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The evolution characteristics of main waterways and their control mechanism in the radial sand ridges of the southern Yellow Sea

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Abstract

The comparison of the underwater topographic data in recent four decades shows that main waterways of the radial sand ridges area in the southern Yellow Sea tend to gradually migrate southward (scour depth and southward extension of the main channels in Xiyang, southward approach of Lanshayang Waterway and Xiaomiaohong Waterway on South Flank). Although there are various hypotheses about the cause and mechanism of the overall southward migration of the radial sand ridges, no universal and reliable understanding has been obtained so far. The mechanism of this process becomes a challenging problem which serves a key issue in the morphodynamics of the radial sand ridges and the harbor construction in this area. On the basis of the shoreline positions and underwater terrains at different development stages of the Huanghe Delta coast in northern Jiangsu Province, China since the northward return of the Huanghe River and flowed into the Bohai Sea, combined with the tidal wave numerical simulation study, the characteristics and hydrodynamic changes of the tidal wave system in the southern Yellow Sea at different evolution stages are investigated. It is shown that due to the shoreline retreat and the erosion of underwater delta, tidal current velocity is enhanced, and the enhanced area gradually migrates southward. It is revealed that this southward migration of a large-scale regional hydrodynamic axis is possibly a dominant mechanism leading to the overall southward migration of the radial sand ridges.

Key words: radial sand ridges, abandoned Huanghe Delta, shoreline change, hydrodynamics, numerical simulation

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1 Introduction

The radial sand ridges of the southern Yellow Sea are radially distributed in the east coast of Jiangsu Province. Shaped by large area distribution of alternate ridge fillets and special complex topographic features, radial sand ridge is a unique geomorphic type of the southern Yellow Sea (Ren, 1986; Li et al., 2001). In recent years, due to the needs of economic and social development, more attention has been paid to those tidal channels with good depth conditions and wide intertidal mud flat in the inshore area of the radial sand ridges. The evolutionary trend and stability have become one of the hot topics in the research on the radial sand ridges. According to recent study on the stability of inshore waterways, sandbars and beaches in the radial sand ridges, such waterways as Xiyang, Lanshayang, Xiaomiaohong waterway on the radial sand ridges and the sandbars among them generally show a trend of gradual southward migration since the 1960s (He et al., 2005; Chen et al., 2007; Chen, 2008). The dynamic mechanism of this trend becomes a challenging problem which serves a key issue in the morphodynamics of the radial sand ridge and the harbor construction in this area.

Previous studies indicated that tidal current is a main dynamic for the formation and maintenance of the radial sand ridges, instead of external sediment (Zhu et al., 1998a, b; Li et al., 2001; Zhu and Chen, 2005). The convergent tidal wave system off the Jiangsu coast is the inevitable result of the propagation of ocean tidal wave in the unique boundary formed by the Korean Peninsula, the Shandong Peninsula and Jiangsu shoreline (Lin et al., 2000). Over nearly half a century, among the main factors influencing the change of tidal wave system in the southern Yellow Sea, the ocean tidal wave, Coriolis force, deep-sea topography and friction coefficient, etc. except the coastal change, are impossible to change significantly. During this period, the tidal wave system pattern is under the control of Huanghe River shorelines, among which only the Jiangsu coast has undergone substantial siltation and erosion changes. It can be seen that the Jiangsu coastline change is the most critical factor influencing the change of tidal wave system in the southern Yellow Sea in this period. During the 100 a since the northward return of the

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Huanghe River in 1855, shoreline retrogradation at the top of the Huanghe Delta in the northern Jiangsu Province has reached more than 20 km and the subaqueous delta has basically been eroded (Cai and Wu, 2002; Yu et al., 2002). Therefore, the local influence of the dramatic changes of shoreline and underwater topography on the tidal wave propagation cannot be ignored. In this study, using a large-scale tidal model and a local tidal current model, the characteristics of tidal wave system of the South Yellow Sea at different evolution stages of the abandoned Huanghe Delta in the northern Jiangsu Province were studied, the hydrodynamic changes caused by coastal changes were analyzed, and the causes for the general southward migration trend of waterways and sandbars were discussed. The macro background of radial sand ridges evolution from the perspective of dynamic mechanism was analyzed, so as to provide a scientific basis for the utilization and protection of tideland resources in Jiangsu, especially for the decision-making activities of harbor development.

