

Rapid Morphological Changes Caused by Intensive Coastal Development in Longkou Bay, China

Dong Li^{†‡}, Cheng Tang[‡], Xiyong Hou^{‡*}, and Hua Zhang[‡]

[†]Institute of Oceanology
Chinese Academy of Sciences
Qingdao, Shandong 266071, P.R. China

[‡]Key Laboratory of Coastal Environmental
Processes and Ecological Remediation
Yantai Institute of Coastal Zone Research
Chinese Academy of Sciences
Yantai, Shandong 264003, P.R. China



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ABSTRACT

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Analyses of the evolution of subaqueous topography in coastal water provide an understanding of the effects of intensive coastal development on bays and estuaries. Analysis of a series of historical bathymetric acoustic surveys has revealed large changes in morphology from the 1960s to 2010s in Longkou Bay, China. Water depths were extracted from digitized admiralty charts to explore the accretion-erosion characteristics in a geographical information system environment, providing quantitative estimates of morphological changes. Multibeam echosounders were used to map and analyze the geomorphologic features caused by the construction of artificial islands. Results illustrated that the shoreline and bathymetry of Longkou Bay have changed rapidly in recent decades. The subaqueous area decreased by about 15%, while land area increased by more than 13 km² in the study area during the last 50 years. From the 1960s to 1990s, the evolution of Longkou Bay was mainly governed by natural processes with a patchy distribution of deposition and erosion, and there were few signs of change related to large-scale human activities. During the period from the 1990s to 2010s, intensive coastal developments, including large port engineering projects, channel dredging, and construction of artificial islands, became the main processes affecting morphological changes in Longkou Bay. The high-resolution bathymetric results near the artificial island showed that the seafloor was dredged at many sites, leaving large areas of borrow pits. The sudden change of the underwater topography will lead to the destruction of local benthic habitat, and effective measures need to be taken to protect and remediate the heavily disturbed subaqueous environment.

ADDITIONAL INDEX WORDS: Bathymetric charts, multibeam mapping, underwater morphology, artificial island, land reclamation.

INTRODUCTION

Morphological changes can have important implications for coastal environments, especially in a bay that has high commercial, recreational, and ecological value. Understanding the long-term morphological change in a bay can provide insights into the historical characteristics of the bay and help researchers to assess the impacts of natural changes and human activities on the coastal system. The likely long-term impacts of physical factors dominating the morphological changes generally include sea-level rise, sediment discharge, tide currents, and wave fields (Blott *et al.*, 2006; Restrepo *et al.*, 2016; Van der Wal, Pye, and Neal, 2002; Wang *et al.*, 2013). Intensive coastal development such as channel dredging, harbor enlargements, sand excavation, and land reclamation can also influence the morphological changes (Van der Wal, Pye, and Neal, 2002; Zhang *et al.*, 2015). During the last century or so, such human activities often have had a greater effect on the morphological development than natural forcing factors (Hou *et al.*, 2016; Wang *et al.*, 2013; Wu, Hou, and Xu, 2014), and few estuaries worldwide still preserve the original broad intertidal area (Wolanski, 2006). Knowledge of the

natural and anthropogenic changes to coastal ecosystems and the design of successful restoration projects require knowledge of patterns of deposition and erosion.

Morphological processes in estuaries have long been investigated by scientists and coastal engineers (Fenster and FitzGerald, 1996; Harris and Collins, 1984; Van der Wal, Pye, and Neal, 2002; Wang, Li, and Li, 2013). Process-based models are regularly used to study morphological changes quantitatively. Short-term changes can often be satisfactorily predicted using hydrodynamic and morphodynamic models (Townend, 2005). Long-term geomorphologic evolution can be simulated using statistical models (Blott *et al.*, 2006; Wang *et al.*, 2013). However, geological and geomorphological evolution models have inherent limitations due to the lack of detailed physics (Blott *et al.*, 2006; Zhang *et al.*, 2015). Geographical information system (GIS) integration and field measurements are effective ways to quantify the long-term morphological changes, and it is possible to elucidate accretion-erosion characteristics from a large-scale perspective by analyzing a long sequence of bathymetric surveys.

For most coastal areas, bathymetric charts and surveys can offer historical information on coastal morphology. Navigational charts, which provide bathymetric information over a vast period of time, are a valuable data source for studying patterns of morphological change. Admiralty charts can be digitized in a GIS, and the data can then be recorded, stored, and analyzed to build an underwater digital elevation model

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*Corresponding author: xyhou@yic.ac.cn

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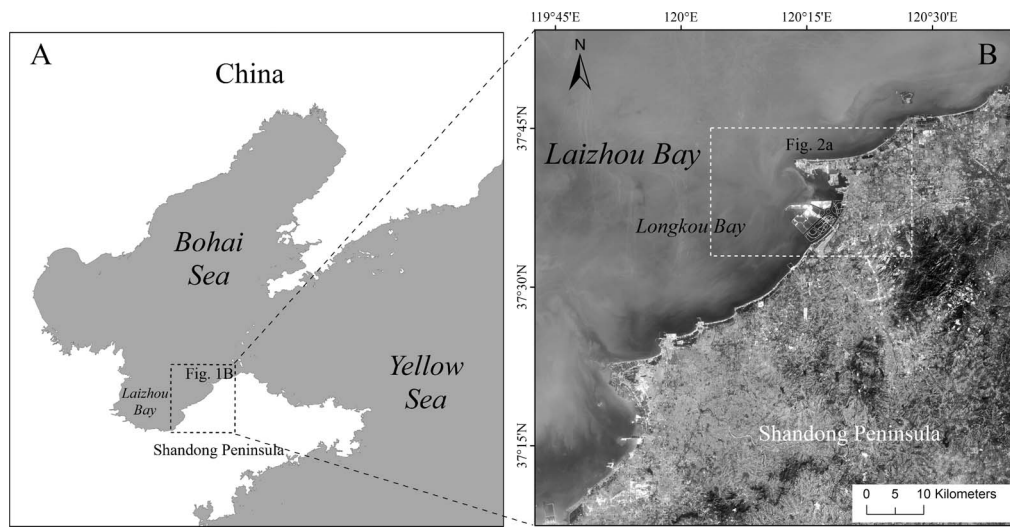


Figure 1. Location of the study area in the southern Bohai Sea, China.

