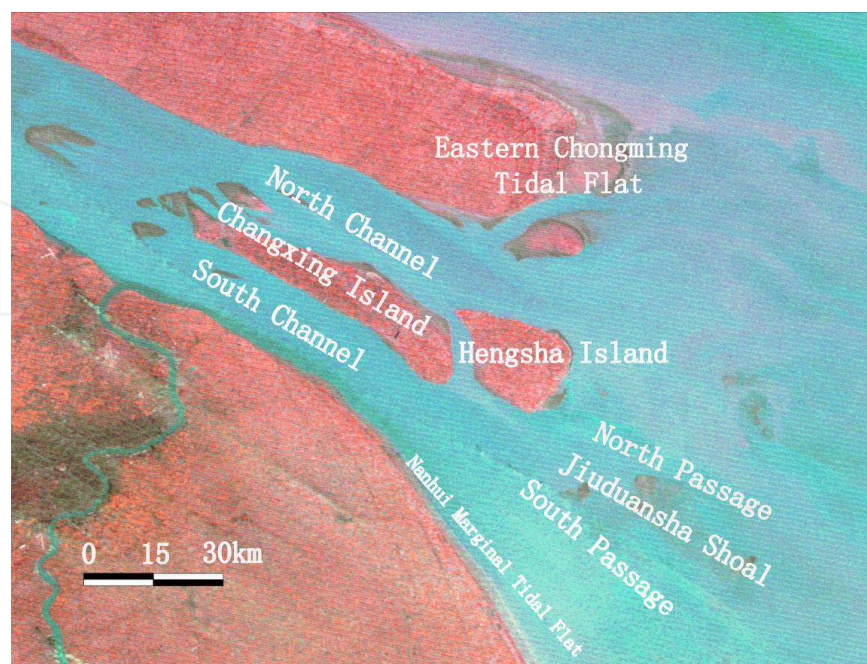


Fig. 11. Main tidal flat in Yangtze Estuary in 1975



Fig. 12. Eastern Chongming Tidal Flat in 1990



Fig. 13. Eastern Chongming Tidal Flat in 2001

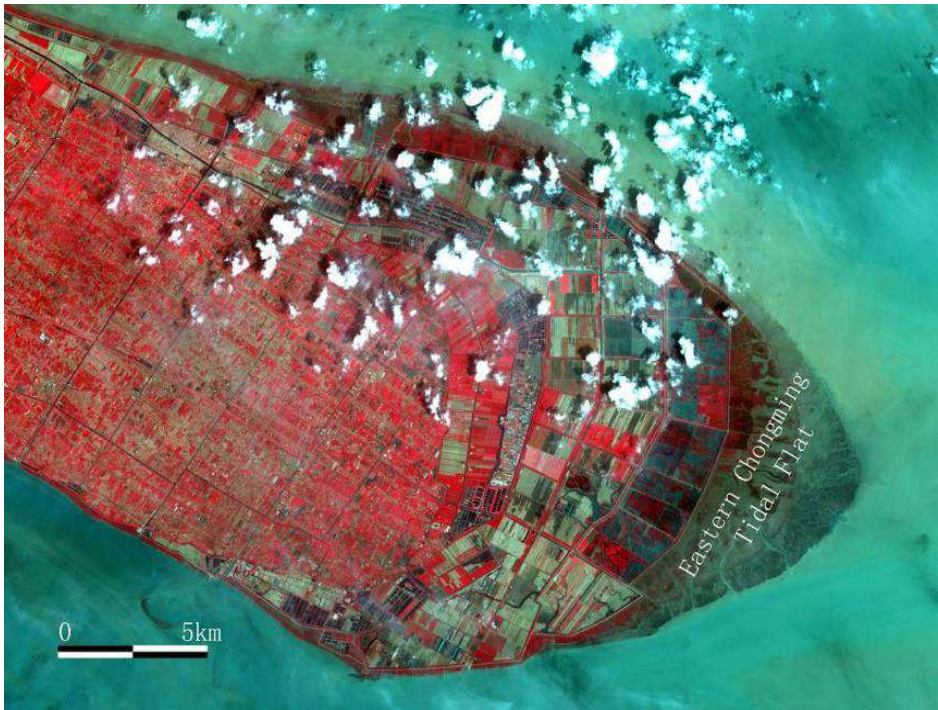


Fig. 14. Eastern Chongming Tidal Flat in 2005

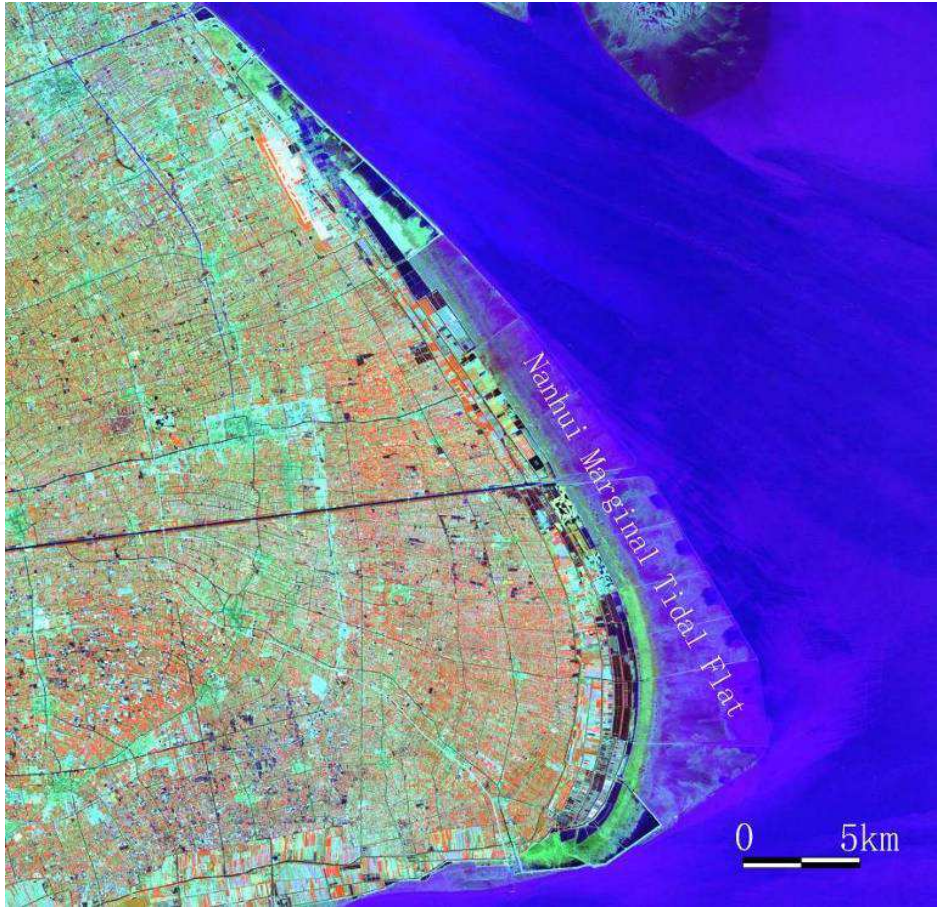


Fig. 15. Nanhui Marginal Tidal Flat in 2001