2 Evolution characteristics of the main waterways of the radial sand ridges

With the northward return of the Huanghe River and the southward migration of the Changjiang (Yangtze River) Estuary, the radial sand ridges have become a relatively independent hydro-geomorphological system. Because of the erosion of sandbar periphery caused by the prevailing wind waves, the pattern of convergent-divergent tidal current makes the sediment partially move towards the inner nearshore area. Affected by the radial tidal wave and the creeping trend of the main tidal channels in varying degrees, erosion and accumulation processes continue to occur inside the sandbars. In particular, the influence of the two major tidal wave systems on the regions of the radial sand ridges varies to some extent. Among them, Xiaomiaohong Waterway in the south and Xiyang Waterway in the north are mainly controlled by the progressive tidal wave of the East China Sea and the rotary standing tidal wave of the Yellow Sea, respectively. The dynamic conditions are relatively simple, and a seawall is used on one side as a fixed boundary, thus their dynamics is relatively weak. Chenjiawucao, Kushuiyang, Huangshayang and Lanshayang Waterways in the middle are significantly affected by the convergence of the two tidal wave systems, where the dynamic conditions are relatively complex, and no fixed boundary is set on either side of the waterways, leading to relatively strong mobility of waterways and sandbars in this area (Fig. 1).

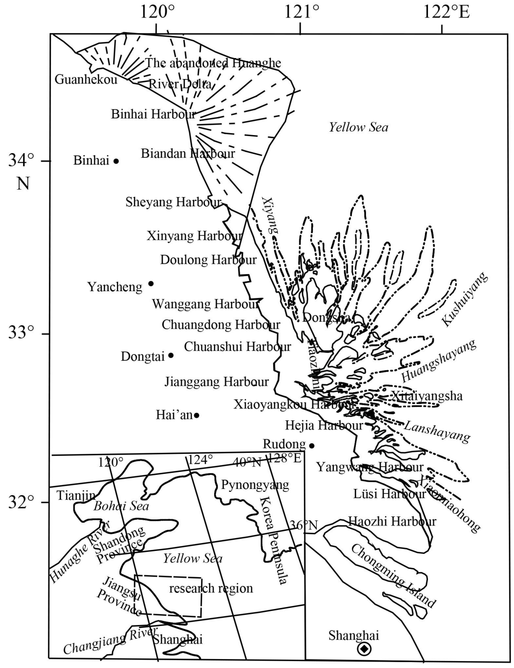

Fig. 1. The location of the radial sand ridges.

2.1 *Evolution characteristics of Xiyang Waterway in the north of radial sand ridges*

Xiyang Waterway is one of the main tidal channels in the radial sand ridges and has a horn shape with the opening facing NNW. Its deep trench axis faces NNW, paralleling to the coastline and adapting to the dynamic axis of the tidal current. It is divided into east and west waterways with Xiaoyinsha and Piaoersha as the boundary. Dongsha, the largest one among all the radial sand ridges, is located on the east side of Xiyang (Fig. 2).

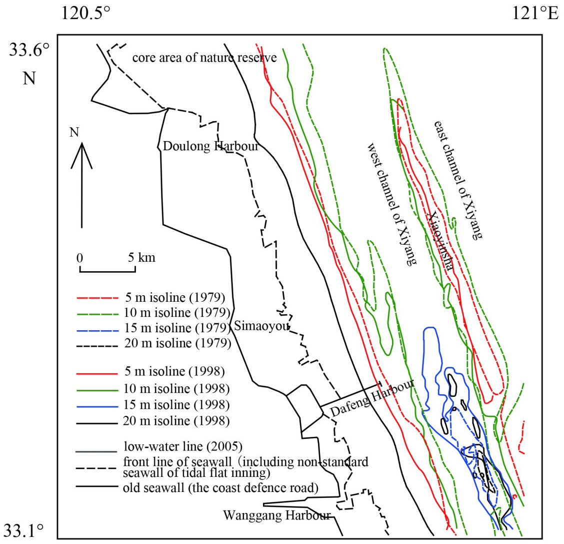

Fig. 2. Isobath comparison of Xiyang Waterway form 1979 to 1998.