(DEM) for further spatial analysis, to calculate sedimentation and erosion rates, for example (Van der Wal and Pye, 2003).

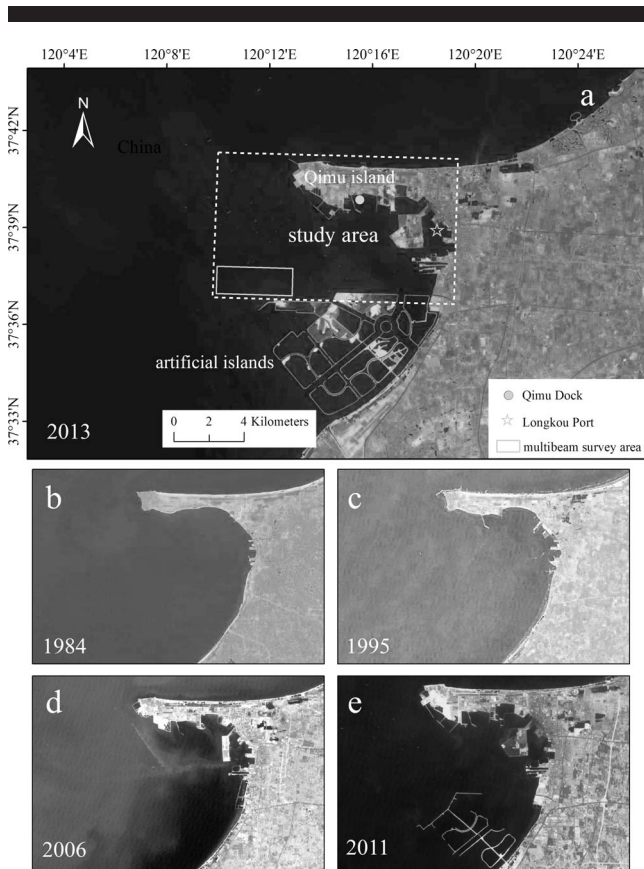


Figure 2. (a) Location of the study area in Laizhou Bay. (b)–(e) Comparison of the morphological changes of Longkou Bay from multitemporal Landsat images.

This technique has been successfully applied in a wide variety of estuarine areas, including the Ribble Estuary (Van der Wal, Pye, and Neal, 2002), the Mersey Estuary (Blott *et al.*, 2006), the Yangtze Estuary (Wang *et al.*, 2013), the Pearl River Delta (Zhang *et al.*, 2015), and Lingding Bay (Wu *et al.*, 2016). Understanding of the morphological evolution and related changes in a bay system is necessarily based on reasonably good knowledge of the leading triggering processes (Jabaloy-Sánchez *et al.*, 2010). There is no doubt that the evolution of bay morphology is closely associated with socioeconomic development. In many parts of the world, reclaiming land from the sea has now become a common practice (Radhi, Sharples, and Assem, 2015). Longkou Bay in China (Figure 1) has also been affected by human activities, and morphological changes are clearly shown on multitemporal remote-sensing images (Figure 2).

Although admiralty charts can be used to demonstrate a comprehensive overview of morphological changes quantitatively, they cannot provide detailed geomorphologic characteristics due to their inadequate accuracy. The development of acoustic seafloor mapping methods has allowed for the creation of detailed seabed morphology maps, and recent developments in multibeam bathymetric survey technology have enabled the visualization of submarine landforms in three dimensions (Kan *et al.*, 2015). High-resolution swath mapping using multibeam echosounding (MBES) allows large areas of the seafloor to be mapped with great detail. Therefore, the objectives of this study were to quantitatively elucidate the rapid morphological changes using the admiralty charts for Longkou Bay in recent decades and show the geomorphologic features caused by the construction of artificial islands using multibeam swath mapping.

Study Area

Longkou Bay extends from 37°33' N to 37°42' N and from 120°09' E to 120°20' E in the southern Bohai Sea, north of the Shandon Peninsula, China (Figures 1 and 2). It is a semi-open

bay with a mouth of 13.4 km. As a part of Laizhou Bay, the region is controlled by a temperate continental monsoon climate, and the direction of the dominant waves is NE (Wang Li, and Li, 2016). The tidal regime in the study area is mixed semidiurnal. The coastal area is characterized by shallow plains, and the coastline is composed of bedrock and sand. Sediments in Longkou Bay are mainly silty clays, and the grain size of the sediments gradually decreases from inside of the bay to outside (An *et al.*, 2010). The water depth is less than 10 m in most of the bay. As a diversion dike, Qimu Tombolo can increase the flow velocity to form a deep trough, and the deepest site at 23 m is located northwest of Qimu Island. Based on data availability, a part of Longkou Bay was chosen as the study area (Figure 2a) to reveal the morphological changes in recent decades.

