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How Does Human Activity Shape the Largest Estuarine Bay of the Pearl River Estuary, South China (1964–2019)

Zhiyuan Han [1,2], Heng Wang [1,2,3,*], Hualiang Xie [1,2], Huaiyuan Li [1,2] and Wendan Li [1,2,*]

1 National Engineering Research Center of Port Hydraulic Construction Technology, Tianjin Research Institute for Water Transport Engineering, M.O.T., Tianjin 300456, China; tkshzy@foxmail.com (Z.H.)
2 Key Laboratory of Engineering Sediment of Ministry of Transport, Tianjin Research Institute for Water Transport Engineering, M.O.T., Tianjin 300456, China
3 School of Marine Engineering and Technology, Sun Yat-Sen University, Zhuhai 519082, China
* Correspondence: heng-heng-wang@163.com (H.W.); liwendan@163.com (W.L.); Tel.: +86-22-59812345-6512 (H.W.); Fax: 86-22-59812375 (H.W.)

Abstract: The morphological changes in an estuarine bay are affected by fluvial and oceanic dynamics, as well as human activities. Human activity has increased considerably in recent years, especially in Lingding Bay of the Pearl River Estuary. Based on mass measured bathymetric data and remote sensing images, morphological changes in Lingding Bay were examined and its long-term morphological evolution from 1964 to 2019 was studied using GIS method and EOF methods. The water area of Lingding Bay gradually decreased through this period due to shore reclamation and the evolutionary characteristics of the underwater topography were different before and after 2007 due to changes in the intensity of human activities. From 1964 to 2007, the water depth and volume of Lingding Bay decreased slightly and the bay experienced a slow silting process with the geomorphic pattern of "three shoals and two troughs" under low-intensity human activity. From 2007 to present, high-intensity sand-dredging activities in the bay have led to considerable deepening and a significant increase in water volume in the East Trough and Middle Shoal areas. The amount of sediment loss caused by the sand-dredging activities after 2007 far exceeded the amount of sediment deposition over the past four decades prior to 2007. Therefore, even if the sand-dredging activities had been banned, the eroded parts of Lingding Bay (i.e., East Trough and Middle Shoal) may not recover in a short time due to the small sediment load from the Pearl River. These recent morphological changes in Lingding Bay may bring about challenges for estuary regulation, disaster control, environmental protection, and the operational safety of the nearby ports and channels. Consequently, the subsequent evolution of the bay requires further research. This will enrich the scientific work for estuarine and coastal research and be conducive to revealing the interaction mechanisms between humans and nature, guiding sustainable development, estuarine disaster control, and promoting interdisciplinary innovation in estuarine research.

Keywords: estuarine bay; morphological evolution; sand dredging; Lingding Bay

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1. Introduction

Estuarine areas with strong land-ocean interactions serve as an important zone for material and energy exchange between land and the ocean. Estuarine areas with unique landforms and rich biodiversity play an important role in the research value of multiple fields such as earth science, ecological science, and environmental science, among others. Morphological evolution is an important field of estuarine research; it is not only influenced by the sediment and runoff from river basins, but also by ocean dynamics including tidal currents, waves, storm surges, and sea level fluctuations. Estuarine areas are usually densely populated and economically developed [1–3]. The impact of human activities on estuarine areas has become significant since the 20th century due to population growth and economic development [4–7]. High-intensity human activities such as estuarine regulation, shoal reclamation, sand dredging, channel regulation, and port construction have reshaped the shoreline, underwater topography, and sediment transport. This has resulted in a more fragile ecological environment and poses increasing challenges for the sustainable management of estuaries as the ecological environment is fragile [8–12]. These types of impacts have been recorded in several large estuaries worldwide in the past decades [1–3,6,13].

The Pearl River Estuary (PRE) is the largest estuary in South China and is comprised of a river delta and two estuarine bays, namely Huangmao Bay and Lingding Bay. Lingding Bay, the largest estuarine bay in South China, is situated in the center of the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), which is the economic center of South China. Lingding Bay is also the intersection of China's two top national development strategies, namely the GBA strategy and the Belt and Road Strategy. Further, there are numerous ports distributed in Lingding Bay, including three world-class ports such as Guangzhou Port, Shenzhen Port, and Hong Kong Port, and some long-distance artificial waterways [14]. In recent years, Lingding Bay has been the site of intense human activity such as estuarine regulation, shoal reclamation, port construction, sea-crossing bridge construction, and sand dredging, which have led to extensive changes in sediment transport, silting rate, and channel evolution [15–18]. These human-induced morphological changes in Lingding Bay have become a serious concern in recent years. Many researchers have examined the short- and long-term evolution of topographic changes in the northern part of Lingding Bay and the channel changes over recent decades under a diverse range of human activities [7,11,19–21]. However, reports on the long-term morphological changes in the whole Lingding Bay are few, especially those related to the morphological changes related to the high-intensity of human activities in recent years.

Based on mass measured topographic data and remote sensing (RS) images from the past 55 years, this study focused on the evolutionary characteristics and processes of Lingding Bay in an attempt to bridge the crucial gap in knowledge regarding the long-term evolutionary mechanisms, especially related to the aberrant morphological changes caused by intensive human activities in recent decades. This study could be beneficial for predicting the future evolution trends, the safe operation of ports, estuarine environment protection, and sustainable management of the PRE. The study could also be of great value for revealing the interaction mechanisms between humans and nature, guiding sustainable development, estuarine disaster control, and promoting interdisciplinary innovation in estuarine research.

2. Study Area

Lingding Bay is a horn-shaped bay covering an area of approximately 1700 km^2 [22]. The northern edge of the bay is at Humen, and the southern edge is at Macao-Dahao Island. The geomorphic pattern of Lingding Bay is known as the "three shoals and two troughs" (Figure 1), comprising the East shoal, the Middle Shoal (Lanjiang, Fanshi, and Tonggu Shoals), and the West Shoal, as well as the East Trough (Chuanbi and Fanshi channels) and the west trough (Lingding Channel). There are four outlets (Humen, Jiaomen, Hongqili, and Hengmen) of the Pearl River in north-western Lingding Bay. The annual runoff and sediment discharge of the Pearl River are approximately 300 billion m^3 and 70 million tons, respectively. As the main water area of PRD for matter and energy exchange, Lingding Bay account for 61.1% and 54.0% of the total Pearl River runoff and sediment load, respectively [23]. The flood season typically occurs from April to September, and the river runoff and sediment loads during the flood season account for more than 70% and 90% of the annual totals, respectively [14].

Lingding Bay is dominated by tidal dynamics, with a mean tidal range of less than 2.0 m and an irregular semidiurnal tidal pattern. The tidal current flows reciprocally with a dominant N–S direction. The annual mean suspended sediment concentration (SSC) in Lingding Bay is 0.1–0.2 kg/m^3. The SSCs in the troughs are lower than those on the shoals, and the highest SSC occurs in the West Shoal. The West Shoal is the accumulating center in Lingding Bay, which receives the most sediment discharged from the Pearl River [14].

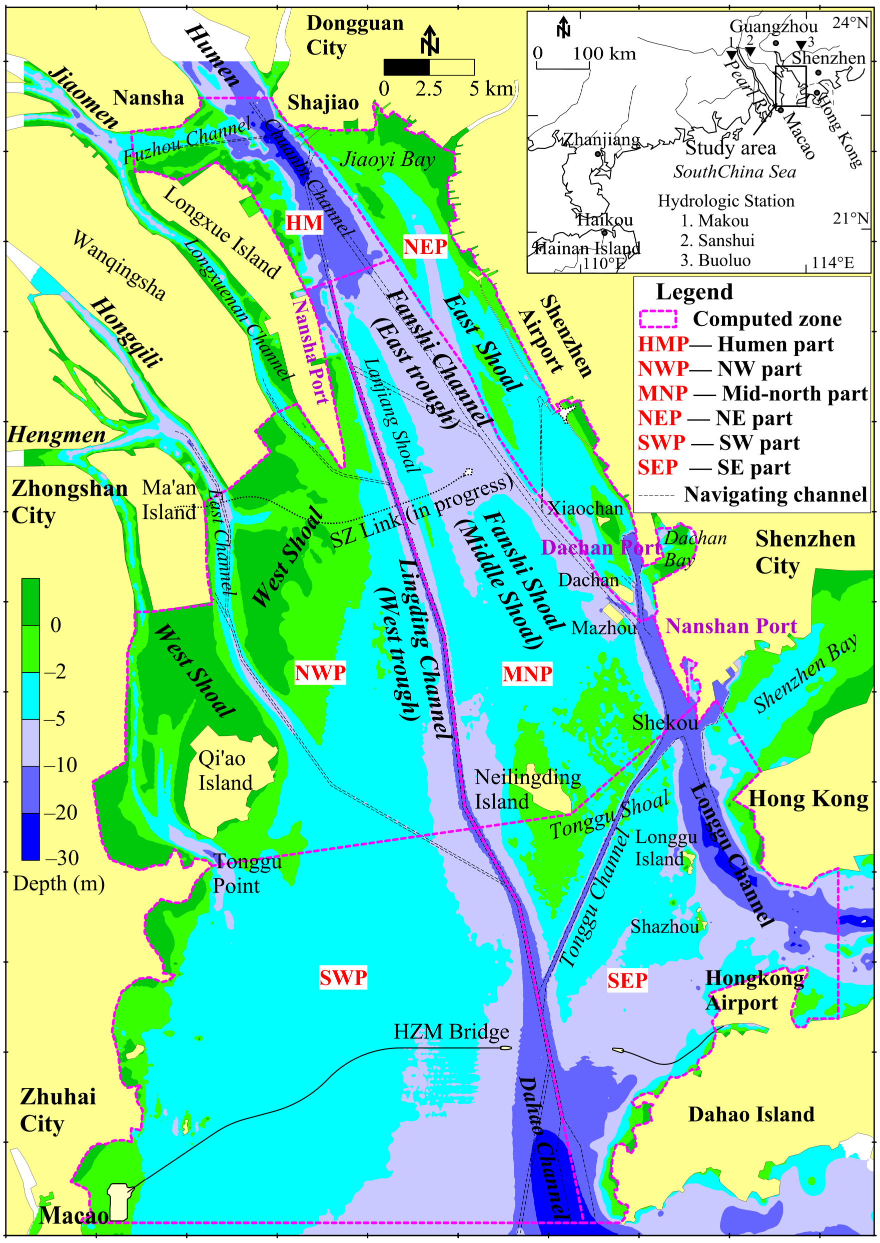

Figure 1. Sketch map of Lingding Bay in the Pearl River Estuary.

3. Data and Methods

3.1. Data

Eight Chinese navigation charts measured in 1964, 1974, 1989, 1998, 2011, 2016, and 2019 which cover Lingding Bay were collected for this research (Table 1). Bathymetric data measured in 2007 were provided by the Hong Kong-Zhuhai–Macao Bridge Bureau (HBB), and that measured in 2011 and 2016 were provided by the Shenzhong Link Administration Center (SLAC). Five Landsat remote sensing (RS) images were acquired from the website of Geospatial Data Cloud (https://www.gscloud.cn/, accessed on 16 October 2023) in 1975, 1988, 1998, 2008, and 2018, respectively (Table 2). The hydrological data of Pearl River runoff and sediment load since 1960 were obtained from the Hydrological Bureau of Guangdong Province.

Table 1. Bathymetric data used in this study.