Although Xiyang Waterway is the tidal channel of the largest scale in the radial sand ridge area, it has a short development history according to its waterway length, width and depth of the deep trench. Since the northward return of the Huanghe River, the interference of the sediment from the Huanghe River is gradually weakened, the offshore tidal current becomes increasing dominant and nearshore tidal current becomes stronger and stronger, providing dynamic conditions for the southward extension and scouring of the Xiyang Waterway, and making it an important channel for the transport of eroded sediment of the abandoned Huanghe Delta to the hinterland of the radial sand ridges. The 1904 British Admiralty Chart shows that the south side of the abandoned Huanghe Estuary still has some large-scale sandbars, and now there is still a series of small sandbars in the middle segment of the Xiyang Waterway outside the Dafeng Harbor, indicating that Xiyang Waterway at that time was not yet perforated. A waterway with a great water depth emerged in the south of the abandoned Huanghe Delta, extending southward until Dachuan Harbor (now east of Longwang Temple), with its maximum depth reaching 11 m, according to the 1937 Japanese Sea Chart. But the 1947 British Admiralty Chart shows that the waterway extends southward to Wanzhuangzi Harbor (now Simaoyou Estuary), with its general water depth of about 12 m and up to 14.6 m. It is evident that in the 1940s, Xiyang Waterway extended to the vicinity of Simaoyou and began to erode sandbars from Simaoyou to Badou Mountain. According to the chart data measured from 1963 to 1967, the southward extension of the waterway stopped, but the deep trench was further deepened to more than 20 m. In the 1979 mapping, the maximum depth point was located outside the Wanggang harbour and it was 28.5 m (Ying et al., 2011). The 1998 measured underwater topographic data shows that the location of the deep trench has little change, but its maximum depth is further increased to –38 m. The isobath comparison of Xiyang Waterway in the west of Xiaoyinsha from 1979 to 2009 shows the following characteristics of seabed erosion and deposition in this water area (Fig. 2): (1) The west groove of Xiyang Waterway is further deepened, as indicated by the change of maximum water depth of outer deep trench of Wanggang from 28.5 m in 1979 to 38.0 m in 2009; (2) in the period of 1979–1993, the south end of Xiyang 15 m-deep trench extended southward for about 6.7 km, and east groove of Xiyang was deepened; (3) in 1993, the south end of 15 m- deep trench was nearly 4 km wide in 2006 and the 15m-isobath close to Xiaoyinsha extended southward for about 6.8 km; (4) during 2006–2009, the 15 m-deep trench was increased by 0.8~3.0 km in width, and extended southward for 2.6 km, with an average annual extension of about 0.9 km/a (Zhang and Chen, 1992).

2.2 *Southward migrations of hydrodynamic spindle of Lanshayang on south flank of radial sand ridges*

Lanshayang Waterway and Xitaiyangsha are located in the middle and south of the radial sand ridges. As indicated by the comparative analysis of underwater topographic data of more than four decades from 1963 to 2006: (1) The main channels of both Huangshayang and Lanshayang had the trend of southward migration and the center line of 10 m-deep trench of Lanshayang in the north of Xitaiyangsha moved southward for about 600 m during the 43 a (Fig. 3); and (2) Lanshayang Waterway tail in the north of Xitaiyangsha was fully developed from 1963 to 1994, with the dynamic spindle deviated to the south. In the same period, south waterway of Lanshayang also extended rapidly, not only the depth and width were increased, but the waterway also became straight gradually and extended westward.

2.3 *Southward migration of the hydrodynamic spindle of Xiaomiaohong Waterway*

Xiaomiaohong tidal waterway with a total length of about 42 km is situated in the southernmost tip of the radial sand ridges, about 60 km from the north branch of the Changjiang Estuary. It is gradually narrowed from outside the estuary to the tail. According to the comparison of topographic data (Lu, 2007). In 1963, 1979, 1989, 1993, 1998, 2003 and 2009 (Fig. 4), it can be seen that Xiaomiaohong Waterway shows a consistent evolution trend of silting in the north and scouring in the south, and the deep trench of the north waterway at the estuary segment continues to shrink until it disappeared, and the south waterway is fully developed. Since the 1980s when the south waterway head is divided into the south and north branches, the south branch has been always in the developing process. The development of Xiaomiaohong south waterway and its south branch shows that the dynamic axis of this waterway also has the trendency of southward movement.

3 Simulation of tidal current field in different historical periods

3.1 *Model establishing*

A Delft-3D modeling system developed by Deltares is used in this study. This system has been widely used in the numerical simulation of coastal engineering. It is based on incompressible

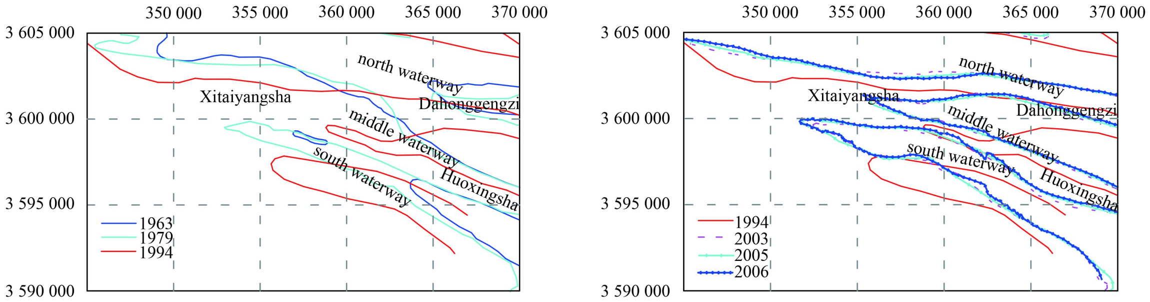

Fig. 3. The change of 10 m isobath of Lanshayang Waterway in different periods (Beijing 54 coordinate system, the central meridian is 123 degrees, the same below).