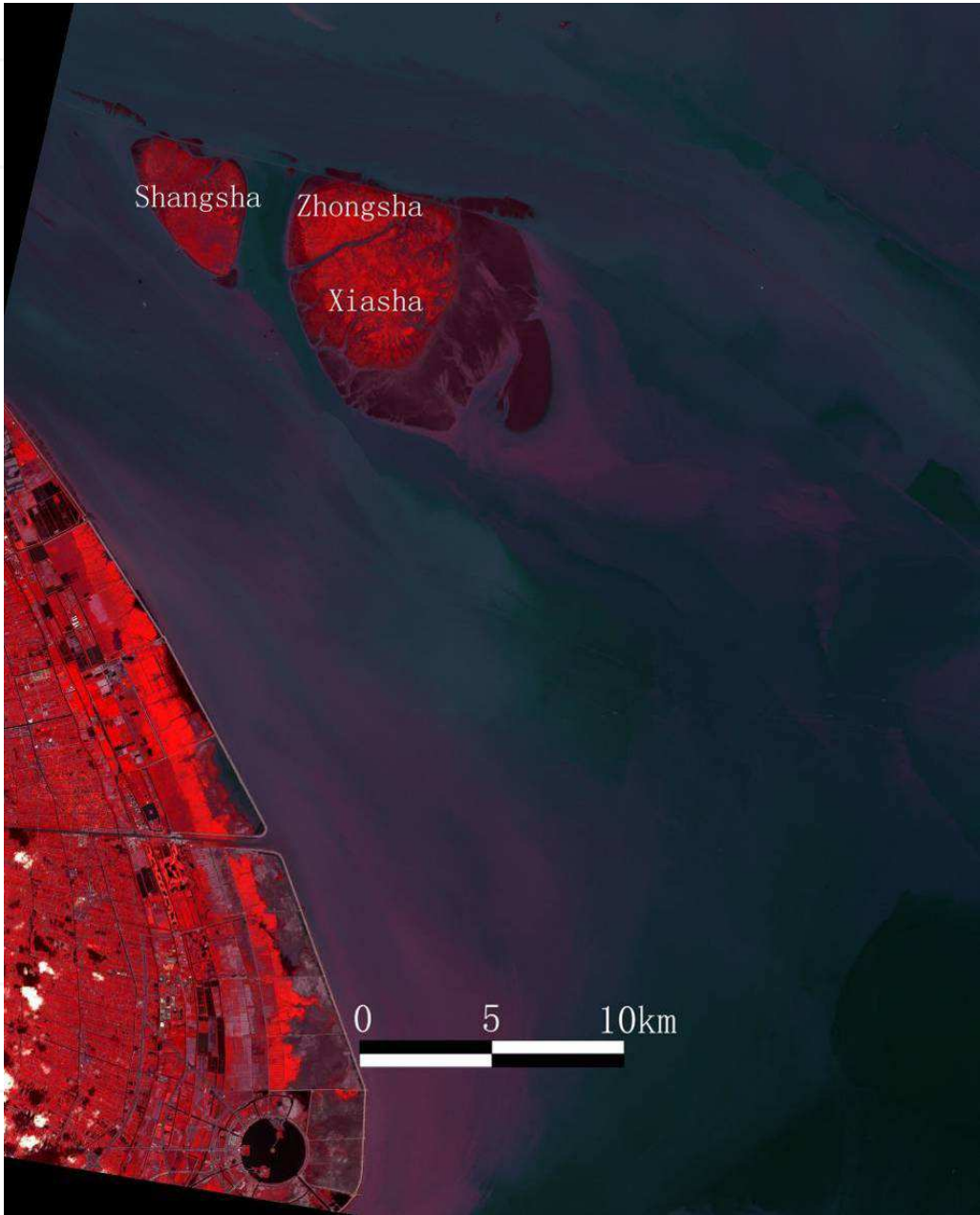


Fig. 16. Nanhui Marginal Tidal Flat in 2005

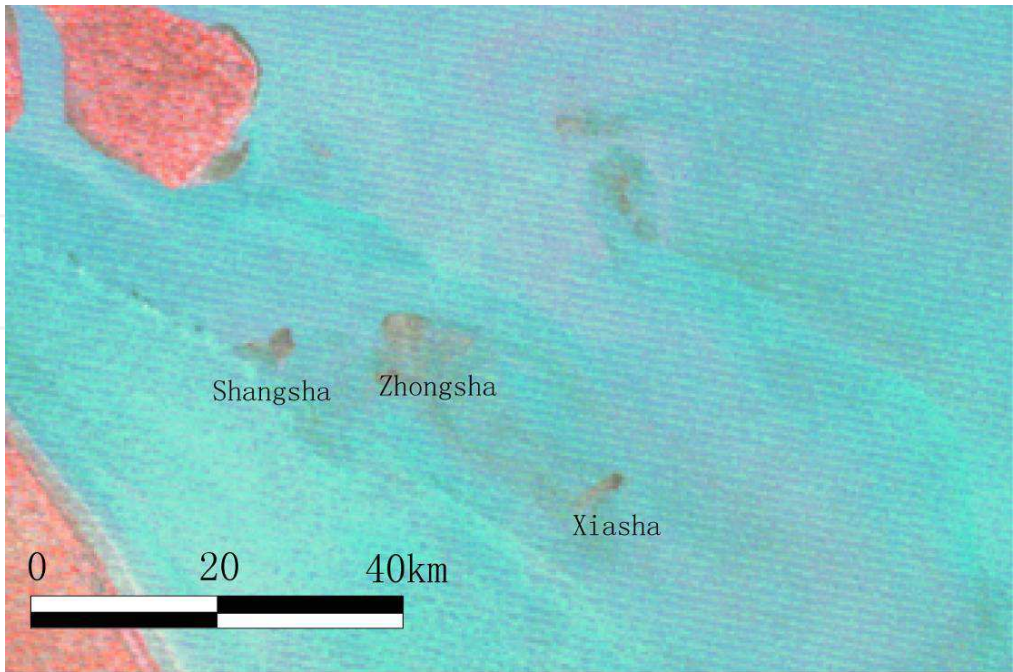


Fig. 17. Jiuduansha shoal in 1975

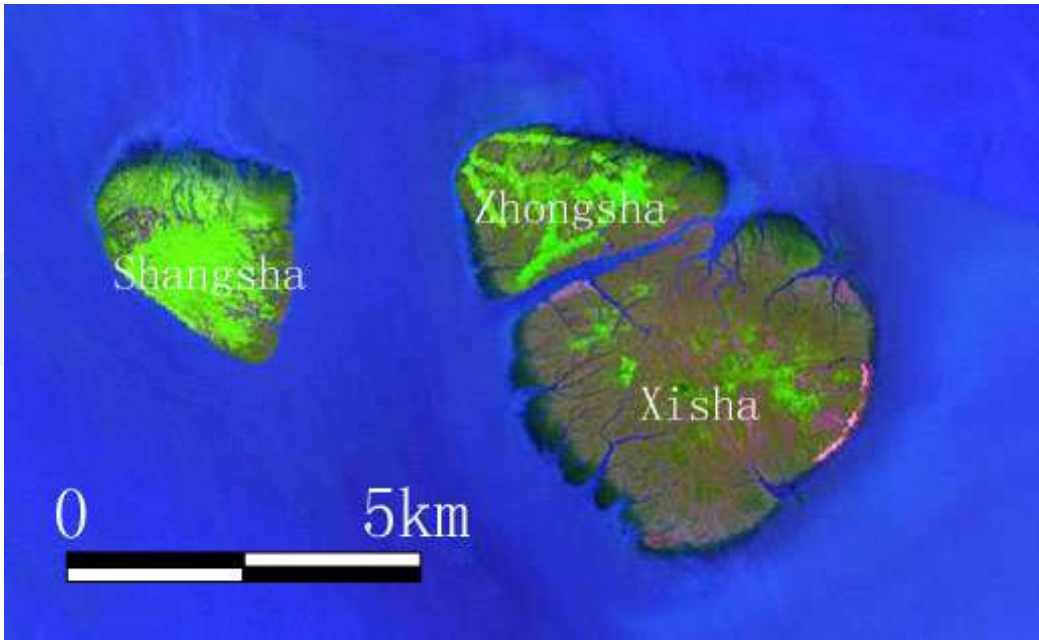


Fig. 18. Jiuduansha shoal in 2001

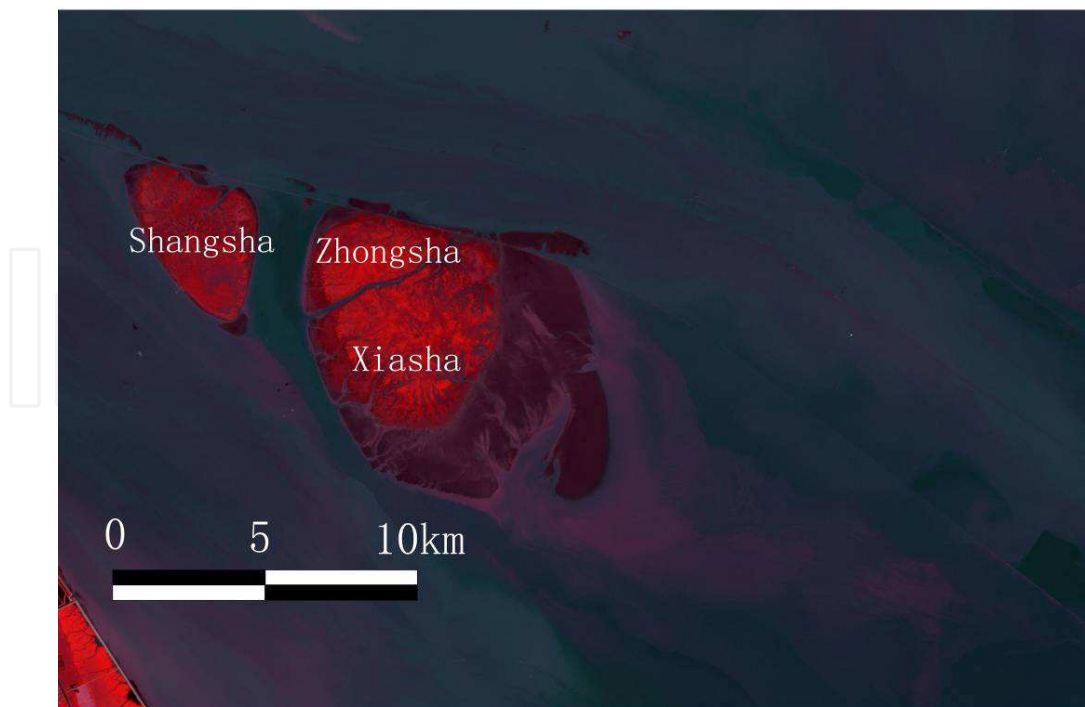


Fig. 19. Jiuduansha shoal in 2005

4. Conclusions