No.	Chart Name	Chart Scale	Publication Date	Measuring Date	Chart Datum	Chart Projection
1	Chinese Chart No. 5713 (Neilinglingdao to Humen)	1:50,000 at Lat. 26°	1968	1964	Theoretical depth datum	Mercator (BJ-1954)
2	Chinese Chart No. 15435 (Niutoudao to Neilinglingdao)	1:50,000 at Lat. 22°16′	1979	1964	Theoretical depth datum	Mercator (BJ-1954)
3	Chinese Chart No. 15445 (Neilinglingdao to Humen)	1:50,000 at Lat. 22°35′	1984	1974	Theoretical depth datum	Mercator (BJ-1954)
4	Chinese Chart No. 15435 (Guishandao to Neilinglingdao)	1:50,000 at Lat. 22°16′	1986	1974	Theoretical depth datum	Mercator (BJ-1954)
5	Chinese Chart No. 15445 (Neilinglingdao to Humen)	1:50,000 at Lat. 22°35′	1991	1989	Theoretical depth datum	Mercator (BJ-1954)
6	Chinese Chart No. 15435 (Niutoudao to Neilinglingdao)	1:40,000 at Lat. 22°18′	1986	1989	Theoretical depth datum	Mercator (BJ-1954)
7	Chinese Chart No. 380801 (Guishandao to Shajiao)	1:75,000 at Lat. 22°27′	1999	1998	Theoretical depth datum	Mecator (BJ-1954)
8	Bathymetric data provided by HBB	1:10,000		2007	Theoretical depth datum	BJ-1954
9	Bathymetric chart provided by SLAC	1:10,000		2011	Theoretical depth datum	BJ-1954
10	Bathymetric chart provided by SLAC	1:10,000		2016	Theoretical depth datum	BJ-1954
11	Chinese Chart No. 84206 (Guishandao to Shajiao)	1:75,000 at Lat. 22°27′	2021	2018–2019	Theoretical depth datum	Mercator (BJ-1954)

Table 2. Remote sensing images used in this study.

No.	Sensor ID	Acquisition Date	Resolution (m)	Data Source
1	Landsat4 MSS	18 November 1975	78	https://glovis.usgs.gov/, accessed on 16 October 2023
2	Landsat5 TM	24 November 1988	30	https://glovis.usgs.gov/, accessed on 16 October 2023
3	Landsat7 ETM	4 November 1998	30	https://glovis.usgs.gov/, accessed on 16 October 2023
4	Landsat5 TM	17 December 2008	30	https://glovis.usgs.gov/, accessed on 16 October 2023
5	Landsat8 OLI	12 February 2018	30	https://glovis.usgs.gov/, accessed on 16 October 2023

3.2. Methods

The coordinate system for each chart was converted to the China Beijing 1954 coordinate system (BJ-1954) with a central longitude of 114° E, and all charts were digitized as bathymetric data using the ArcGIS 10 with the bathymetric datum of the theoretical depth datum. The eight digital elevation models (DEM) of Lingding Bay from 1964 to 2019 were generated with 50 m × 50 m grids using the Kriging interpolation method in the ArcGIS software, and then isobathic maps of 2 m, 5 m, 10 m, and 20 m were draw for the different years. The cut-fill tool in the ArcGIS software was used to calculate the mean water depths and volumes below different isobaths from 1964 to 2019 [24]. Furthermore, Lingding Bay was divided into six zones, including the Humen part (HMP), NW part (NWP), Mid-North part (MNP), NE part (NEP), SW part (SWP), and the SE part (SEP) (see Figure 1 for locations). The mean depth for each zone below the different isobaths were calculated from 1964 to 2019 and the corresponding silting or scouring rates during the different decades were calculated the formula as $R = H/T$ (where R is silting or scouring rate (cm/a), H is the change value of water depth (cm), and T is the change time (year)).

The shorelines of Lingding bay from 1964 to 2019 were extracted from the Chinese chart and five RS images. The shoreline in 1964 was extracted from the Chinese chart measured in 1964, and the shorelines from 1975, 1988, 1998, 2008, and 2018 were extracted from the five RS images. According to the remote sensing images, the processing methods were as follows [11,25]: (1) The pre-processing of the RS images including radiometric correction and geometric registration was performed using the related tools in ENVI 4.8, and then the digital number (DN) values of the images were changed to radiance values. The coordinate systems of the RS images were converted to the Beijing 1954 Coordinate System, and more than 10 ground control points with a root mean square error for each image of less than 0.5 pixels were chosen to ensure the geometric accuracy of all the images. (2) The artificial shorelines were directly extracted based on visual interpretations using ENVI 4.8, such as embankments of reclamation and port shorelines. (3) The natural shorelines were extracted based on the Normalized Difference Water Index (NDWI) method [26]. (4) All the shorelines were placed on the same map using ArcGIS software, and the reclamation area was calculated for the different decades.

Empirical Orthogonal Functions (EOF) is a classical multivariate statistical technique, providing an efficient means of extracting the dominant modes of variability from a given DEM dataset [27]. The advantages of the EOF are that complex original dataset can be compressed to a smaller series of uncorrelated variables (eigenvalues) by isolating the temporal and spatial dependence of the data through a series of linear combination functions [28], which has been widely applied in studies on estuarine morphodynamics and sedimentation, obtaining the main factors on morphodynamics [29,30]. In this study, the bathymetric variation in Lingding Bay between 1966 and 2013 can thus be described by a set of eigenvalues. Morphodynamics in Lingding Bay is affected by natural (e.g., tides, waves, sea-level rise) and anthropogenic (e.g., channel dredging, reclamation) factors. The bathymetric changes are the results of the interactions between such factors. EOF can be used to extract the most important factors.

4. Results

The spatiotemporal changes in Lingding Bay were analyzed from 1964 to 2019 using the bathymetric data, and the evolutionary characteristics were examined.

4.1. Planar Changes in Underwater Topography during Different Decades

4.1.1. Planar Changes to the Bay from 1964 to 1989

In 1964 and 1989 (Figure 2a,b), the geomorphic pattern named "three shoals with two troughs" was quite clear in Lingding Bay. The shallowest area of the bay is the West Shoal with a depth of less than 2 m. The second shallowest area is the East Shoal with a predominant depth of 2–5 m with some sections of less than 2 m in depth. The water depth of the Middle Shoal is 2–5 m, and a deep trough with a depth of more than 5 m expanded to the east of Neilingding Island in the southern Tonggu Shoal. The deepest area is the Chuanbi, Dahao, and Longgu Channels, with a depth of more than 10 m. The depth of the Lingding and Fanshi Channels is between 5 and 10 m. The 5 m deep troughs in the east and west troughs are connected from north to south, but the 10 m deep troughs are only found in the Chuanbi, Dahao, and Longgu Channels.

From 1964 to 1989 (Figure 3), the 2 m isobaths in the West Shoal moved considerably eastwards, and at the 5 m isobaths there has been little change. In the East Shoal, there was little change in the 2 m and 5 m isobaths. The 5 m isobaths in the northern Lanjiang Shoal retreated slightly, and those in the northern and eastern Fanshi Shoal moved eastwards considerably, and that in the southern Tonggu Shoal moved southward. The 2 m and 5 m isobaths north of Tonggu Point showed little change except for the local 5 m isobaths at the NW of Dahao Channel moving southward. The 10 m and 20 m isobaths in the Chuanbi, Longgu, and Dahao Channels showed little change. The planar shape of the deep trough in the Chuanbi and Lingding Channels changed little, and the Fanshi Channel became narrow. Moreover, the area of the entire bay below the 2 m, 5 m, and 10 m isobaths decreased by 3%, 5%, and 5%, respectively, and that below the 20 m isobaths showed little change from 1964 to 1989 (Figure 4).

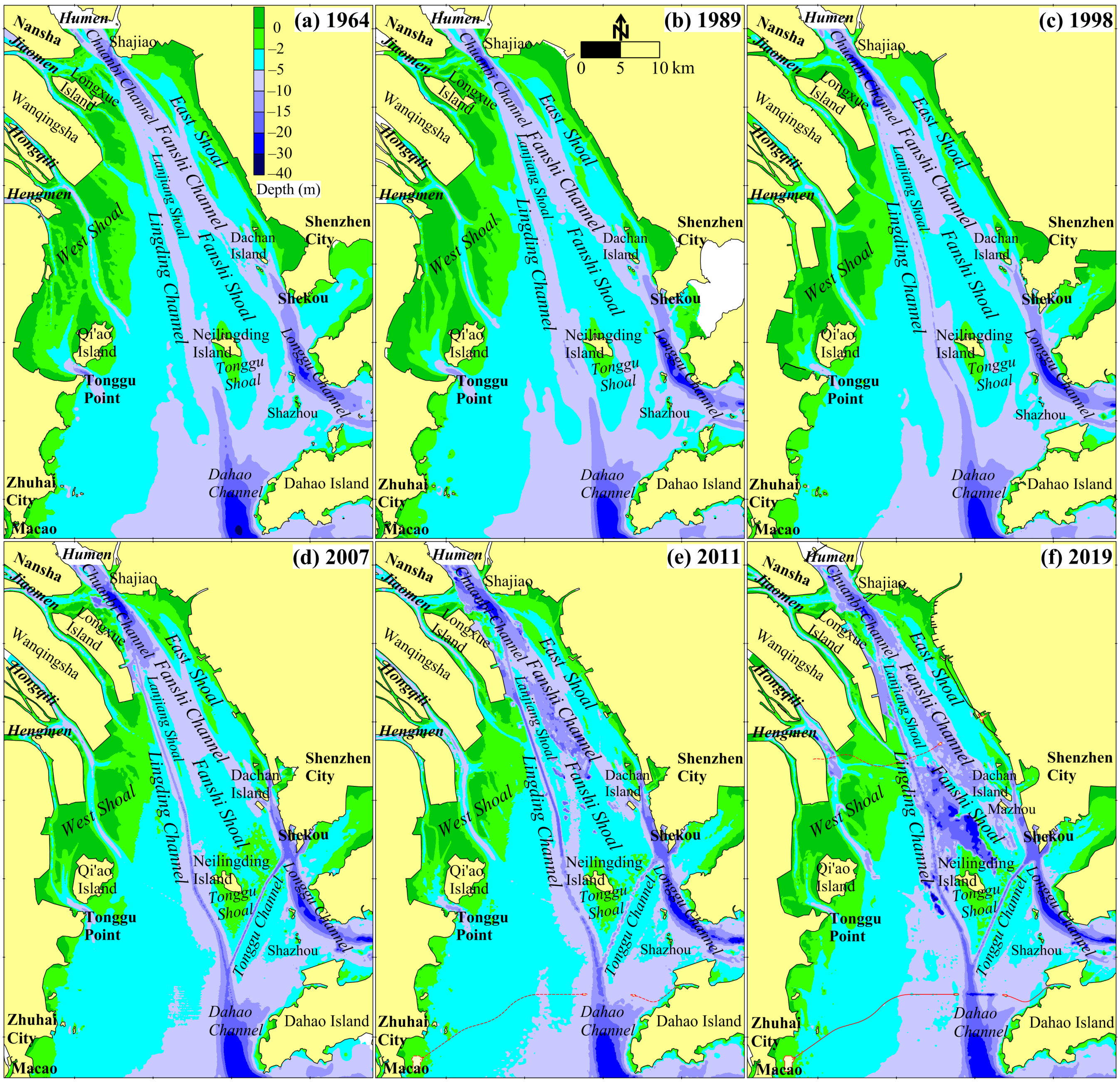

Figure 2. Subaqueous topography of Lingding Bay in the year (**a**) 1964, (**b**) 1989, (**c**) 1998, (**d**) 2007, (**e**) 2011, and (**f**) 2019.