The Longkou Port has been the largest domestic port trading with Africa in China since 2009, with throughput of over 70 million tons in 2014, and it will grow up to 100 million tons by 2020. Today, the main channel is 15.5 m in depth and 200 m in width, allowing access for ships up to the 100,000 ton level. Early in the 1980s, small-scale coastal land reclamation took place in Longkou Bay. In recent decades, with the enlargement of Longkou Port and the continued improvement of infrastructure around the port, large volumes of coastal waters have been occupied, and the sea area near the port has been deepened by dredging. Moreover, with the development of technology and growth of the population, the local government began large-scale artificial island construction to support private sector development, particularly in the ecotourism and the high-tech industries. As China's largest artificial islands (Figure 2a), the Longkou artificial islands, covering 45 km², were built in the sea at a distance from the coast to protect the natural coastline and reduce the loss of marine ecology. A huge reclamation project began in January 2011, and a 120 km cofferdam was completed in the first half of 2012. The large-scale artificial island projects greatly changed the morphology of Longkou Bay, including the land and underwater areas.

METHODS

The historical time series of admiralty charts were analyzed in a GIS environment, and detailed geomorphologic characteristics of the seafloor near the artificial island were obtained using a MBES. The estimates of underwater topography changes and current features were quantitatively demonstrated through the analysis of DEMs from the digitized admiralty charts and multibeam swath mapping.

Admiralty Chart Processing

Bathymetric surveys in Longkou Bay have been carried out many times throughout the latest decades. To quantitatively estimate the morphological changes in Longkou Bay, five historical time series of admiralty charts were collected in this region, and the detailed information is shown in Table 1. The admiralty charts for each period were a composition of surveys and do not represent the bathymetry at a single point in time. Although water depth measurements may have some inherent errors, such as correction of tidal level, boat posture, and wave effects, *etc.*, they are generally not considered to be large enough to cause serious calculation errors due to the maturity

Table 1. Admiralty charts used in the study.

Publisher	Chart No.	Publish Date	Survey Date	Scale
NGD	10302	1966/04	1963/1964	1:15,000
NGD	11892	1984/05	1980/1982	1:15,000
NGD	11892	1999/08	1994/1996	1:15,000
NGD	11892	2011/08	2007/2009	1:15,000
MSA	34112	2014/02	2012/2013	1:25,000

NGD = the Navigation Guarantee Department of the Chinese Navy Headquarters, MSA = Maritime Safety Administration of the People's Republic of China

of the technology (Wang *et al.*, 2013). A significant source of inaccuracy in the measured elevations recorded in bathymetry charts arises from inconsistencies in the datum levels in relation to tides (Van der Wal and Pye, 2003). To account for this, the water depths used in this study were referenced to the lowest astronomical tide (LAT).

Using the latitude/longitude information, each admiralty chart was georeferenced into the UTM WGS84 coordinates of China. Then, the isobaths, spot depths, and bay outlines were digitized to the same datum in a GIS (*i.e.* ArcGIS software). The kriging approach, which can provide a good interpolation for sparse data when sufficient data points are available to compute variograms (Burrough, 1987), was used to interpolate the depth points, for building an underwater DEM with 50 × 50 m resolution. Using the spatial analyst tools, the DEMs for multiple periods were compared to calculate volumetric changes in order to quantitatively estimate the morphological changes, such as isobath evolution, scour, and silting development in this area. A conservative approach was applied in this study, the same as previous studies, which suggested that elevation changes greater than ±0.5 m between subsequent surveys can be considered significant (Blott *et al.*, 2006; Van der Wal, Pye, and Neal, 2002; Zhang *et al.*, 2015). Although the estimated quantities for sediment volume, in particular, are unlikely to be truly accurate, the data are considered to provide a reliable indication of relative net accretion and erosion trends during different time periods (Blott *et al.*, 2006). All height and depth values extracted from charts were converted into meters to allow volumes to be calculated.

Multibeam Swath Mapping

In order to obtain the detailed depth information in this area, and to further understand the underwater topography changes caused by the construction of artificial islands, a rectangular area spanning 4.4 × 1.6 km² near the artificial island (Figure 2) was selected for multibeam swath mapping. The survey was performed from 27 May to 2 June 2016 using an MBES (Sonic 2024, R2 Sonic, LLC) pole mounted on the research vessel. The system produced 256 beams, operated at a frequency of 400 kHz, and gave a swath width at 130° of more than 4 times water depth. The navigation system used was the differential global positioning system (DGPS; Hemisphere, Inc., Canada), with an Octans IV gyrocompass and motion sensor (iXBlue, France), which provided submeter and 0.01° accuracy for heave, roll, and pitch. Real-time sound speed was measured using a sound velocity sensor (Minos SVP, AMLTM, Canada) that was installed near the transducers for beam steering. Offsets between sensors were measured from the survey ship. Angular misalignment among transducer, gyrocompass, and motion