1. Eastern Chongming Tidal Flat is increased consistently in area and altitude. After the construction of 1992 and 1998 levee and 2001 dike, the higher tidal flat has been reclaimed, but due to the deposition of the sediment from the drainage basin, the higher tidal flat, inter-tidal flat and lower tidal flat are increased continuously.
2. The Jiuduansha Shoal formed in 1954 because of the historically large Flood in the Yangtze River Basin, the Flood caused the ebb channel and flood channel merge, and the Jiuduansha Shoal isolated from the Southern Tongsha Tidal Flat. Because of the Siltation on the Jiuduansha Shoal, the area and altitude of the Jiuduansha shoal increased consistently.
3. Nanhui Marginal Tidal Flat once an important tidal flat in southern bank of the Yangtze River Estuary, it is had lost the ecological situation because of the reclamation to 0m isobathic line.

5. Acknowledgements

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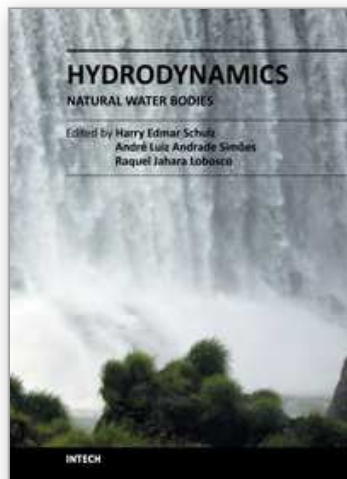
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