According to the planar distribution of scouring and siltation from 1964 to 1989 (Figure 5a), the West and Middle Shoals, the Fanshi, Fuzhou, and Dahao Channels underwent a silting process with a silting thickness of predominantly 0–1 m and more than 1 m in some areas. The East Shoal and southern Lingding Bay except the Dahao Channel showed little change. The Lingding Channel was being scoured with a range of 1–2 m.

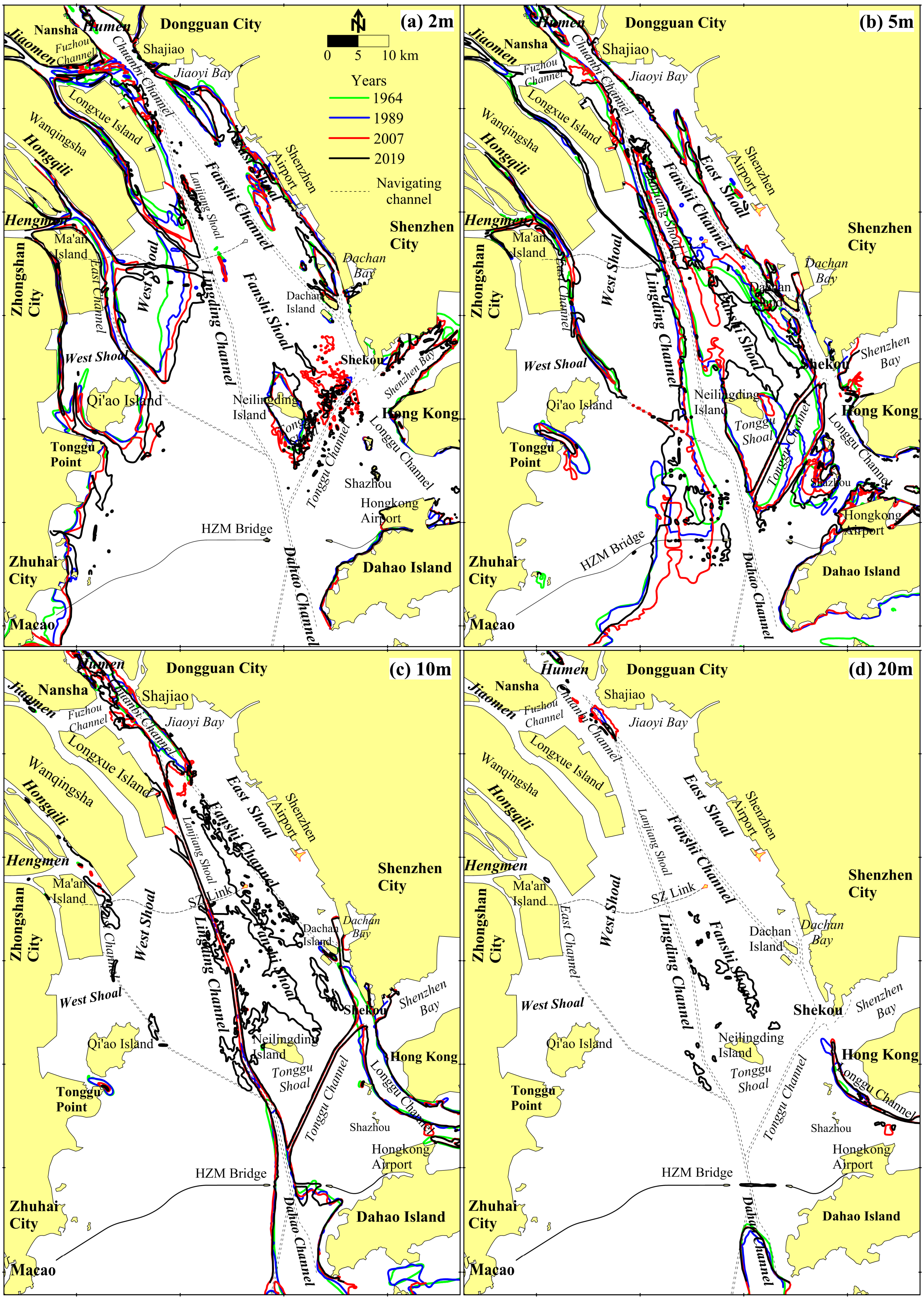

Figure 3. Planar changes in the (**a**) 2 m, (**b**) 5 m, (**c**) 10 m, and (**d**) 20 m isobaths from 1964 to 2019.

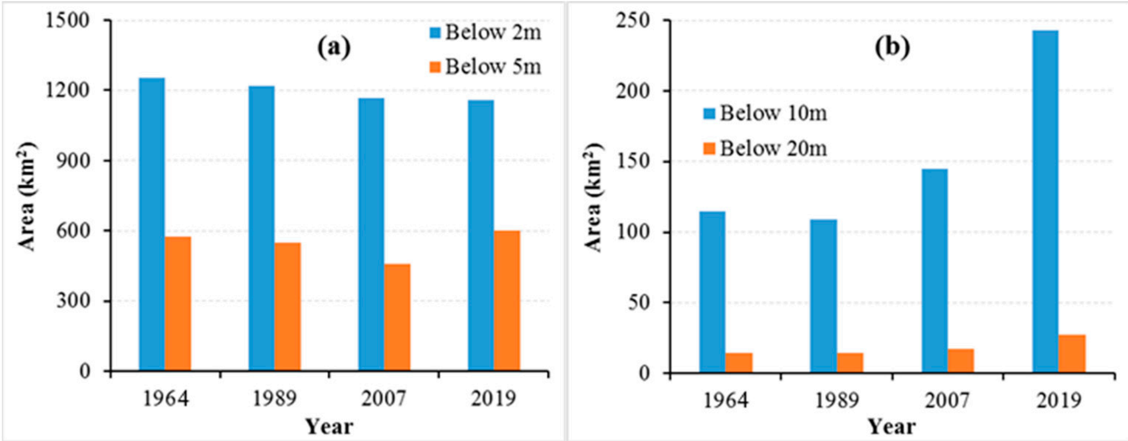

Figure 4. Changes in the water area below the 2 m, 5 m, 10 m, and 20 m isobaths from 1964 to 2019. (**a**) Below the 2 m and 5 m isobaths, (**b**) below the 10 m and 20 m isobaths.

The silting process in Lingding Bay was most pronounced from 1964 to 1989, especially in the West and Middle Shoals, the Fanshi and Fuzhou Channels. The West and Middle Shoals expanded eastward and southward considerably, and the Fanshi Channel became narrow and shallow. The width of the Lingding Channel remained stable with a significant increase in depth. The silting process in the East Shoal and southern Lingding Bay was less visible.