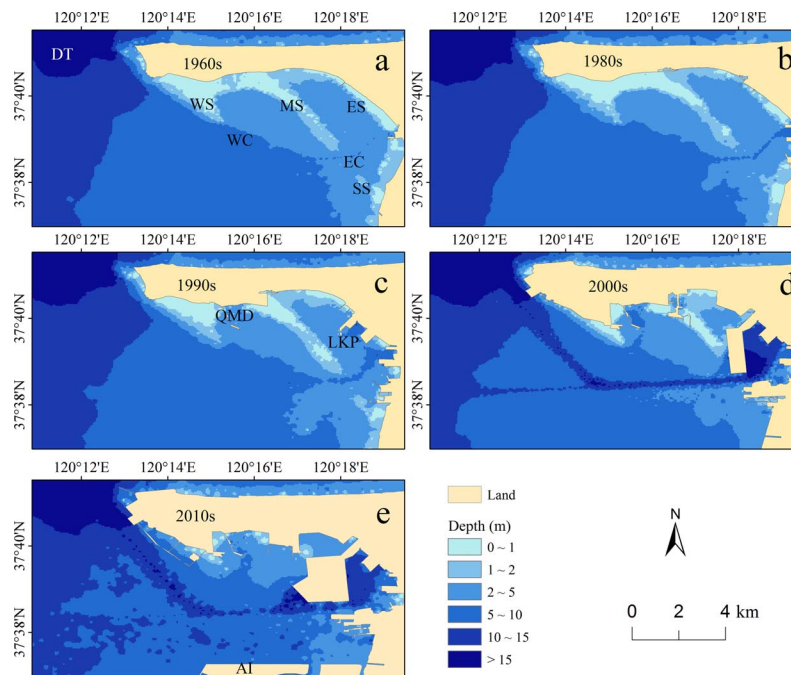


Figure 3. Digitized bathymetry charts of Longkou Bay from 1960s to 2010s: (a) 1960s, (b) 1980s, (c) 1990s, (d) 2000s, (e) 2010s. The abbreviations marked in the figure are indicated: west shoal (WS), middle shoal (MS), east shoal (ES), south shoal (SS), west channel (WC), east channel (EC), deep trough (DT), Qimu Dock (QMD), Longkou Port (LKP), and artificial islands (AI).

sensor was calibrated by a patch test before the survey. Data logging, real-time quality control, display, and navigation were conducted using QINSy v8.1 (QPS, The Netherlands). Sound velocity profiles were also taken during data acquisition every 3 hours at different depths to account for variations in sound speed in the water column. The vessel's speed was maintained at around 6 knots, and the distance between each parallel survey line was 30 m to assure 100% coverage of the area.

Raw multibeam data were processed using Caris HIPS/SIPS 8.1 (Caris, Canada). Postprocessing steps included editing, cleaning, and calculating the calibration parameters (*i.e.* roll, pitch, and heading). The combined uncertainty and bathymetry estimator (CUBE) surface was used as a cleaning tool and for product gridded surface creation. Soundings were weighted and contributed to surface grid nodes based on total propagated uncertainty (TPU) values during the CUBE surface creation. Tidal correction was applied to depth soundings using verified tide data derived from Longkou tide station. Finally, processed bathymetry data were gridded at 0.5 m spatial resolution and imported into ArcGIS v.10.2 for further processing and evaluation.

RESULTS

Figure 3 shows the bathymetric charts in Longkou Bay that were used to estimate the subaqueous morphological changes in this area. The analyses of the bathymetric changes are shown in Figure 4. The land and subaqueous area in the study area have changed significantly in recent decades. The subaqueous area decreased by about 15%, while land area

increased by more than 13 km² from the 1960s to 2010s (Tables 1 and 2). The change was not gradual but occurred abruptly from the 1990s to 2010s. The morphological changes in the Longkou Bay study area can be divided into three stages, 1960s–1990s, 1990s–2000s, and 2000s–2010s.

1960s–1990s

The subaqueous topography of Longkou Bay (Figure 3a,b,c) essentially maintains a configuration with one deep trough, four shoals (west shoal, middle shoal, east shoal, south shoal), and one channel, composed of the west channel and east channel. In general, prior to the 1990s, there had been no major morphological changes for a 30 year period, and the system was largely in equilibrium. From the 1960s to 1980s, more than 3/4 of the sea area showed no significant depth change (Table 3), with about 1/5 of the area showing erosion (Figure 4a). The average water depth in the study area increased from 7.19 m to 7.43 m, and the subaqueous area shrank from 85.12% of the study area in the 1960s to 84.99% in the 1980s (Table 2). Figure 4a shows that the depth of the deep trough, Longkou Port, and east channel decreased slightly more than 0.5 m, and the morphology of the west shoal, middle shoal, and south shoal changed as a result of minor deposition of less than 1 m. From the 1980s to 1990s, more than 80% of the subaqueous area had significant depth change, with the deposition and erosion area accounting for about 10%, respectively (Figure 4b; Table 3). During this period, the deep trough continued to deepen, but deposition occurred in some local areas (Figure 4b). The depth of the middle shoal and south shoal continued to increase, and relatively minor deposition occurred, while erosion of less than

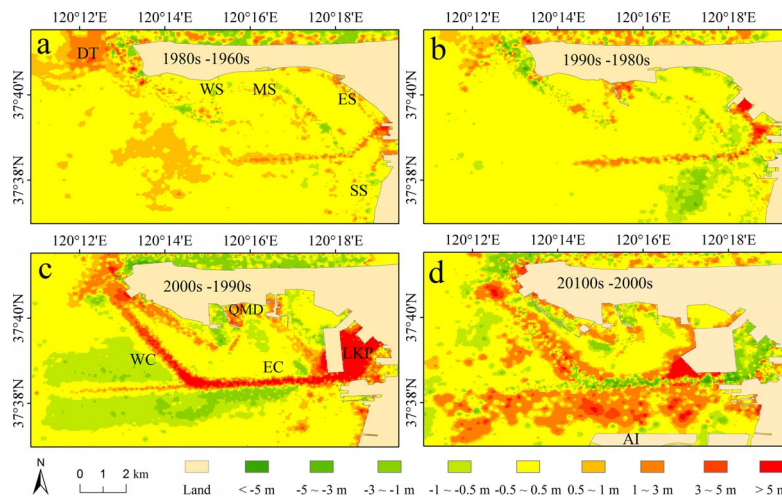


Figure 4. Bathymetric changes (depth of later time minus that of the previous time) in Longkou Bay in the following periods: (a) 1960s–1980s, (b) 1980s–1990s, (c) 1990s–2000s, (d) 2000s–2010s. The abbreviations marked in the figure are the same as Figure 2.