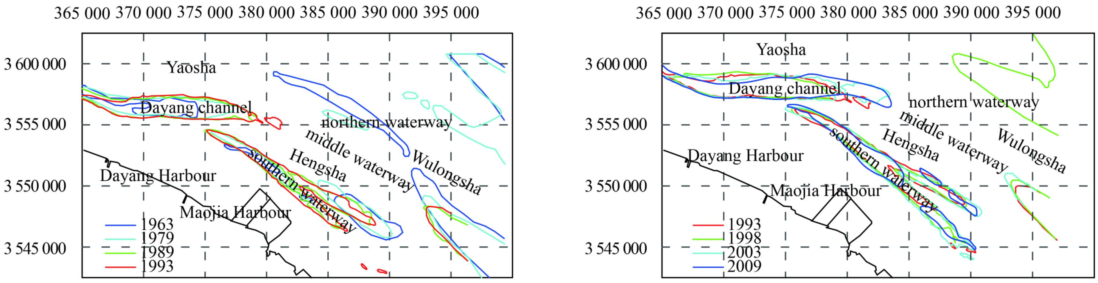

Fig. 4. The change of 10 m isobath of Xiaomiaohong Waterway in different periods.

shallow water equations under a static pressure assumption. Because this study involves a large modeling domain, the earth curvature and the change of Coriolis acceleration with latitude should be considered. Therefore a 2-D tidal wave propagation equation in spherical coordinates is used. In this research, a 2-D horizontal mathematical model of the tidal wave of the East China Sea is established firstly. The model region (24°–41°N, 117°–131°E) includes the Bohai Sea, the Yellow Sea and the East China Sea. The tidal wave movement of eight tidal constituents, i.e., M_2, S_2, K_1, O_1, N_2, K_2, P_1 and Q_1 was simulated in this model. The mathematical model of tidal current in the Jiangsu sea area is then established based on the boundary conditions provided by this large-scale tidal wave model. The grid scale of the large-scale tidal wave mathematical model is 2′×2′; and a grid number is 162×205; while the grid number of the tidal current model in Jiangsu sea area is 171×202, with the maximum grid scale of 5 km and the minimum of 500 m. An ADI method is used as a numerical calculation method (Chen, 2008).

3.2 *Model validation*

According to the British Tide Table, the four tidal constituents, including M_2, S_2, K_1 and O_1 of 91 tide gauge stations within this region are selected as validation data. Among them, M_2 tidal wave amplitude variance is 9.4 cm, phase lag error is 7.51°; K_1 amplitude variance is 2.5 cm and phase lag error is 6.52°. However, in terms of spatial error distribution, the validation points with large errors are concentrated near the Changjiang Estuary and the Hangzhou Bay. From the perspective of the number and location of amphidromic points, the distribution patterns of tide and tidal current obtained in this study are basically consistent with previous studies (Zhang et al., 2005; Li et al., 2006; Jiang and Lü, 2007). Four full amphidromic points of semidiurnal tide are confirmed in the China offshore area, Thers are two amphidromic points located in the Bohai Sea and the Yellow Sea, respectively. Besides, there is a degenerated amphidromic point located on the north end of Taiwan Island. There are two amphidromic points of diurnal tide, with each one located in the Bohai Sea and the Yellow Sea, respectively (Chen, 2008).

3.3 *Determination of shoreline and water depth in different historical periods*

Referring to the results of previous studies, combined with the drilling data of nearshore and land, compared with modern Jiangsu shoreline and underwater topographic features, the Jiangsu coastal landform evolution is analyzed. The Jiangsu coastal evolution is divided into the folloflank four major periods: (1) the period when the abandoned Huanghe Delta was developed (before 1885); (2) the delta was eroded and migrated southward (1855–1904); (3) the subaqueous delta was eroded and leveled rapidly (1904–1930s); and (4) the isobath migrated inward in general (the 1930s–2007). On the basis of previous studies (Cai and Wu, 2002; Xu and Lu, 2005; Ling, 2006), the shorelines of the four periods are determined respectively (Fig. 5). In calculating the paleo-tidal current fields in different historical periods, the paleowater depth, that is ancient landform, should be determined. The research on cylindrical core and sub bottom and bottom profiles shows that the north and east boundaries of subaqueous delta of the abandoned Huanghe River were located at the isobath of approximately 30–40 m, and the south flank has now been covered by the radial sand ridges in northern Jiangsu Province, with coordinate starting from 33°05′N in the south and to 34°50′N in the north, from 120°30′E in the west and to 122°30′E in the east. The thickness of the subaqueous delta does not exceed 3 m and its average thickness is about 2 m (Xu and Lu, 2005). For the depth data within the delta range, the paleowater depth before 1855 is recovered according to Chen Lunjiong's Coastal Map, charts published in Germany and the slope of the modern Huanghe Delta. For the ancient landform in the early 1900s, British Sea Chart in the 1930s and Japanese Sea Chart in 1937 are consulted. Modern depth is utilized to the depth outside the range, which is read from the millionth chart (Lin et al., 2000; Chen et al., 2013).