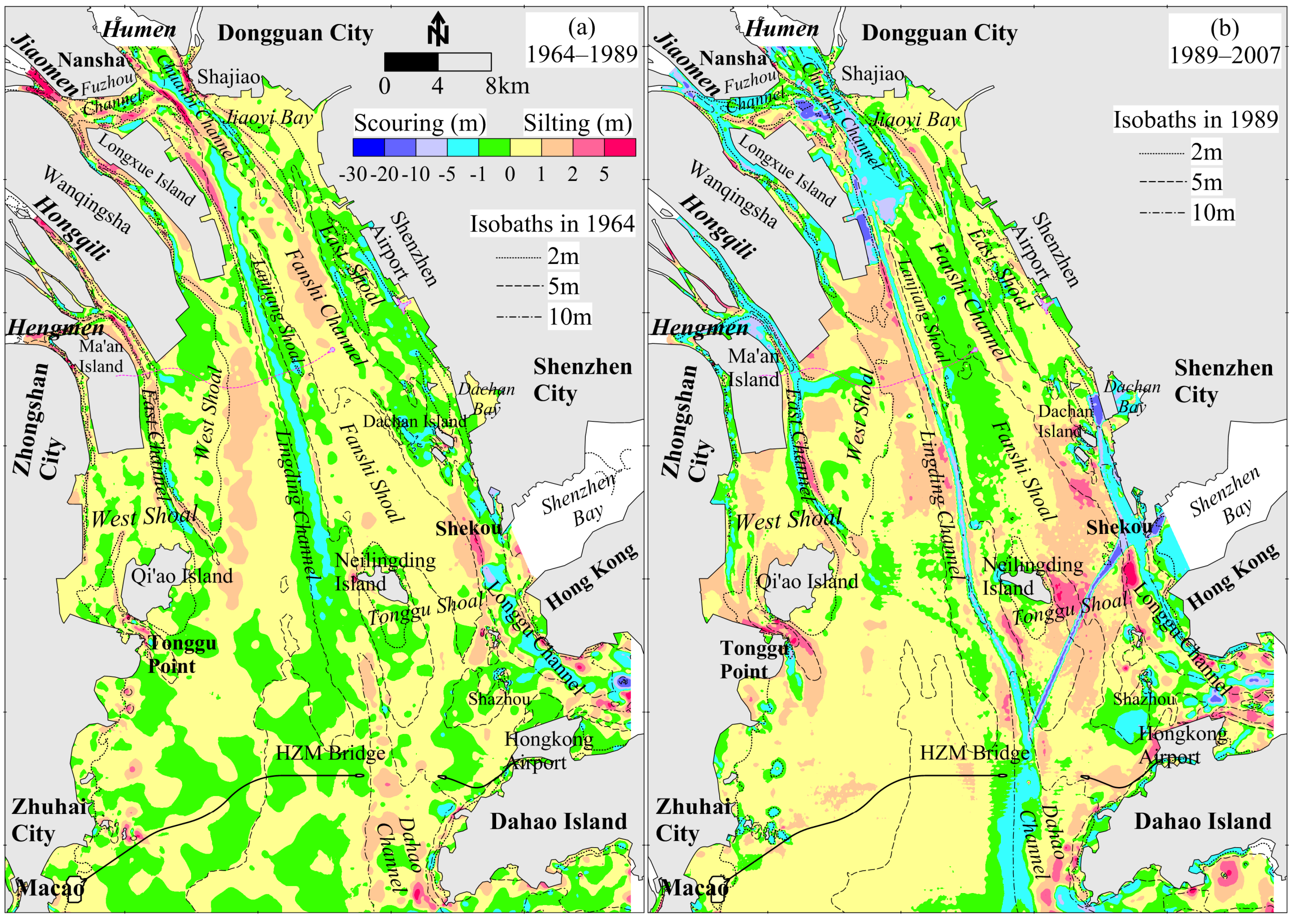

Figure 5. *Cont.*

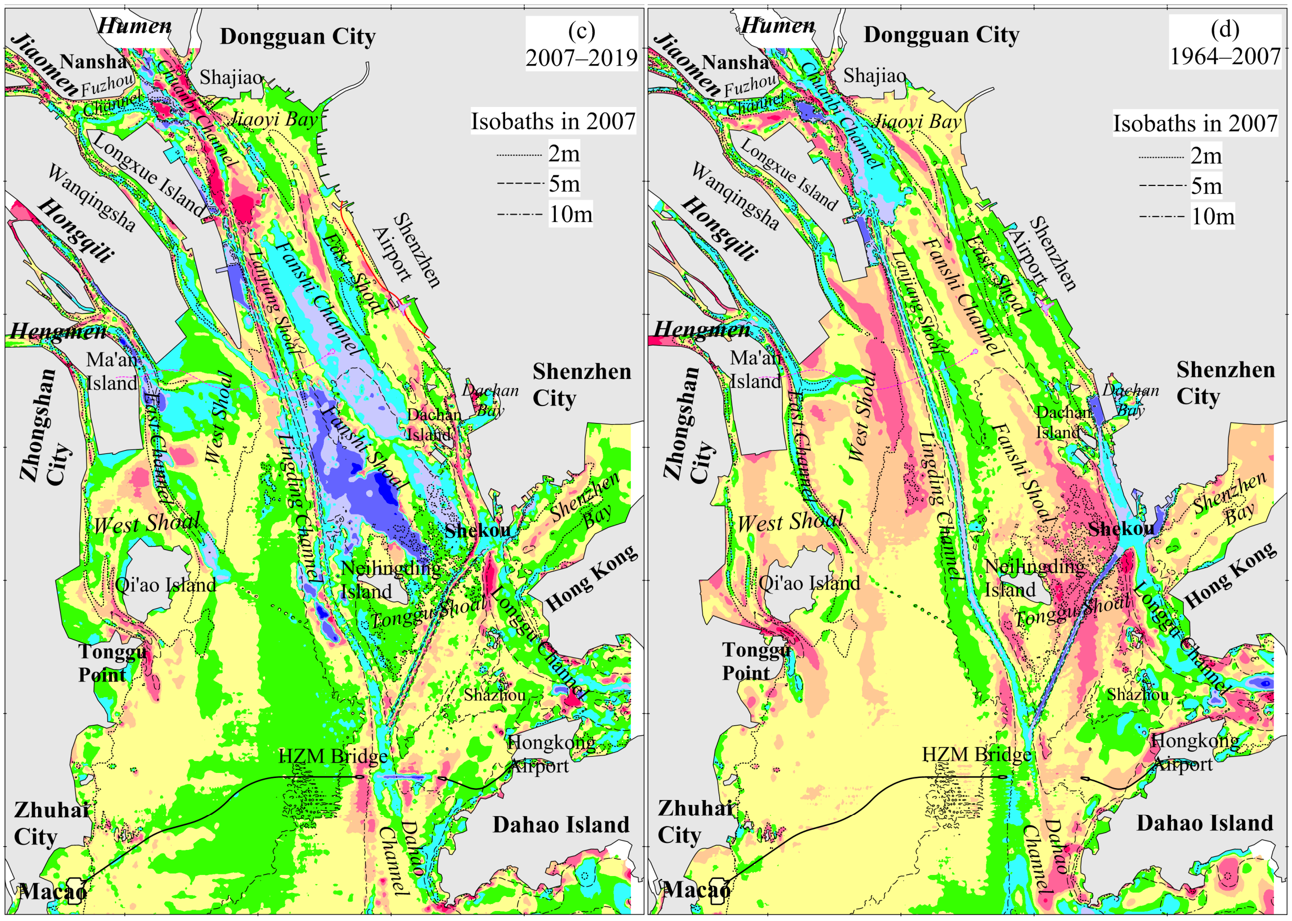

Figure 5. Planar distribution of erosion and accretion in Lingding Bay from 1964 to 2019. (**a**) 1964–1989; (**b**) 1989–2007; (**c**) 2007–2019; (**d**) 1964–2007.

4.1.2. Planar Changes in the Bay from 1989 to 2007

In 1998 and 2007 (Figure 2c,d), the geomorphic pattern of "three shoals with two troughs" was clear in Lingding Bay. The depth of the southern Chuanbi Channel, the deep trough of the Lingding Channel, the shallow area near southern Longxue Island, and east of Dachan Island increased substantially to more than 10 m. The 10 m deep trough in the Lingding Channel connected the Chuanbi and Dahao Channels and went through the whole Lingding Bay. The 10 m deep trough in the Longgu Channel extended to the north of Dachan Island. Two new 5 m deep troughs appeared on the north and south sides of the connecting part of the Lanjiang and Fanshi Shoals, respectively, and the deep troughs on both sides of the shoal had the potential to become connected. The Tonggu Shoal expanded southwards and closed to the Shazhou Island and the 5 m deep trough in the central shoal disappeared. The local depth to the east and south of Neilingding Island was less than 2 m, indicating the local siltation. In 2007, the Tonggu Channel with a direction of NE–SW was excavated on the Tonggu Shoal with a depth of more than 10 m.

From 1989 to 2007 (Figure 3), the 2 m isobaths in the West Shoal moved eastwards considerably, and the 5 m isobaths showed little change. In the East Shoal, the 2 m and 5 m isobaths changed little. The 5 m isobaths in the north and south sides of the connecting part of the Lanjiang and Fanshi Shoals had a strong potential to connect. The 5 m isobaths in the eastern Fanshi Shoal moved eastward. In the East Shoal, the 2 m isobaths in the Tonggu Shoal had expanded considerably, and the 5 m isobaths near the Shazhou Island retreated substantially. In the Chuanbi Channel, the 5 m isobaths showed little change, but the 10 m and 20 m isobaths extended southwards considerably. The 2 m, 5 m, and 10 m isobaths west of Longxue Island became separated from those in the West Shoal. In the

Lingding Channel, the 5 m isobaths showed little change, but 10 m isobaths formed in the channel. In the Longgu Channel, the 5 m isobaths showed little change, but the 10 m and 20 m isobaths extended considerably further northwards. The 2 m and 5 m isobaths north of Tonggu Point showed little change except the 5 m isobaths at the NW of the Dahao Channel moving southward. In the Dahao Channel, the 10 m and 20 m isobaths showed little change. In the whole bay, the area below the 2 m and 5 m isobaths decreased by 4% and 16%, respectively, and that below the 10 m and 20 m isobaths increased by 33% and 23% respectively from 1989 to 2007 (Figure 4).

According to the planar distribution of scouring and siltation from 1989 to 2007 (Figure 5b), the west, Fanshi, and Tonggu Shoals, the southern Fanshi Channel, and north of Dahao Island underwent siltation with a range of predominantly 0–2 m and more than 2 m in the northern Tonggu Shoal near Neilingding Island. The sea area south of Tonggu Point underwent a slight silting process with a silting range of 0–1 m. The Lingding Channel underwent a silting process except the central trough, with a scouring process with a range of 1–5 m. The Chuanbi, Dahao and Tonggu Channels, the northern Longgu Channel, and the south of Shazhou Island underwent a pronounced scouring process with a predominant range of 1–5 m and more than 5 m in some areas. The western Fanshi Shoal underwent slight scouring with a range of 0–1 m. Meanwhile, the East Shoal showed little change.

The West and Middle Shoals accreted significant from 1989 to 2007, as well as the Fanshi and Lingding Channels. The largest silting thickness in Lingding Bay was in the northern Tonggu Shoal with value of more than 2 m. The depth increased substantially in the southern Chuanbi Channel, the northern Longgu Channel, the east of Longxue Island, the central trough of Lingding and Tonggu Channels.

4.1.3. Planar Changes in the Bay from 2007 to 2019

In 2011 (Figure 2e), a large and irregular deep hole (north hole) with a NW–SE direction was formed in the Fanshi Channel and the eastern Fanshi Shoal, with a length of approximately 15 km, a width of approximately 3–4 km and a depth of 10–20 m. There were several irregular small deep holes with a depth of more than 10 m in the southern Lanjiang Shoal and the northwestern Fanshi Shoal. A north-south deep trough with a width of approximately 1.2 km and a depth of 5–10 m formed between the Lanjiang and Fanshi Shoals which connected the Fanshi and Lingding Channels. According to the underwater topography in 2019 (Figure 2f), the north hole extended considerably to the southeast with the length increasing to 18 km. A new large and irregular deep hole (south hole) appeared in the western and central Fanshi Channel with a length of approximately 16 km from the northwest to the southeast, a width of about 1–4.5 km from the east to the west and a depth of 20–40 m. The south hole connected with the Lingding Channel in the west and extended to the eastern Neilingding Island. A new deep hole (the eastern hole) also appeared south of Mazhou Island in the eastern Fanshi Shoal, with a length of 7 km from the north to the south, with a width of 2 km from the east to the west, and a depth of 10–20 m. The width of the shallow water area between the east hole and the north and south holes was only 1–2 km. The width of the shallow water between the north and south holes was less than 1 km, and the two holes connected locally with each other. There were also several small irregular holes with a depth of more than 20 m on both sides of the Lingding Channel near Neilingding Island, and a long deep hole with a depth of more than 20 m also formed between the east and west islands of the Hong Kong-Zhuhai-Macao Bridge (HZMB).

From 2007 to 2019 (Figure 3d–f), the 2 m isobaths in the West Shoal moved substantially eastwards, and the 5 m isobaths retreated westwards locally, indicating steeper seaward edge of shoals. In the East Shoal, the 2 m isobaths moved slightly eastwards, where the 5 m isobaths showed little change. In the Middle Shoal, the 2 m isobaths north of Neilingding Island moved outwards, and the isobaths in the other part of the Middle Shoal reduced in size. The 5 m isobaths in the Lanjiang and Fanshi Shoals separated, and those in the western and eastern Fanshi Shoal retreated considerably towards the center, but those in the southern Tonggu Shoal moved slightly to the south. In eastern Fuzhou Channel, the 2 m, 5 m, and 10 m isobaths retreated westward, and the 5 m and 10 m isobaths near the southern Longxue Island retreated northwards and southwards. In the south of the Tonggu Point, the 2 m isobaths moved considerably eastwards, but the 5 m isobaths greatly retreated westwards. The 2 m and 5 m isobaths near the Dahao Island showed little change. The 10 m isobaths along the western edge of the northern Lingding Channel moved partially westwards, and those along the eastern edge of the northern channel showed little change near the Lanjiang Shoal and Neilingding Island, but those moved significantly eastwards to the central Fanshi Shoal and extended to east of Neilingding Island. Large closed 10 m isobaths formed in the Fanshi Channel, and small closed 10 m isobaths formed at the eastern Fanshi Shoal. The nearest distance of the 10 m isobaths between the Lingding and Fanshi Channels was less than 1 km. The 10 m isobaths showed little change in the southern Lingding Channel, the Longgu, Dahao, and Tonggu Channels. Several small closed 10 m isobaths were formed in the west of the Lingding Channel and outside the Hengmen. The 20 m isobaths in the Longgu Channel and the Dahao Channel showed little change, while those in the Chuanbi Channel shrunk substantially with the area decreasing considerably. There were many small, irregular, and closed 20 m isobaths in the Fanshi Channel, the Fanshi Shoal, and near the southern Lingding Channel, and there were closed 20 m isobaths between the east and west artificial islands of the HZMB. During this period, the shape of the 5 m and 10 m isobaths in the Lingding Channel, the Fanshi Channel and Shoal changed from smooth to highly irregular. In the entire bay, the area below 2 m in depth showed little change, and that below the 5 m, 10 m, and 20 m isobaths increased by 30%, 68%, and 54%, respectively, from 2007 to 2019 (Figure 4).

According to the planar distribution of scouring and siltation from 2007 and 2019 (Figure 5c), the Fanshi Channel and Shoal underwent considerable scouring with a large area of deepening. The scouring range in the Fanshi Channel was predominantly between 5 and 10 m and 1 and 5 m locally, and that in the Fanshi Shoal was mainly between 10and 20 m, and locally more than 20 m. The scouring range in the eastern Fuzhou Channel, southeast of Longxue Island, outside the Hengmen, the deep trough of the Lingding Channel was also large with a scouring range of more than 1 m. The Chuanbi Channel, the southern Tonggu Shoal, the central West Shoal, and the southern bay near the Tonggu Point and the artificial islands of the HZMB underwent a pronounced silting process with a silting range of predominantly 0–2 m. The other areas of Lingding Bay showed little change.