1 m could be detected in the west shoal. With the enlargements of Longkou Port, the area of the east shoal gradually decreased from the 1980s to 1990s, and notable dredging to depths of over 3 m took place near the port. Compared with the 1980s, the Qimu Dock was expanded, and the channel dredging intensity increased in the 1990s. Thus, the depth exceeding 1 m decreased near Qimu Dock, and there was a remarkable depth change of 1–3 m in east channel (Figure 4b).

1990s–2000s

During the 1990s–2000s, evidence of human activities increased markedly. Most of the east and south shoals disappeared. The west shoal aggraded less than 1 m, while minor erosion of less than 1 m occurred in the middle shoal. Similarly, the area of the middle shoal and west shoal gradually decreased as a result of coastal land reclamation of Qimu Island. The proportion of subaqueous area (Figure 3c,d) decreased from 82.9% of the study area in the 1990s to 78.2% in the 2000s (Table 2). The mean water depth of the study area increased from 7.56 m in the 1990s to 8.16 m in the 2000s. From the 1990s to 2000s, the area of erosion grew to 18.85%, and the

area of deposition increased to 28.70% of the subaqueous area (Table 3). The area of the deep trough expanded to the island and continued to deepen to a small extent (Figures 3d and 4c). Compared with the 1990s, the most significant changes in the 2000s were that Longkou Port expanded over a large area, and the channel widened and deepened correspondingly (Figure 3c,d). The deep-water area was enlarged near Longkou Port, and the depth on the east side of the wharf was more than 20 m. The depth of the navigation channel (including west channel and east channel) was deepened to more than 10 m, locally reaching over 15 m (Figure 3d). Figure 4c displays a notable polygonal line with depth changes larger than 3 m or 5 m along the navigation channel. Areas of aggradation were created near the channel by dumping of excavated sands. In addition,

Table 3. Sizes and changes of deposition and erosion areas, water column, and land area in the Longkou Bay study area during 1960s–2010s.

	Time Period			
	1960s– 1980s	1980s– 1990s	1990s– 2000s	2000s– 2010s
Deposition area (km ²)				
<–5 m	0.00	0.04	0.04	0.18
–5 to –3 m	0.13	0.09	0.17	0.55
–3 to –1 m	2.25	2.45	5.96	4.17
–1 to –0.5 m	2.22	6.59	17.65	7.28
No significant change area (km ²)				
–0.5 to 0.5 m	68.58	70.66	43.53	37.95
Erosion area (km ²)				
0.5–1 m	12.76	4.35	5.03	8.71
1–3 m	4.08	3.27	5.32	14.76
3–5 m	0.26	0.43	2.02	2.42
>5 m	0.05	0.25	3.28	0.91
Percentage of deposition area (%)	5.09	10.40	28.70	15.83
Percentage of erosion area (%)	18.98	9.42	18.85	34.83
Water volume net gain (10 ⁶ m ³)	20.96	–5.02	10.97	6.51
Land area gain (km ²)	0.14	2.23	4.95	6.25

Table 2. Land and subaqueous areas in the Longkou Bay study area, 1960s–2010s.

	Year				
	1960s	1980s	1990s	2000s	2010s
Land area (km ²)	15.78	15.92	18.15	23.10	29.35
Subaqueous area (km ²)					
0–1 m	4.48	4.17	3.38	1.93	0.40
1–2 m	5.54	5.06	4.81	3.10	1.56
2–5 m	20.47	19.80	19.67	16.26	13.50
5–10 m	37.11	36.46	36.09	36.49	31.52
10–15 m	18.08	19.26	18.61	18.30	23.37
>15 m	4.62	5.44	5.42	6.78	6.44
Subtotal	90.29	90.19	87.98	82.85	76.78
Subaqueous area (%)	85.12	84.99	82.90	78.20	72.34
Mean water depth (m)	7.19	7.43	7.56	8.16	8.89
Water volume (10 ⁶ m ³)	649.15	670.11	665.09	676.06	682.57

the Qimu Dock maintained its state of expansion as in the period of the 1980s–1990s, and the sea area near the dock was deepened, with dredging depth of over 1 m.

2000s–2010s

Between the 2000s and 2010s, with the continuous improvement of the infrastructure of Longkou Port and the implementation of large-scale artificial island projects, the land and underwater morphology of Longkou Bay study area changed drastically. Land area increased from 23.10 km² to 29.35 km², while the proportion of subaqueous area decreased from 78.20% of the study area to 72.34% during this period (Table 2). The average water depth in the study area increased from 8.16 m to 8.89 m, and the water volume net gain was 6.51×10^6 m³ (Table 3). Erosion of more than 0.5 m occupied 26.79 km², that is to say, 34.83% of the subaqueous area (Table 3), which was larger than that of any other previous period. Figure 3e shows that most of the west and middle shoals disappeared. Compared with the 2000s, Longkou Port was expanded westward in 2010s. The west side of the port was dredged with a wide range, connecting it with the channel, and the water depth changed far more than 3 m (Figure 4d), with local depth reaching over 20 m (Figure 3e). Deposition less than 1 m took place in the east area of Longkou Port during this period. The change of the deep trough area was basically consistent with that of the period of the 1990s–2000s. The channel was further deepened overall, with some deposition in local areas (Figure 4d). The most significant feature at this stage was that mud and sand excavation was conducted on a large scale between the channel and artificial islands. The depth changes were mostly near 3 m. Near the northern part of the artificial islands, a great deal of sediment was dredged out by a cutter suction dredger for filling the artificial islands, leaving a large number of deep pits, which will be described in detail below.