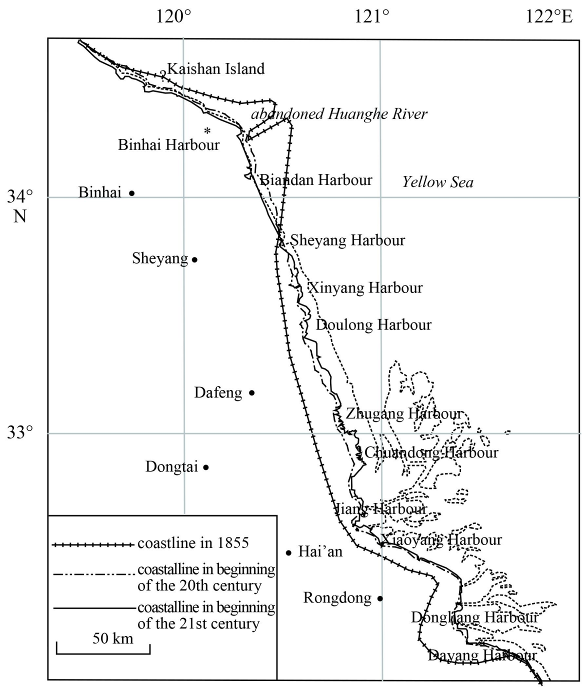

Fig. 5. The shoreline locations in different periods.

4 Results

4.1 *Effect of erosion and retreat of the abandoned Huanghe Delta on amphidromic point*

The radial sand ridges are located in a special tidal environment. The convergent-divergent tidal current field was generated by the progressive tidal wave of the East China Sea and the rotary tidal wave in the northern waters converge in the Jianggang coast. As shown by the numerical simulation results at different periods, local changes of Jiangsu shoreline do not change this convergent-divergent tidal wave system. However, because of the continuous coastal erosion of the abandoned Huanghe Delta over the past century, the amphidromic points of M_2, K_1 and other tidal constituents are constantly moving southwestward, indicating that the rotary tidal wave propagating from the Shandong Peninsula has been strengthened due to the delta erosion and shoreline retrogradation (Table 1). This makes its meeting point with the progressive tidal wave of the East China Sea shift southwestward (Chen, 2009).

Table 1. Moving distance (km) of amphidromic point

	1855–1930s	The 1930s–early 21st century
M_2	16.5	8.1
S_2	13.1	7.4
K_1	0.8	0.2
O_1	2.4	0.4

4.2 *Effect of the abandoned Huanghe Delta erosion on large scale tidal current field*

Before the northward return of the Huanghe River in 1855, as the abandoned Huanghe Estuary shoreline protruded outward for more than 20 km, and there was a huge subaqueous delta, the tidal wave propagating from north to south was blocked by the protruding shoreline and subaqueous delta, exhibiting a strong deflecting effect on the water flow, and the water flow outside the delta had a strong dynamics. The hydrodynamics of the radial sand ridges in the south was relatively weak due to the cover of the abandoned Huanghe Delta (Figs 6 and 7). With the shoreline retrogradation and erosion of subaqueous delta, the propagation of tidal wave from north to south becomes smoother, the convergence point of two tidal waves gradually migrates southward, and the hydrodynamics of the radial sand ridges becomes stronger and stronger (Figs 8 and 9).

To study the impact of erosion and recession of the abandoned Huanghe Delta on the hydrodynamics of deep channel of different waterways, representative points were taken in Xiyang Waterway and Lanshayang Waterway to calculate and analyze the variation of flow rate in different historical periods. The results show that from 1855 to 1904, although the underwater topography of the abandoned Huanghe Delta was changed to some extent, a large subaqueous delta always exists, so that the water flow in the deep trench of Xiyang Waterway was relatively weak. The mean flow velocity is only 0.4 m/s and the maximum velocity is about 0.7 m/s. With the erosion of subaqueous delta and the rapid retrogradation of the shoreline, the propagation of tidal wave from north to south became smoother, the flow intensity of Xiyang Waterway continued to increase. In 1921, its mean and maximum velocities are increased to 0.8 and 1.4–1.5 m/s, respectively, nearly twice that of 1904. As the delta is eroded away, the abandoned Huanghe River migrated backward as a whole, and water flow in Xiyang Waterway was further increased, but at a greatly reduced rate. By the beginning of the 21st century, the mean velocity was 0.9 m/s and the maximum flow velocity was about 1.5 m/s, increased by about 10% compared with those in 1930 (Table 2).