According to the planar distribution of scouring and siltation from 1964 to 2007 (Figure 5d), before 2007, the West, Fanshi, and Tonggu Shoals, and the Fanshi Channel underwent a strong silting process with a silting range of predominantly 1–5 m, only the deep troughs of the Chuanbi, Longgu, Lingding, and Tonggu Channels underwent a scouring process in a small scour area. After 2007, the Fanshi Channel and Shoal underwent a pronounced scouring process with a large scouring area and a magnitude scouring range of 5–20 m. Therefore, the change characteristics in Lingding Bay after 2007 were different from that before 2007, especially in the Fanshi Channel and Shoal.

Overall, the topography of the Fanshi Channel and Shoal in northern Lingding Bay have greatly deepened since 2007, and some large areas and irregular deep holes have appeared in the Fanshi Channel and Shoal, near the Lingding Channel, which showed the aberrant changes in northern Lingding Bay.

4.2. Long-Term Evolutionary Characteristics from 1964 to 2019

According to our analysis, the differences in the morphological changes in Lingding Bay over different decades are considerable, so it is important to continue further study. The evolutionary changes in the water area, water volume, and the silting rate of the bay were calculated using bathymetric data from 1964 to 2019, and the long-term morphological evolution of the bay was analyzed.

4.2.1. Long-Term Water Area and Volume Changes in the Bay

The water area and volume of Lingding Bay below the different isobaths from 1964 to 2019 are shown in Figure 6.

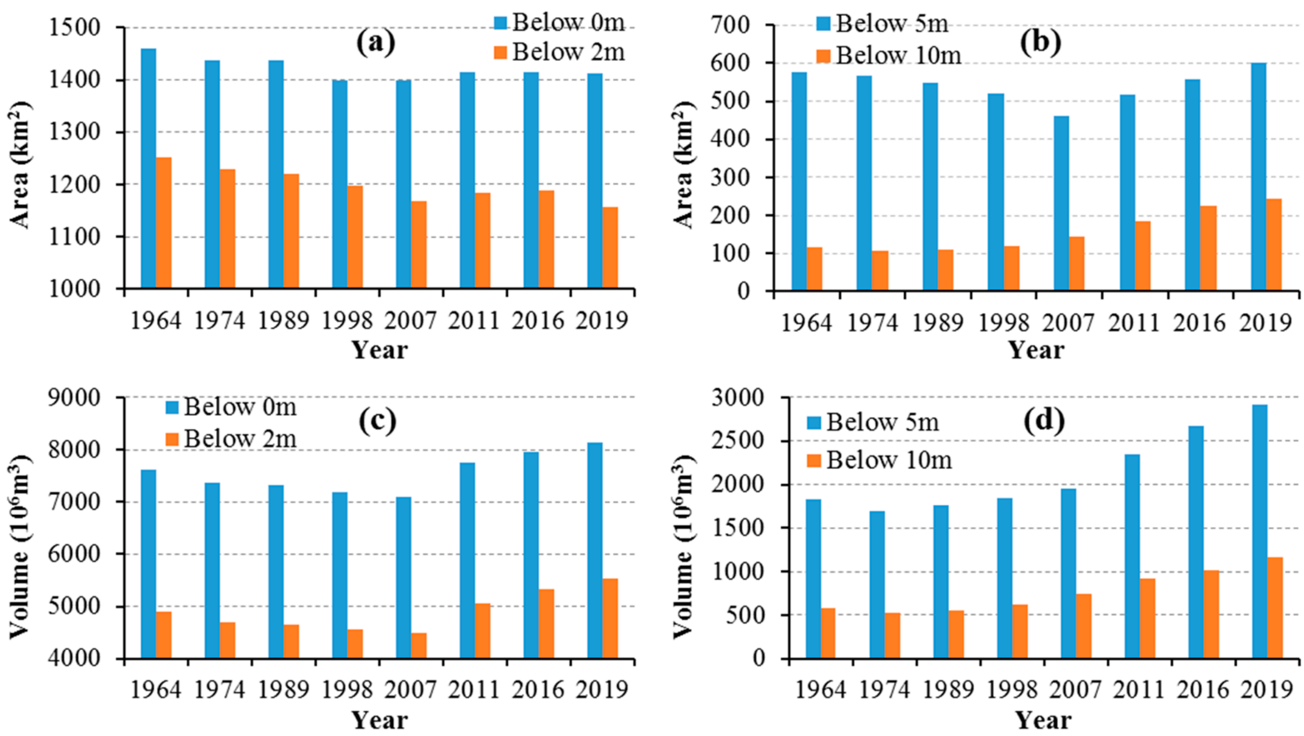

Figure 6. Changes in the water area and the volume in Lingding Bay from 1964 to 2019. (**a**) Water area below the 0 m and 2 m isobaths; (**b**) water area below the 5 m and 10 m isobaths; (**c**) water volume below the 0 m and 2 m isobaths; (**d**) water volume below the 5 m and 10 m isobaths.

The water areas below 0 m and 2 m isobaths were approximately 1400 km^2 and 1200 km^2 in 1964, respectively (Figure 6a); they decreased from 1964 to 2007 by 3% and 7%, respectively, and changed slightly from 2007 to 2019. The area below the 5 m isobaths were approximately 580 km^2 (Figure 6b) in 1964, and gradually decreased from 1964 to 2007 with a total decrease of 20%, but gradually increased from 2007 to 2019 with a total increase of 30%. The area below the 10 m isobaths were approximately 120 km^2 in 1964 (Figure 6b), and slightly decreased from 1964 to 1974, and gradually increased from 1974 to 2019 with a total increase of 130%. However, the change value of the area below the 10 m isobaths from 2007 to 2019 was 2.6 times greater than that from 1974 to 2007.

The water volumes below the 0 m and 2 m isobaths were approximately 7620 × 10^6 m^3 and 4890 × 10^6 m^3 in 1964, respectively (Figure 6c); they gradually decreased from 1964 to 2007 by 7% and 8%, respectively, but gradually increased from 2007 to 2019 by 15% and 23%, respectively. The water volumes below the 5 m and 10 m isobaths were approximately 1830 × 10^6 m^3 and 580 × 10^6 m^3 in 1964, respectively (Figure 6d); they decreased from 1964 to 1974 by 8% and 11%, respectively, but gradually increased from 1974 to 2019 by 72% and 123%, respectively. The water volumes below the different isobaths in 2019 were all greater than those in 1964 and those below the 5 m and 10 m isobaths had a far greater increasing proportion.

The water areas and volumes of Lingding Bay below the 0 m and 2 m isobaths decreased slightly before 2007, which indicates that the bay underwent a low level of silting. The water areas below 0 m and 2 m isobaths showed little change, but the volumes below 0 m and 2 m isobaths increased considerably after 2007, which indicates that the bay underwent a pronounced scouring process. The water volumes below the 5 m isobaths in 2019 had a far greater increasing proportion after 2007. The water volumes below the

5 m isobaths began to increase from 1974 to 2019, which is inconsistent with the change characteristics of the bay.

4.2.2. Silting and Scouring Characteristics during Different Decades

The mean depth, silting volume, and the silting rate of Lingding Bay from 1964 to 2019 are shown in Figure 7. The mean depth, the silting volume, and the silting rate in the six computed zones including the Humen part, the NW part (West Shoal), the mid-north part (East Trough and Middle Shoal), the NE part (East Shoal), the SW part, and the SE part (see Figure 1 for locations) from 1964 to 2019 are shown in Figure 8.

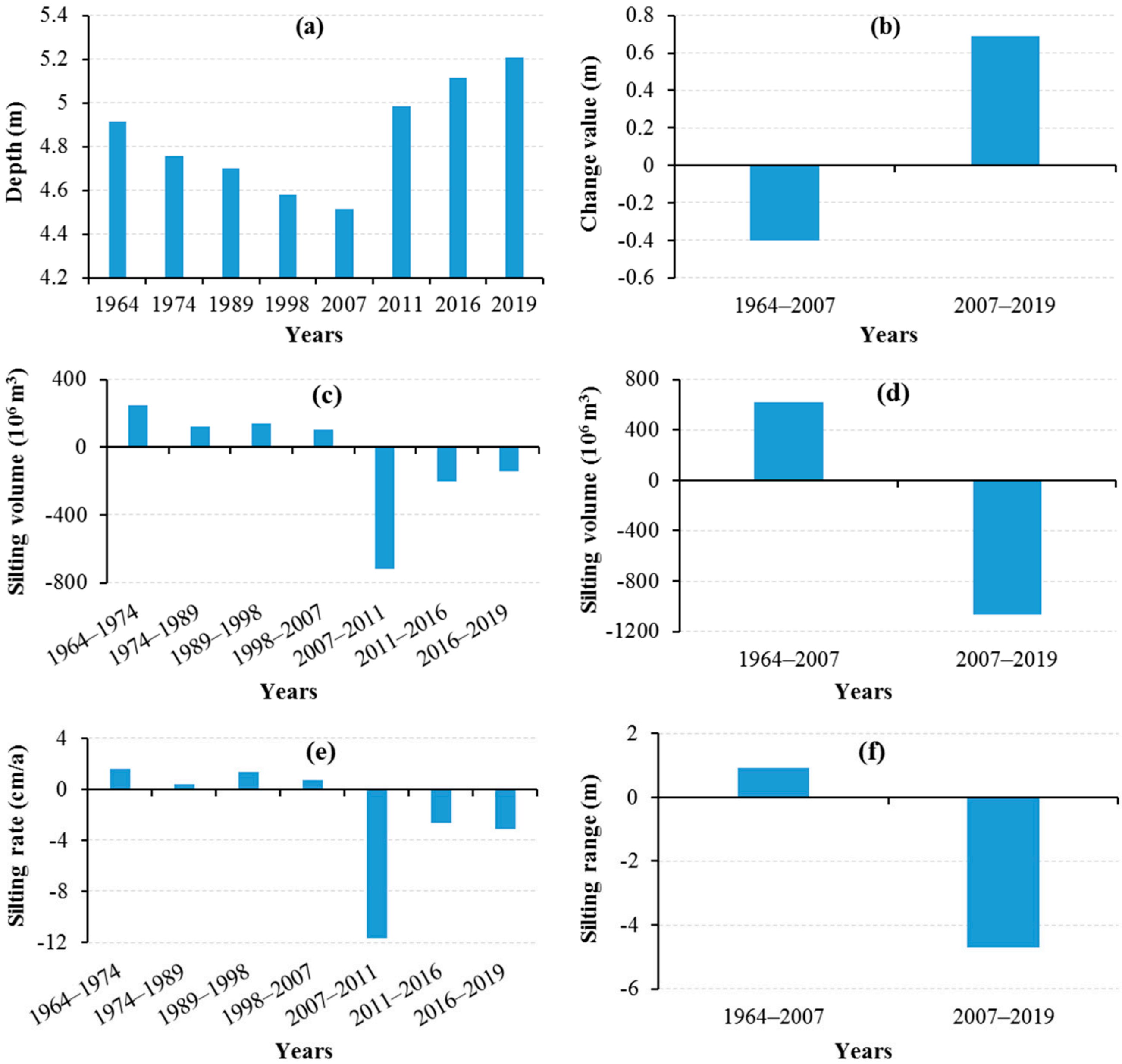

Figure 7. Changes in the water depth, silting volume, and silting rate in Lingding Bay from 1964 to 2019. (**a**) Mean water depth during different years; (**b**) change value of the depth before and after 2007; (**c**) silting volumes during different decades; (**d**) silting volumes before and after 2007. (**e**) Silting rates during different decades; (**f**) silting rates before and after 2007.