Geomorphologic Characteristics

The high-resolution bathymetric results near the artificial island are presented in Figure 5a, which clearly shows the seabed topographic characteristics because of dredging and filling engineering. The location, shape, and size of the deep pits can be easily identified from the multibeam bathymetry. The bathymetry of the survey area exhibits a depth ranged from 10.2 to 18.5 m, and 43% of this area is under 16 m. Before construction of the artificial islands, the area was relatively flat and gradually deepened seaward (from east to west). The cutter suction dredgers with long pipes (Figure 5g), playing an important role in dredging and reclamation projects, were used to blow sand and water from the seafloor into the target circle enclosed by embankment dams (Figure 5e). The seabed was dredged at a great many sites, leaving a lot of borrow pits like seafloor “scars,” with the longest up to 1200 m, drastically changing the underwater topography. Figure 5a shows that the borrow pits were mostly rectangular, and a majority of pits are connected together because of the dense mud pumping sites. These excavated pits vary in depth, with some 1–2 m, and some up to 7–8 m deep. The three-dimensional map of an irregularly shaped pit located in the southwest part of the survey area is shown in Figure 5b; it is about 530 m in length and between 130 and 220 m in width. The three-dimensional rendering reveals an intuitive-looking depiction of the borrow pit. A bathymetric

profile across the deep pit is shown in Figure 5c, exhibiting obvious relief change and indicating that the pit has a depth of about 4 m. It is estimated that about 3.9×10^5 m³ of material was extracted from this dredge pit. As the hydraulic reclamation work was completed less than a year ago, significant sediment erosion and siltation were not found in the survey area.

DISCUSSION

Longkou Bay has experienced rapid morphological changes during the last 50 years. The available evidence suggests that, from the 1960s to 1990s, Longkou Bay existed in a condition of dynamic equilibrium. During these three decades, net changes appear to have been fairly limited, and no significant evidence of large-scale human activities could be found. This situation evidently began to change significantly in the 2000s, and particularly in the 2010s. The large-scale human activities, as revealed in the previous section, greatly changed the land and underwater morphology of Longkou Bay.

Although the admiralty charts are suitable for studying patterns of morphological change (Van der Wal and Pye, 2003), their accuracy is insufficient to reveal detailed topographic changes. Advances in multibeam echosounders have enhanced researchers' ability to characterize physical aspects of the benthic environment at fine scales (Brown and Blondel, 2009; Li *et al.*, 2017; Pickrill and Todd, 2003). In order to better understand the topography changes caused by the dredging and filling engineering, a multibeam survey should be carried out at regular intervals during the construction process of artificial islands, once a year for example.

Several factors could have contributed to the observed morphological changes in Longkou Bay. These include changes in natural environmental forcing factors, such as sea level, tidal regime, wave climate, and sediment supply (Blott *et al.*, 2006), or human activities such as channel dredging, artificial island construction, and port development. An expert geomorphological assessment of past changes in the bay requires identifying and quantifying these environmental constraints, natural forcing factors, and human activities. However, it depends on the scope and quality of available data (Blott *et al.*, 2006). A full discussion of each factors and their interactions relevant to the geomorphology of Longkou Bay is beyond the scope of the study, but the dominant aspects are discussed below.

The report on China's sea level compiled by the State Oceanic Administration (SOA) in 2012 suggests that the sea level along China's coastlines has risen by 2.9 mm per year over the past three decades (Zhang *et al.*, 2015). Under natural conditions, the rising sea level can flood more land and erode the coast, causing retreat. Contrary to this, most coastlines of the Longkou Bay displayed a seaward-extending tendency. Land area increased from 15.92 km², 15.78% of the study area, in the 1980s to 29.35 km², 27.65% of the study area, in the 2010s (Table 2). The conclusion can be drawn that human influence overwhelms the natural coastal response to sea-level rise.

In general, sediment supply plays an important role in changing estuarine geomorphology (Van der Wal, Pye, and Neal, 2002; Wu *et al.*, 2016). There is no long-standing river in this area, and only several small rivers flow into Longkou Bay.