Lanshayang Waterway is located in the middle of the radial sand ridges and in the transition area of rotary tidal wave of the

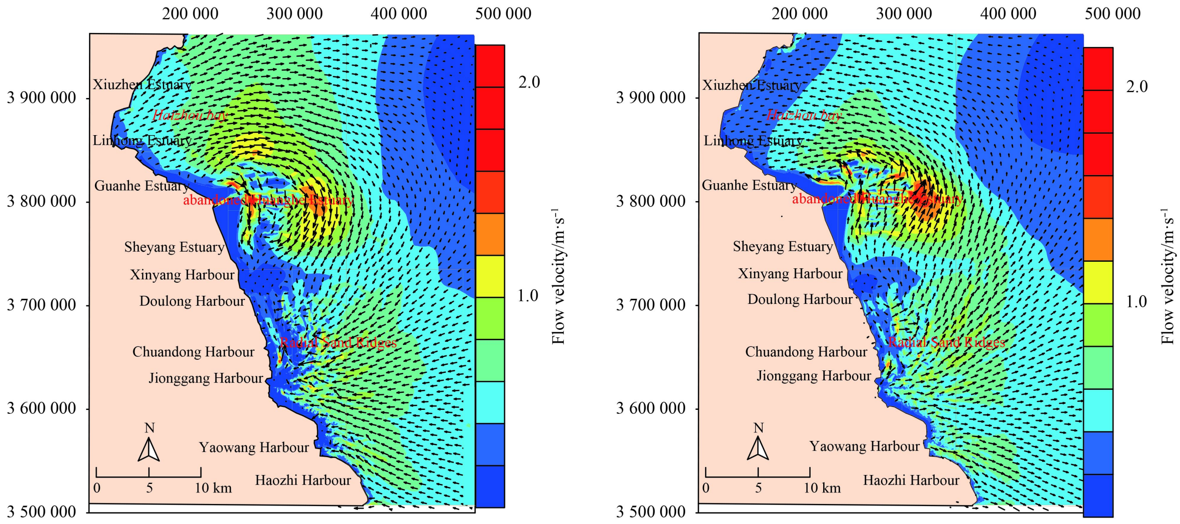

Fig. 6. Flow vector of the radial sand ridges during the flood (a) and ebb (b) tides (1855) .

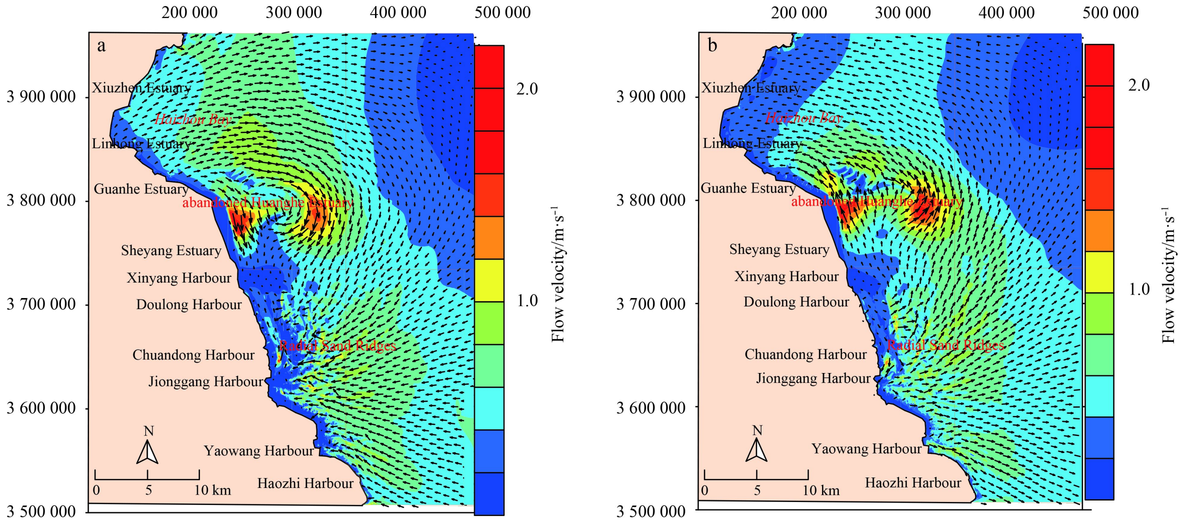

Fig. 7. Flow vector of the radial sand ridges during the flood (a) and ebb (b) tides (1904).