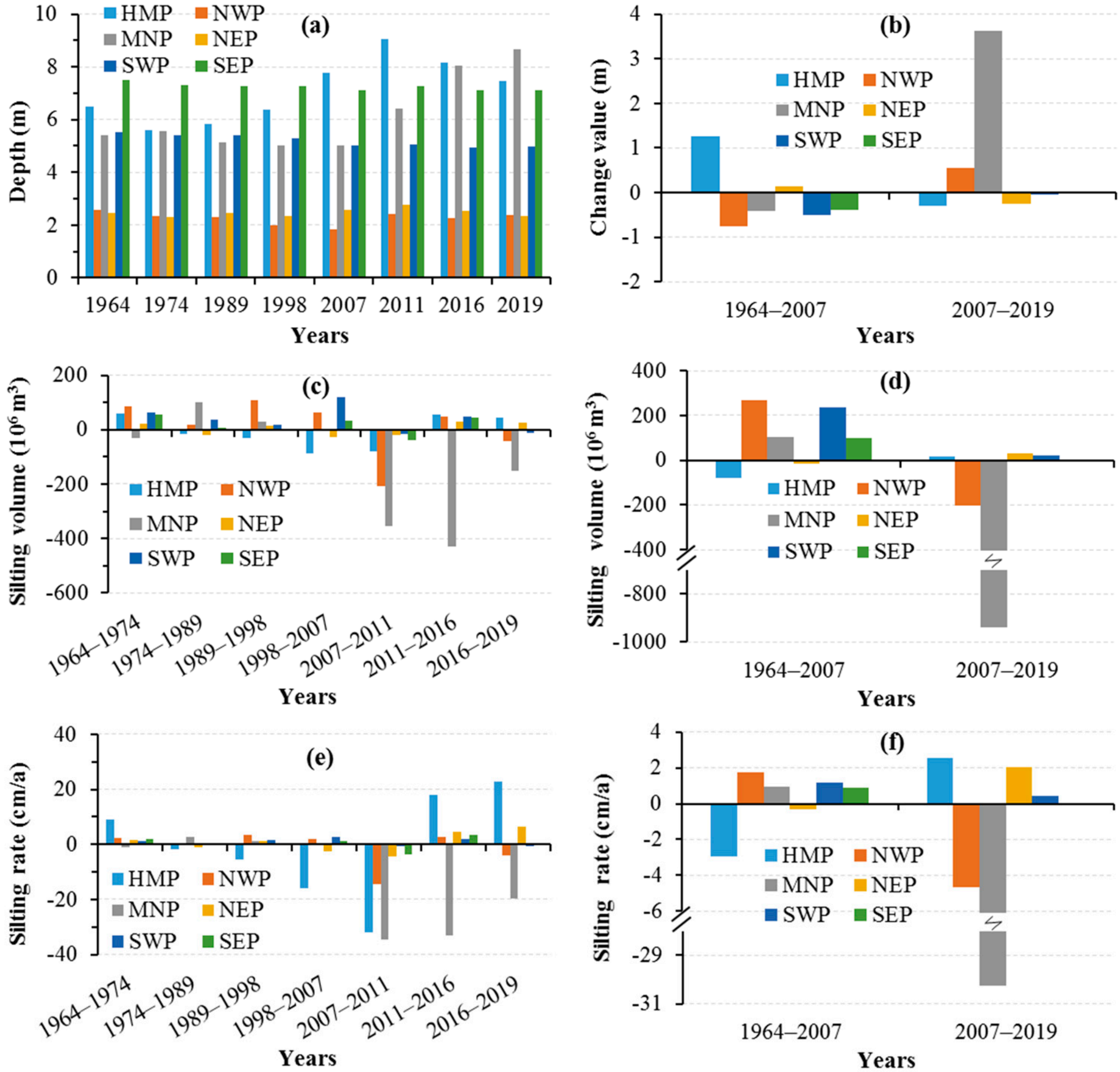

Figure 8. Changes in the water depth, silting volume, and the silting rate of different zones from 1964 to 2019. (**a**) The mean depth in different years; (**b**) the change value of the depth before and after 2007; (**c**) the silting volume in different decades; (**d**) the silting volume before and after 2007; (**e**) the silting rate in different decades; (**f**) the silting rate before and after 2007.

According to Figure 7, the mean depth of Lingding Bay in 1964 was approximately 4.9 m. From 1964 to 2007, the bay underwent a silting process with a silting range of 0.4 m, a total silting volume of 620 $\times$ 10^6 m^3 and a mean silting rate of 0.9 cm/a. From 2007 to 2019, the bay underwent a scouring process with a range of 0.7 m, a total volume of 1100 $\times$ 10^6 m^3 and a scouring rate of 5.8 cm/a. The scouring range of the bay from 2007 to 2019 was much greater than from 1964 to 2007, and the depth and volume of the bay in 2019 exceeded those of 1964.

According to Figure 8, the mean depth of the Humen part, the NW part, the mid-north part, the NE part, the SW part, and the SE part in 1964, was approximately 6.5 m, 2.6 m, 5.4 m, 2.5 m, 5.5 m, and 7.5 m, respectively. The NW part and the NE part were shallow, and the SW part and the Humen part were deep. From 1964 to 2007, the mean depth of the NW part, the mid-north part, the SW part, and the SE part gradually decreased with a total silting thickness of 0.4–0.8 m. The mean depth of the NE part increased slightly with a scouring thickness of 0.1 m. Therefore, the NW part, the mid-north part, the SW part, and the SE part underwent a silting process from 1964 to 2007, with a total silting volume of 99–270 $\times$ 10^6 m^3 and a mean silting rate of 0.9–1.7 cm/a. The NE part underwent a slight scouring process with a total scouring volume of 16 $\times$ 10^6 m^3 and a mean scouring rate of 0.3 cm/a. From 2007 to 2019, the mean depth of the NW and the mid-north parts increased with a total scouring thickness of 0.6 and 3.6 m, respectively. The mean depth of the NE part decreased with a total silting thickness of 0.2 m, and that of the SW and the SE parts slightly changed. Therefore, the NW and the mid-north parts underwent a scouring process from 2007 to 2019, with a total scouring volume of 200 $\times$ 10^6 m^3 and 940 $\times$ 10^6 m^3, respectively, and a mean souring rate of 4.7 cm/a and 30.2 cm/a, respectively. The NE part underwent a slight silting process with a total silting volume of 30 $\times$ 10^6 m^3 and a mean silting rate of 2.0 cm/a. The depth of the Humen part decreased with a silting thickness of 0.9 m from 1964 to 1974 and gradually increased to 9.1 m with a total scouring thickness of 3.5 m from 1974 to 2011, and then decreased to 7.5 m with a total silting thickness of 1.6 m from 2011 to 2019. The total scouring thickness and volume of the Human part from 1964 to 2007 were 1.3 m and 77 $\times$ 10^6 m^3, respectively, and the total silting thickness and volume from 2007 to 2019 were 0.3 m and 19 $\times$ 10^6 m^3, respectively. The scouring volume from 2007 to 2019 of the mid-north part was approximately 9.2 times more than the silting volume from 1964 to 2007, and 1.5 times more than the silting volume of the whole bay from 1964 to 2007. Furthermore, the mid-north part became the deepest zone in the bay in 2019 with a mean depth of 8.7 m.

In all, Lingding Bay had undergone a low level of silting from 1964 to 2007 with a silting rate of 0.9 cm/a, but a pronounced scouring process from 2007 to 2019 with a scouring rate of 5.8 cm/a, and the depth and volume of the bay in 2019 were greater than those in 1964. The East Trough and Middle Shoal underwent considerable change after 2007 and became the deepest zones in the bay. Therefore, the evolutionary characteristics of Lingding Bay after 2007 showed pronounced differences in comparison with prior to 2007, and the turning point for the morphological evolution occurred around 2007.

4.3. Aberrant Changes in Recent Years

According to our analysis, the geomorphic pattern and the evolutionary characteristics of Lingding Bay had considerable differences between different decades. Before 2007, the geomorphic form of the bay had been maintained as “three shoals and two troughs”. The depth of the shoals was less than 5 m and that in the Fanshi Channel was approximately 5–10 m. Only the depth in the Chuanbi, Lingding, Dahao, and Longgu Channels was greater than 10 m. The whole bay underwent a slight silting process with a mean silting rate of 0.9 cm/a, and the silting rate in the West Shoal was slightly higher than the rest of the bay.

After 2007, the East Trough and the Middle Shoal in the bay underwent a considerable deepening process and some large and irregular deep holes with a depth greater than 10 m have formed. At the same time, the other parts of the bar underwent a slight silting process except for the West Shoal which had a small range of scouring. The amount of sediment loss in the East Trough and the Middle Shoal and the whole bay between 2007 and 2019 was 9.2 and 1.7 times the amount of sediment deposition between 1964 and 2007, respectively. The amount of sediment loss between 2007 and 2019 in the East Trough and the Middle Shoal was approximately 1.5 times more than the amount of sediment deposition of the whole bay between 1964 and 2007. The East Trough and the Middle Shoal became the deepest zone in the bay, and the deep holes had connected the deep troughs of the Fanshi and Lingding Channels in 2019.

Therefore, the morphological evolution characteristics of the East Trough and the Middle Shoal after 2007 were highly different to prior to 2007, and these strong topographic changes were aberrant compared with the natural silting process. These aberrant changes considerably altered the geomorphic form of the Middle Shoal and would further change sediment transport processes.

4.4. Patterns of Morphological Change Obtained by EOF

Morphological changes and their patterns in Lingding Bay were influenced by human activities. To obtain the major characteristics of and factors causing morphological changes in Lingding Bay, underwater topography data from the years 1964, 1974, 1989, 1998, 2007, 2011, 2016, and 2019 were used to quantify the major modes of morphological change using the EOF method. The first two modes explained the main patterns of morphological variation (over 95.05%, Figure 9) in Lingding Bay from 1964 to 2019, while the remaining modes accounted for 5% of the covariance. These were considered to be noise and were neglected.