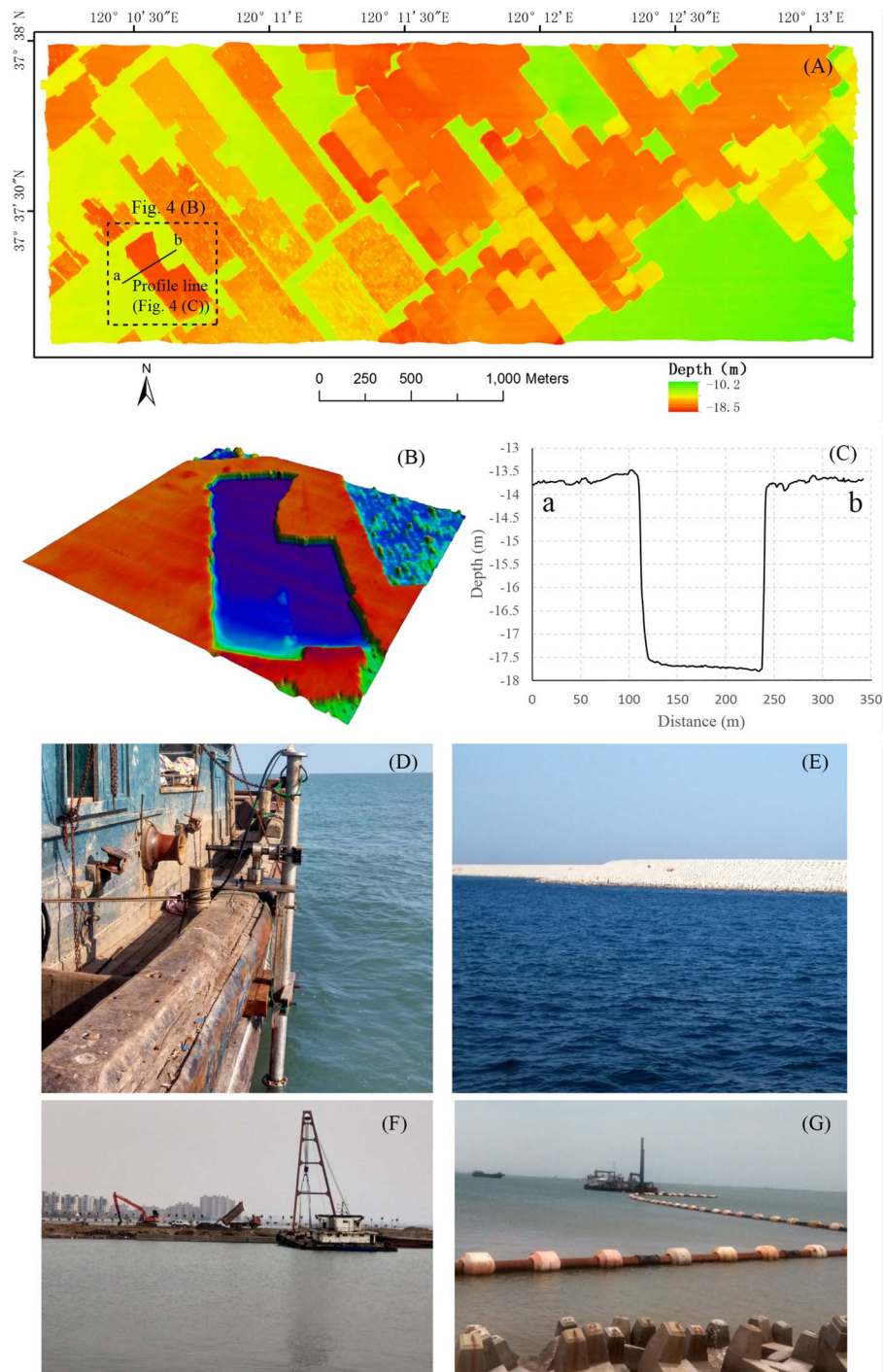


Figure 5. (a) Detailed bathymetry based on multibeam data with the location of the three-dimensional view and the profile shown in Figure 4b,c. (b) Three-dimensional map of a typical deep pit as a result of sand pumping. (c) Bathymetric profile across the deep pit. (d) Multibeam survey vessel with the transducer mounted on the port side. (e) The dam for bank protection at the edge of the artificial islands. (f) New dock in construction near the Longkou Port. (g) A cutter suction dredger near the artificial island.

In the absence of reservoirs, the amount of river sediment transport was merely 35.7×10^4 to 58.3×10^4 t/yr (Qu, Wang, and Feng, 1995). The sediment supply was greatly reduced due to the rapid increase of dam constructions and the integrated

management of small watersheds. The natural deposition rate of this area was very small, only about 0.1 cm/yr (Qu, Wang, and Feng, 1995). This study showed that the water depth did not change significantly before the 2000s (the average water

depth in the 1960s, 1980s, and 1990s was 7.19, 7.43, and 7.56 m, respectively) without large-scale human activities in Longkou Bay (Table 2). Table 3 also confirms that the percentage of no significant depth change area was 75.93% during the period of 1960s to 1980s and 80.18% from the 1980s to 1990s.

The navigation channel of Longkou Bay was maintained by dredging, particularly after the 1990s. Dredging was especially required in two areas: the vicinity of Longkou Port and the waterway (about 9600 m) leading to Longkou Port (Figure 3d,e). The dredge spoil was disposed on the seafloor near the channel in the southwest, resulting in a large area of slight deposition, which is shown in Figure 4c. The broadening and deepening of the navigation channel could be explained by the extension of Longkou Port, with the construction of a few 100,000 ton berths.

Land reclamation is one of the important human activities that can affect the morphology of bays (Dai, Liu, and Wen, 2015; Jaffe, Smith, and Foxgrover, 2007; Lane, 2004). It not only changes the length of the coastline and the shape of land in a direct way (Zhang *et al.*, 2015), but it also changes the seabed topography tremendously. From an analysis of Table 2, 13.57 km² of land was reclaimed during 1960s–2010s in the study area. Significant coastal area was reclaimed from the 1960s to 2010s, causing an obvious decrease of subaqueous area in Longkou Bay (Figure 3). For example, three underwater sand spits developed in Longkou Bay, *i.e.* Jianzitou Spit, Guandao Spit, and Yatan Spit, which corresponded to the west shoal, middle shoal, and south shoal, respectively. Early in the 1980s, a small amount of authigenic pyrite, indicating weak sedimentation and dynamic conditions, was found in Longkou Bay by the First Institute of Oceanography, SOA, and it showed the demise of Longkou inner bay would be fast if not protected (Qu, Wang, and Feng, 1995). However, the Yatan Spit gradually disappeared before the 2000s because of the coastal land reclamation, while most of the Jianzitou Spit and Guandao Spit have been occupied by the expansion of the Qimu Dock and recent coastal engineering projects.