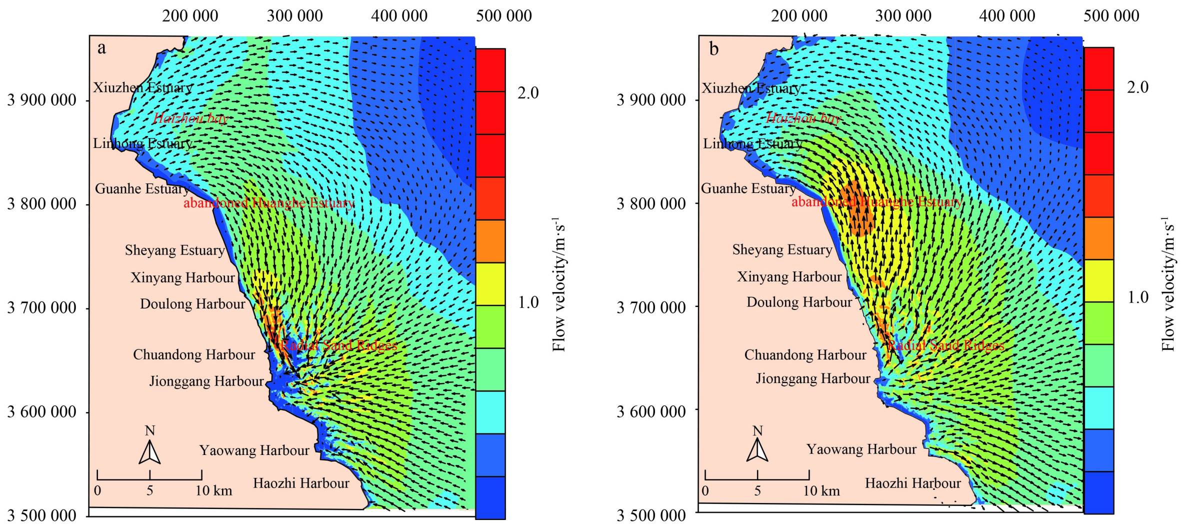

Fig. 8. Flow vector of the radial sand ridges during the flood (a) and ebb (b) tides (1921).

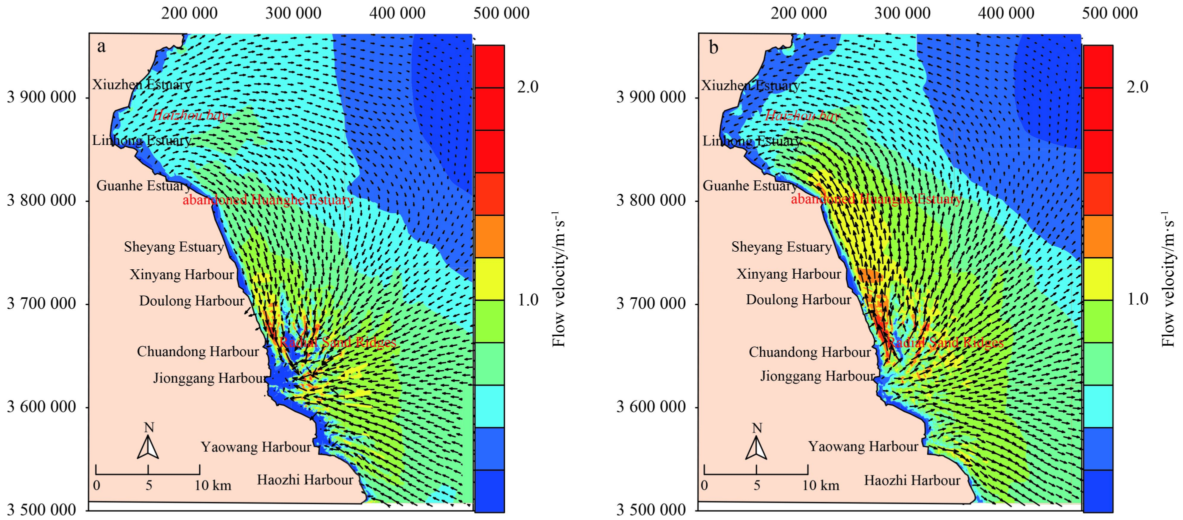

Fig. 9. Flow vector of the radial sand ridges during the flood (a) and ebb (b) tides (early 21st century).