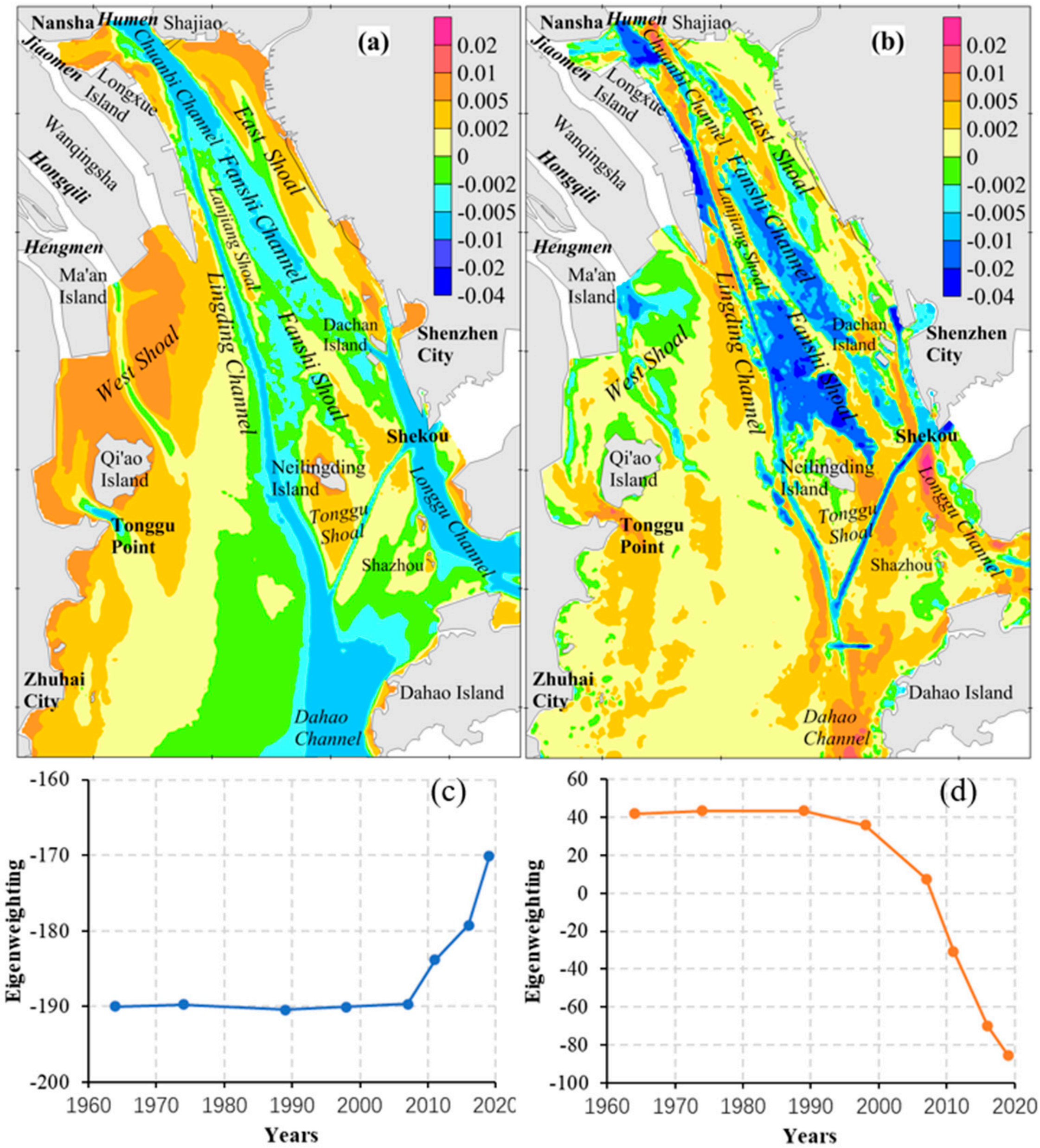

Figure 9. Patterns of morphological changes in Lingding Bay quantified by EOF analysis. (**a**) Contoured eigenvectors of the first mode; (**b**) contoured eigenvectors of second mode, (**c**) eigenweightings of the first mode, (**d**) eigenweightings of the second mode.

The first mode accounted for 88.6% of variance, representing accretion in the shoals and erosion in the deep channel. The contour plot of the first mode eigenvector shows the high values of eigenvector occurred in shallow areas, such as the west, east, and Tonggu Shoal, and the south of Tonggu Point, while the low values occurred in the deepened channels, such as the Chuanbi, Lingding, Dahao, Longgu, and Fanshi channels, and the Fanshi Shoal (Figure 9a). The distribution of accreting and eroding areas depicted in Figure 5 corresponds with the contour plot of the first mode eigenvector. The temporal pattern of the eigenvalues shows that all coefficients were negative, with some periodic fluctuations from 1964 to 2007, and an increasing trend after 2007, eventually reaching a value of 20 (Figure 9c), corresponding with the trend of morphodynamics before and after 2007 (Figure 7a). Therefore, the first mode reflected the major pattern of morphological change in Lingding Bay over the past five decades.

The second eigenmode contributed to 6.45% of the covariance. The eigenvector was negative through most of Lingding Bay (Figure 9b), with positive values mainly concentrated near the Longgu and Dahao Channels. Negative eigenvectors with high absolute values were located in the Fanshi Channel and Shoal, Lingding Channel, Humen and Hengmen, and eastern Longxue Island, where intensive human activities (e.g., sand-dredging and waterway dredging) occurred frequently. The temporal characteristics of this mode were represented by the eigenvalues curve which showed a secular decline at a significance level of −100 (Figure 9d). The temporal characteristics of this mode varied little before 1989, decreased slightly from 1989 to 2007, and decreased abruptly after 2007. This was aligned with the small-scale sand-dredging near Humen and waterway regulation in Lingding Channel during 1989–2007, and the disordered sand-dredging activities in Fanshi Channel and Shoal after 2007. Therefore, the second mode represented the effects of human activities on the morphological changing of Lingding Bay. Compared with the eigenvalues of the first mode, those of the second mode displayed an opposite trend. Moreover, the slope of the decreasing trend in the second mode was larger than that of the increasing trend in first mode (Figure 9c). This indicates that the role of human activities in morphological change exceeded that of the natural evolution process.

5. Discussion

5.1. Impacts of Sediment Inputs

Upstream sediment discharge, as the typical input condition, is important for the morphological evolution in estuarine regions. In recent years, upstream sediment discharge has decreased through human activities such as artificial afforestation and dam construction. The silting rate of the estuarine topography has decreased and scouring processes have occurred in some estuarine areas [2,3,10,25].

The sediment load discharged into Lingding Bay accounted for 54.0% of the total of the Pearl River. The annual runoff and the sediment load of the Pearl River changed slightly from the 1960s to the 1990s, and the annual sediment load decreased by 65% after the 1990s to the present with the annual runoff changed slightly (Figure 10), which was predominantly caused by dam construction in the river basin rather than a precipitation change [21,25]. Therefore, the sediment input of the bay decreased considerably after 2000.

The impact of the decrease in the sediment input on the estuarine evolution usually had a lag effect, so the estuarine bay would undergo a slow transition process from siltation to slow erosion, and the silting or erosion rate should be relatively slow. The sediment input from 1998 to 2007 was the same as that from 2007 to 2019; however, the evolutionary characteristics differed significantly. Therefore, the evolutionary characteristics of the bay in recent decades could not be dominated by the decrease in upstream sediment input.

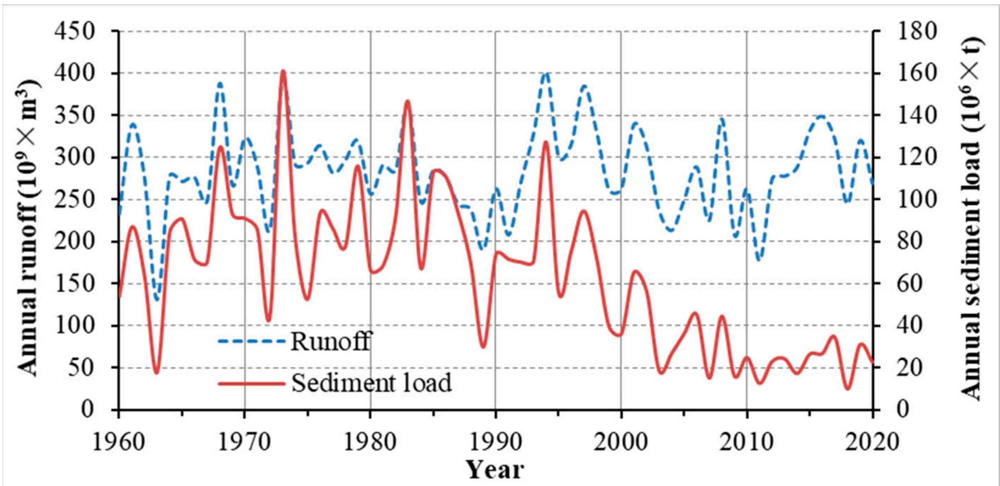

Figure 10. Annual changes in the runoff and the sediment load of the Pearl River after 1960.

5.2. Impacts of Human Activities in Lingding Bay

Estuarine regions are usually well-developed and frequently affected by human activities including estuarine regulation, shoal reclamation, port construction, sand dredging, and sea-crossing bridge construction, changing the estuarine boundary and topography, and then affect the morphological evolution and the geomorphic form of estuarine regions [1,2,4,10,14,31]. In recent decades, the main human activities in Lingding Bay have included estuarine reclamation, sand dredging, and port construction [7,14,17,32,33].

5.2.1. Impacts of Shoal Reclamation

The shallow shoals in estuarine regions are valuable resources, and shoal reclamation is an important way to increase land resources for meeting the needs of economic development and population growth. The large-scale reclamation of the estuarine bay could not only reduce the water area, but also extend the flow path of estuary channels, resulting in the change in the sediment deposition center and a slight increase in the average silting rate of the bay [11,14].

There is a large area of shallow shoals in Lingding Bay. Over the last 55 years, the total reclamation area of Lingding Bay has been approximately 323 km^2 (Figure 11). The total reclamation area in the northern bay including Human, NW, and the NE parts accounted for 93% of the total amount, and that which occurred from 1975 to 2008 accounted for 93% of the total amount. The reclamation rate has been more than 6 km^2/a, which is approximately three times greater than that from 2008 to 2019 and from 1964 to 1975. According to the mean silting rate of Lingding Bay before 2007, the silting rate of the bay has changed little during the large-scale reclamation, so the bay could maintain a geomorphic form of “three shoals and two troughs” for a long time. Therefore, the considerable deepening of the East Trough and the Middle Shoal likely had little relation to shoal reclamation in the bay.

In addition, the reclamation area in the West Shoal accounted for 64% of the total amount in the bay, and the large-scale reclamation could cause the deltaic channels to rapidly extend south-eastward. Therefore, the deposition center in the West Shoal moved southeast simultaneously, and the 2 m and 5 m isobaths moved southward and eastward, which caused the West Shoal to expand and the Lingding Channel to narrow from 1964 to 2007 [14].