Analysis of all available evidence strongly suggests that rapid and extensive morphological changes took place in Longkou Bay as a result of artificial island construction (Figures 3e, 4d, and 5a). In the construction of artificial islands, the use of a cutter suction dredger is currently the most common method for extracting sediment from the seafloor. While the dredger is moored in deeper waters, dredged materials are pumped into a floating pipeline. These tools can help to reduce the release of fine sediment into the marine environment by discharging dredged materials close to the seabed (Zainal *et al.*, 2012). However, it leaves dredge scars and pits (Figure 5a,b), which act as traps for sediment moved by the longshore current, further denuding adjacent beaches (Smith and Collen, 2006). Chew (1999) showed beach and nearshore sand and gravel extraction increases surface erosion by allowing waves to reach further inshore, often resulting in rapid shoreline retreat.

It is important to understand whether a given bay is infilling, eroding, or exists in morphodynamic equilibrium (Canestrelli, Lanzoni, and Fagherazzi, 2014). Natural coasts are basically in a stable or equilibrium state after a long history. Intensive anthropogenic activities will affect the balance, resulting in

erosion or siltation. Human activities such as port dredging and artificial island building can alter the environment, both directly and indirectly (Barnes and Hu, 2016). Although the artificial islands will provide more stable navigation conditions and a better berthing situation for Longkou Port, at the same time, there will be a certain degree of siltation due to the weakening hydrodynamic conditions. Previous research showed that the channel between the land and artificial islands was in a strong depositional state in Longkou Bay (An *et al.*, 2013). Through numerical simulation, Zhou *et al.* (2014) found the velocity of the current in Longkou Bay decreased by 4–8 cm/s with the influence of the artificial island construction, causing deposition of about 4 mm per month, which will lead to an increase of dredging requirements. This concurs with the finding of Wang, Li, and Li (2013), who showed that the sea area in the north of Tangshan Bay, China, was deposition area because of the artificial island construction.

The bay ecosystem is an important spawning ground and habitat for many marine organisms, and it is of great significance for the supplement of marine ecosystem fishery resources. Due to overfishing and intensive coastal development, the Laizhou Bay ecosystem is under unprecedented pressure, and its sustainability capacity is gradually weakening. Previous studies have shown that the individual fishery resources of Longkou Bay are significantly diminished. For example, the yellow croaker, as the dominant species in Laizhou Bay, tends to be simple in length composition and age structure, and it has obvious characteristics of younger age and smaller size in recent decades (Zhang, Wu, and Jin, 2015). Moreover, the dominant macrozoobenthos in Laizhou Bay have changed in the past few decades. Shrimps and crabs with larger size and longer life span were substituted by those being tolerant to environment changes with smaller size and shorter life span, such as some smaller bivalves, which shows that the benthic habitat of the bay has been disturbed to some degree (Cai *et al.*, 2013). This trend is likely to be related to changes in the sediment conditions of the bay, and anthropogenic disturbances such as land reclamations projects and excess input of pollutants (Jin *et al.*, 2013).

The terrain change caused by such a massive reclamation project will lead to the destruction of the original benthic habitat. Despite the extensive program of dredging, published data on the recovery of the marine community following dredging are limited (Jones *et al.*, 1998). There is a danger that the submarine ecosystem reach a point of collapse, where it could no longer support the current levels of activities. Naser (2011) used a microcosm experimental approach to investigate the survival of marine organisms following the impact of infilling, and a compensatory solution for the infill and reclamation impacts was provided by Jones *et al.* (2007). Recovery may be possible but influenced by site-specific features. Today, huge dredging and reclamation projects are being conducted in full swing in Longkou Bay (Figure 5f). Fortunately, the Chinese government has promulgated the most stringent measures for reclamation control to ensure the sustainable development of the coastal area. Different mitigation measures will be undertaken to minimize the benthic habitat damages and create the required balance.

CONCLUSIONS

Using admiralty charts and multibeam swath mapping in a GIS environment, this study estimated the morphological changes and showed the geomorphologic features of Longkou Bay. The method has proven efficient to explore the relationship between accretion-erosion characteristics and coastal development. Results based on 50 years of historical bathymetric data indicated that the morphological changes in the study area can be divided into three stages. (1) From the 1960s to 1990s, topographic changes showed a patchy distribution of deposition and erosion, with natural evolution of the subaqueous topography, and there were few signs of large-scale human activities. (2) During the 1990s to 2000s, with the enlargements of Longkou Port, dredging of the channel, and the reclamation of coastal land, the land area increased by 27.3%, and mean water depth rose from 7.56 to 8.16 m. (3) Rapid morphological changes took place from the 2000s to 2010s due to the continuous construction of Longkou Port and the implementation of large-scale artificial island project with an increase of land area from 23.10 to 29.35 km² and a water volume net gain of 6.51 × 10⁶ m³. Intensive coastal developments such as port expansion, channel dredging, and artificial island construction were the main processes affecting the observed morphological changes in Longkou Bay. The detailed multibeam swath bathymetric map demonstrated the geomorphologic characteristics of the seafloor, with quantities of borrow pits due to dredging and filling engineering. Timely and effective measures need to be taken to reduce the impact caused by drastic morphology changes on the environment.

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