Table 2. Velocity (m/s) variation at the representative points of different waterways

Year	Xiyang Waterway			Lanshayang Waterway			Xiaomiaohong Waterway		
	Mean of flood	Mean of ebb	Max velocity	Mean of flood	Mean of ebb	Max velocity	Mean of flood	Mean of ebb	Max velocity
1855	0.40	0.37	0.73	0.74	0.56	1.05	0.75	0.79	1.34
1904	0.44	0.39	0.95	0.74	0.55	1.04	0.74	0.78	1.33
1921	0.83	0.55	1.45	0.77	0.69	1.12	0.76	0.94	1.53
2007	0.94	0.64	1.55	0.80	0.70	1.14	0.77	0.97	1.57

southern Yellow Sea to the progressive tidal wave of the East China Sea. After the erosion and recession of the abandoned Huanghe Delta, the hydrodynamics of the channel in the Lanshyang Waterway is further strengthened. In particular, the flow velocity of the channel in Lanshayang Waterway is changed substantially after the delta was eroded away, with the mean velocity increasing by about 15%. As the erosion rate of the abandoned Huanghe River is slowed down, the velocity variation of the channel is also weakened accordingly.

The Xiaomiaohong Waterway lies on the southernmost flank of the radial sand ridges, with relatively simple properties. It is greatly influenced by the progressive tidal wave of the East China Sea, but the hydrodynamics of the channel is also further enhanced with the erosion and recession of the abandoned Huanghe Delta. After the delta erosion, the mean velocity of the channel in Xiaomiaohong Waterway is increased by about 10% (Table 2).

5 Discussion

The radial sand ridges off the coast of Jiangsu Province is origin of ancient Huanghe River, the ancient Changjiang River of the huge amount of sediment by radiation tidal wave system transformation. However, with the Huanghe Estuary to the north and the Changjiang Estuary to the south, it ceases to be a large supply of sediment, and become a quasi closed sediment system, external sediment is no longer the main factors controlling the development of the radiate sand ridges (Wang, 2002; Ge et al., 2009; Wang et al., 1998; Song et al., 1998; Zhang and Zhang, 1998). Since the return of the Huanghe River to the north, the radial sand ridge area has been in the redistribution of matter, water and sand are very active. The sandbar overall in the etching back, reduced area, but backward erosion intensity more and more small sandbar generally tends to be stable (Huang and Li, 1998; Huang, 2004; Wu et al., 2006; Li and Wang, 2002).

Off the coast of Jiangsu Province convergence of the tidal wave system is the inevitable result of the ocean tidal wave in the Korean Peninsula, the Shandong Peninsula and Jiangsu coastline constitute the unique boundary spread (Lin et al., 2000; Chen et al., 2009). Influence of local shoreline changes on the tidal wave system can not be ignored, the coastline change will cause tidal wave system of the amphidromic point flank, tidal rang changes (Lin et al., 2000; Chen, 2008; Chen et al., 2009; Le et al., 1995; Huang et al., 2005; Liu et al., 2012). Because of the continuous coastal erosion of the abandoned Huanghe Delta over the past century, the amphidromic points of M_2, K_2 and other tidal constituents are also constantly moving southwestward, indicating that due to the delta erosion and shoreline retrogradation, the rotary wave propagating from the Shandong Peninsula has been strengthened, which makes its meeting point with the progressive wave of the East China Sea shift southwestward. Thus, it is possible to make the diversion ridge line near the radial sand ridges migrate southward (Chen, 2008; Chen et al., 2009).

Considering that the abandoned Huanghe Delta coast is the major sediment source of the radial sand ridges, and that the rotary wave of the southern Yellow Sea needs to propagate southward through the offshore area of the abandoned Huanghe Delta to enter the radial sand rides so as to form the pattern of the convergent-divergent tidal current. Owing to the shoreline retreat and the erosion of underwater delta, the tidal current velocity is enhanced, and the enhanced area gradually migrates southward. It is revealed that this southward migration of a large-scale regional hydrodynamic axis is possibly a dominant mechanism leading to the overall southward migration of the radial sand ridges (Chen, 2008; Chen et al., 2013).

6 Conclusions

(1) The calculation results of the mathematical model in different periods show that: the convergence - divergence tidal wave system off Jiangsu Province does not changed with local variations in Jiangsu coast line. However, Because of the continuous coastal erosion of the abandoned Huanghe Delta over the past century, the amphidromic points of M_2, K_1 and other tidal constituents are also constantly moving southwestward.

(2) With the shoreline retrogradation and erosion of subaqueous delta, the propagation of the tidal wave from north to south becomes smoother, the hydrodynamics of the radial sand ridge area is enhanced and two tide wave convergence point gradually migrated southward.

(3) With the retreat of Jiangsu shoreline and the erosion of the subaqueous delta at the abandoned Huanghe Estuary, the rotary wave of the South Yellow Sea is further strengthened. The area with strengthening hydrodynamics gradually migrates towards the radial sand ridges, that is, the hydrodynamic axis migrates southward obviously. The mean velocity and maximum velocity of the deep trenches in Lanshayang Waterway and Xiaomiaohong Waterway on the south flank show a tendency to increase with the erosion and recession of the abandoned Huanghe Delta, and the hydrodynamic axis also has a tendency to migrate southward.

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