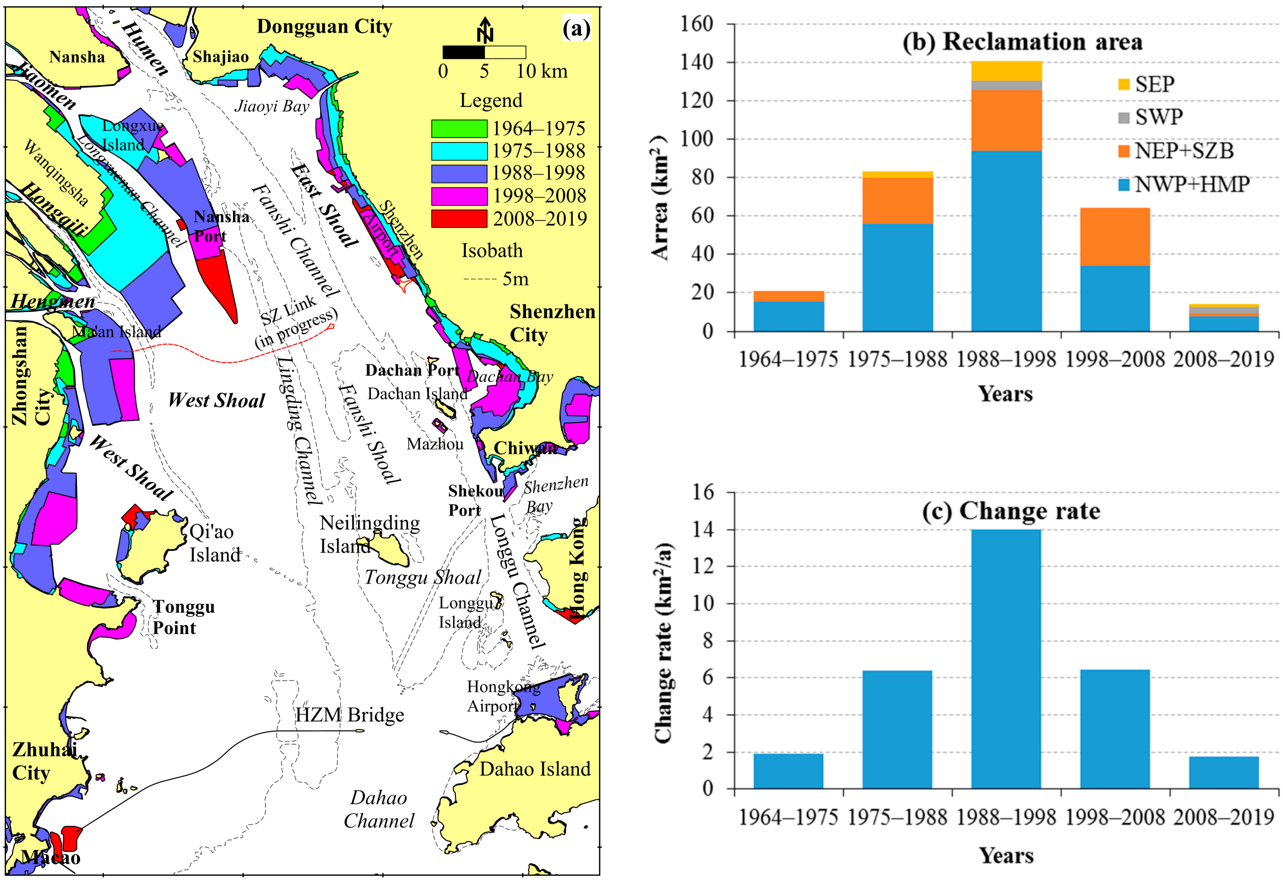

Figure 11. Planar distribution of the reclamation area in Lingding Bay (**a**), and the reclamation area (**b**) and its change rate (**c**) during different decades. (SZB: Shenzhen Bay).

5.2.2. Impacts of Sand-Dredging in Lingding Bay

Recently, sand-dredging activities have played an essential role in the morphological evolution of the estuarine region, especially in the PRE, which is a well-developed region in China [16,25,30].

Sand-dredging activities in Lingding Bay were related to regional economic development and surrounding reclamation projects. In the 1980s, sand-dredging activities began in the Chuanbi Channel near Human and moved to the East Trough and the Middle Shoal after the mid-2000s, which was synchronized with the time of the topographic changes. In 2012 and 2014, there were 25 sand-dredging zones in northern Lingding Bay approved by the local authority encompassing a total area of 13.14 km^2. These sand-dredging zones were predominantly distributed in the Fanshi Channel and Fanshi Shoal, with only a few in the West Shoal and Chuanbi Channel (Figure 12). This result agrees with the dominant mode of morphological change, with reduction in channel depth and deposition the deepened areas (Figure 9). Therefore, the high-intensity sand-dredging activities resulted in large and irregular deep holes and caused the aberrant changes in Lingding Bay recorded in recent years.

In addition, the high-intensity sand-dredging activities produced a large amount of turbid water and increased the local SSC, which could increase the siltation rate of the nearby navigation channel. The silting process of the southern Lingding Channel after 2007, which is different to the deepening process prior to 2007, has likely been impacted by the sand-dredging activities [14]. The turbid water could be transported southward over long distances and negatively influenced the installation of the immersed tunnel of the HZMB [34,35]. Therefore, the influence of the sand-dredging activity on the back siltation of the ports and channels requires intense evaluation.

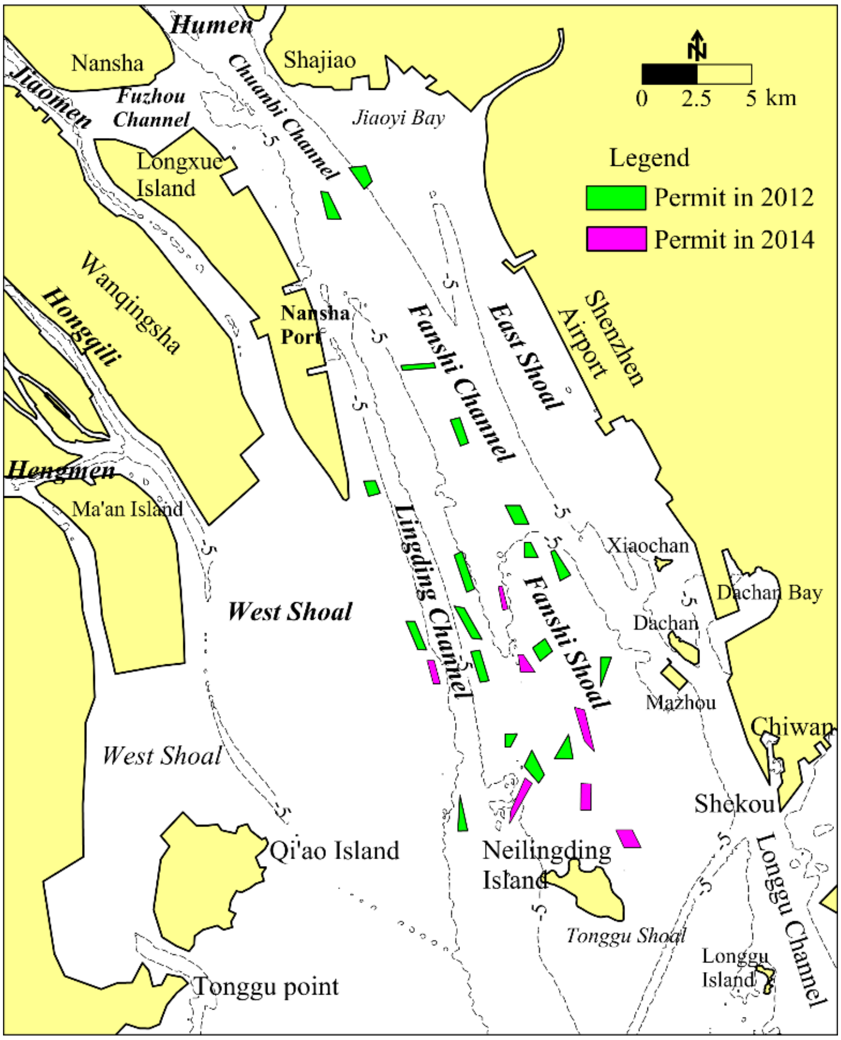

Figure 12. The recently approved sand-dredging zones in Lingding Bay.

5.2.3. Impacts of Port and Waterway Construction

The regulation and development of port and waterway in the estuarine regions can change the local topography and water and sediment transport, and its impact on the geomorphic evolution of the estuary area cannot be ignored [36,37].

Lingding Bay has the largest density of navigation and shipping routes worldwide. There are two world-class ports in the bay, namely the Guangzhou Port and the Shenzhen Port, as well as some important ports for China, such as the Humen Port, the Zhongshan Port, and the Zhuhai Port. The Nansha port of Guangzhout, the Nanshan and Dachan port of the Shenzhen are all deep-water ports of 100,000 tons and were excavated on shallow shoals or troughs. The Nansha port is connected to the open sea through the excavated trough in the Lingding Channel, and the Nanshan and Dachan port are connected to the southern Lingding Channel through the excavated Tonggu Channel.

The Lingding Channel had been regulated since 1959 through dredging with a channel depth and width of 6.9 m and 120 m respectively, and the channel depth and width in 1998 were increased to 10.5 m and 160 m, respectively [14]. Frome the 2000s to present, with the development of the Nansha port, the Lingding channel has been gradually upgraded to a two-way channel with a channel depth and width of 17 m and 384 m respectively. The Nanshan port area has been developed since the 1980s, and the Dachan port and the Tonggu Channel has been developed since the early 21st century. As a 100 000-ton channel, the Tonggu Channel was excavated in the Tonggu Shoal with a total length of 17 km, and the channel depth and width are 15.8 m and 204 m, respectively [33].

Under the background of the port and channel development in Lingding Bay, although affected by the continuous expansion eastwards of the West Shoal, the deep trough in the Lingding Channel is gradually deepening, and the shape of the deep trough remained relatively stable. At the same time, the deep trough in the north Longgu Channel continued to extend northward and increased in depth and width. The continuous increase in the water volume of deep troughs in Lingding Bay from 1989 to 2007 was mainly caused by port and channel development. Furthermore, the water area of the harbor basin and the channel being dredged periodically in Lingding Bay is more than 40 km^2 at present, which is of benefit in maintaining the stability of the deep troughs.

5.3. Sustainable Management of the Bay

Recently, high-intensity human activities have posed significant pressure and challenges to the sustainable management of the estuarine regions [2,3]. In Lingding Bay, the high-intensity sand-dredging activities play a key role in the geomorphic changes in recent years, which have caused the aberrant changes in the east trough and the middle shoal and had destroyed the geomorphic form of the "three shoals and two troughs". Recently, the amount of sediment loss caused by the sand-dredging activities had far exceeded the amount of sediment deposition in the past four decades before 2007. Therefore, the recent aberrant changes in the geomorphic from of Lingding Bay had brought great uncertainty to the sediment environment and the morphological evolution of the bay, which would bring about many challenges for estuary regulation, disaster management, and the operational safety of the ports and channels.

The sand-dredging activities in Lingding Bay will not be banned soon, and may expand to the Tonggu Shoal and the West Shoal, so the dredging holes in the Middle Shoal and the West Shoal may continue to enlarge and deepen, and its impact on the ports and channels need more attention from the relevant authorities. Against the background of the abrupt decrease in upstream sediment input, it will likely be difficult for the East Trough and the Middle Shoal to recover to the previous geomorphic form over shorter timescales. The sediment transport and morphological evolution under the condition of aberrant changes need further empirical data to carry out more in-depth research, which will enrich the scientific work of estuarine and coastal research, and be conducive to improving the sustainable use and management of estuaries and coastlines.

6. Conclusions

This study explored the long-term morphological changes in Lingding Bay in the PRE from 1964 to 2019 using GIS and EOF methods. In the last 55 years, the water area of Lingding Bay has gradually decreased due to shore reclamation. Further, the evolutionary characteristics of the underwater topography were different before and after 2007 due to the different intensity of human activity. From 1964 to 2007, Lingding Bay experienced a slow silting process with the water depth and volume decreasing slightly; the geomorphic form was "three shoals and two troughs" due to the low-intensity of human activity. From 2007 to present, high-intensity sand-dredging activities in Lingding Bay have led to aberrant changes with a considerable increase in the water depth and volume, especially in the East Trough and Middle Shoal; the geomorphic pattern of "three shoals and two troughs" was destroyed. The large amount of sediment loss caused by the sand-dredging activities after 2007 far exceeded the amount of sediment deposition over the four decades before 2007; it will likely be difficult for the East Trough and the Middle Shoal to recover over a shorter timescale against the background of considerable reduction in sediment discharge.

The recent aberrant morphological changes in Lingding Bay have led to considerable uncertainty in the sedimentary environment and morphological evolution of the future, and bring many challenges to estuary regulation, disaster management, environmental protection, and the operational safety of ports and channels. Therefore, subsequent evolution of the bay against the background of a high-intensity of human activity requires intensive assessment and further research. This will enrich the body of scientific work regarding estuarine and coastal research and be conducive to revealing the interaction mechanisms between humans and nature, guiding sustainable development, estuarine disaster control, and promoting interdisciplinary innovation in estuarine research.

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