water

MDPI

Article

Study of the Long-Term Morphological Evolution of the Modaomen Channel in the Pearl River Delta, China

Zhiyuan Han [1,2,*], Huaiyuan Li [1,2], Hualiang Xie [1,2], Shuhua Zuo [1,2,*] and Ting Xu [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; lhy07031@126.com (H.L.); xh-liang@foxmail.com (H.X.); xuting1228@163.com (T.X.)

[2] Key Laboratory of Engineering Sediment of Ministry of Transport, Tianjin Research Institute for Water Transport Engineering, M.O.T., Tianjin 300456, China

* Correspondence: tkshzy@foxmail.com (Z.H.); zsh0301@163.com (S.Z.); Tel.: +86-22-59812345-6416 (Z.H.)

Abstract: Deltaic channels in river deltas usually play important roles in flood discharge, water supply, and navigation development. Under the combined influences of fluvial and ocean dynamics and human activity, the complex long-term morphological evolution of deltaic channels requires further research, in particular the Modaomen Channel in the Pearl River Delta (PRD), China. This study explored the morphological evolution of the Modaomen Channel from 1962 to 2017. During the study period, the characteristics of the Modaomen Channel after 1977 differed substantially from those before 1977. Before 1977, the channel evolution was mainly controlled by natural processes, with a low silting rate. From 1977 to the present, the channel was strongly influenced by human activities, including sand mining and channel regulation, and then, the channel deepened sharply. Therefore, the deep trough of the channel at the upstream was linked completely to that at the downstream, which became much wider and deeper compared to that in the past. Although the deepening of the channel was beneficial for flood discharge and shipping development, serious environmental problems also developed, including strengthened tidal dynamics and saltwater intrusion. Owing to the severely reduced sediment discharge from the Pearl River and the deepening trend in the channel, the future evolution of the channel and its impacts by extreme flood and storm surge require further detailed investigation and research.

Keywords: deltaic channel; channel evolution; human activities; Pearl River Estuary

check for updates

Citation: Han, Z.; Li, H.; Xie, H.; Zuo, S.; Xu, T. Study of the Long-Term Morphological Evolution of the Modaomen Channel in the Pearl River Delta, China. *Water* **2022**, *14*, 1331. https://doi.org/10.3390/w14091331

Academic Editor: Ian Prosser

Received: 11 March 2022
Accepted: 19 April 2022
Published: 20 April 2022

1. Introduction

River deltas not only host large human populations, but also sustain the most productive ecosystems in the world, so exploring the morphological evolution of deltas is critical for coastal management and restoration [1–4]. In recent decades, with the economic development of river basins and estuarine regions, human activities, including reservoir construction, estuarine regulation, nearshore reclamation, coarse sand mining, and the construction of ports and channels, have notably altered river discharge, sediment inputs, and underwater topography [5–11]. Consequently, the deltaic environment has become more fragile and sustainable management of deltas has faced great challenges [2,10,12].

Complex branching channels generally form in river deltas, in particular in tidally dominated deltas such as the Ganges Delta and Pearl River Delta (PRD) [9,12–15]. These branching channels in deltaic regions play an important role in flood discharge, navigation, and water supply. The morphological evolution of deltaic channels is usually impacted by strong runoff, tidal currents, sea-level rise, storm surge, and human activities and is therefore critical for understanding land–ocean interactions in the coastal zone (LOICZ) [9,16–18]. In recent years, human activity in deltaic regions, including channel regulation and coarse sand mining, have led to problems such as riverbed scouring, declining water levels, and saltwater intrusion, which have escalated into problems related to embankment safety, flood control, water supply safety, and environmental protection [2,9–12,19].

The PRD is the largest delta in South China and has a dense river network in the deltaic region. The Modaomen Channel is located at the southeastern end of the PRD and connects the West River (upstream, the main stream of the Pearl River) with the river mouth (downstream). The Modaomen Channel is the main passage along which the Pearl River flows into the sea, particularly during flood events [4]. Cities including Macao, Zhuhai, Jiangmen, and Zhongshan are located along the Modaomen Channel, which plays a critical role in flood discharge, navigation, urban water supply, and agricultural irrigation. Since the 1960s, the Modaomen estuarine region has experienced large-scale anthropogenic activity, including estuary regulation, sand mining, and navigation development, and its geomorphic form has changed dramatically. Previous studies of this region have mainly focused on recent morphological changes, saltwater intrusion, and changes in tidal dynamics that result from human activity, such as estuarine regulation and navigation projects [20–24]. However, long-term (>50 y) morphological changes in the Modaomen Channel have rarely been investigated. In this study, we used more than 50 years of topographic data of Modaomen Channel to explore long-term evolutionary processes and mechanisms related to the deltaic channel and tried to address the research gap. The new findings can add knowledge on the geomorphologic system of the PRD and are helpful for the sustainable management and protection of the PRD.

2. Study Area

The Pearl River is the second-largest river in China and forms a large-scale river delta (the PRD) and two large estuarine bays (Lingding and Huangmao Bays) in central Guangdong Province [10]. The PRD is a complex delta deposited by the sediment from the three main tributaries—the West, North, and East Rivers of the Pearl River. One fifth of the delta is dotted with hills and platforms [20]. The Modaomen Channel is located upstream of the Modaomen Estuary, which is one of the eight outlets into the sea in the PRD. The Modaomen Channel starts at Baiqingtou and ends at Denglong Hill and has a length of ~44 km and a width of 400–3800 m. River islands are also located along this channel.

The Modaomen Channel is the main flow passage of the Pearl River and experiences large amounts of flow and sediment discharge. Makou hydrologic station (see Figure 1a for location), located at the apex of PRD, is the main control station of the Pearl River. The annual runoff and sediment load observed at Makou station are 224.4 billion m^3 and ~61.29 million tons, respectively, accounting for 76% and 85% of the river total, respectively [10], and those observed at Denglong Hill station (see Figure 1b for location) of the Modaomen Channel account for 35–40% of those observed at Makou station [4]. During the flood season (April–September), the total runoff and sediment load at Makou station account for 76.5% and 94.5% of the annual totals, respectively. The Modaomen Channel is a fluvial channel with weak tidal dynamics. The tidal range is ~0.87 m at Denglong Hill station, which experiences an irregular semidiurnal tide.

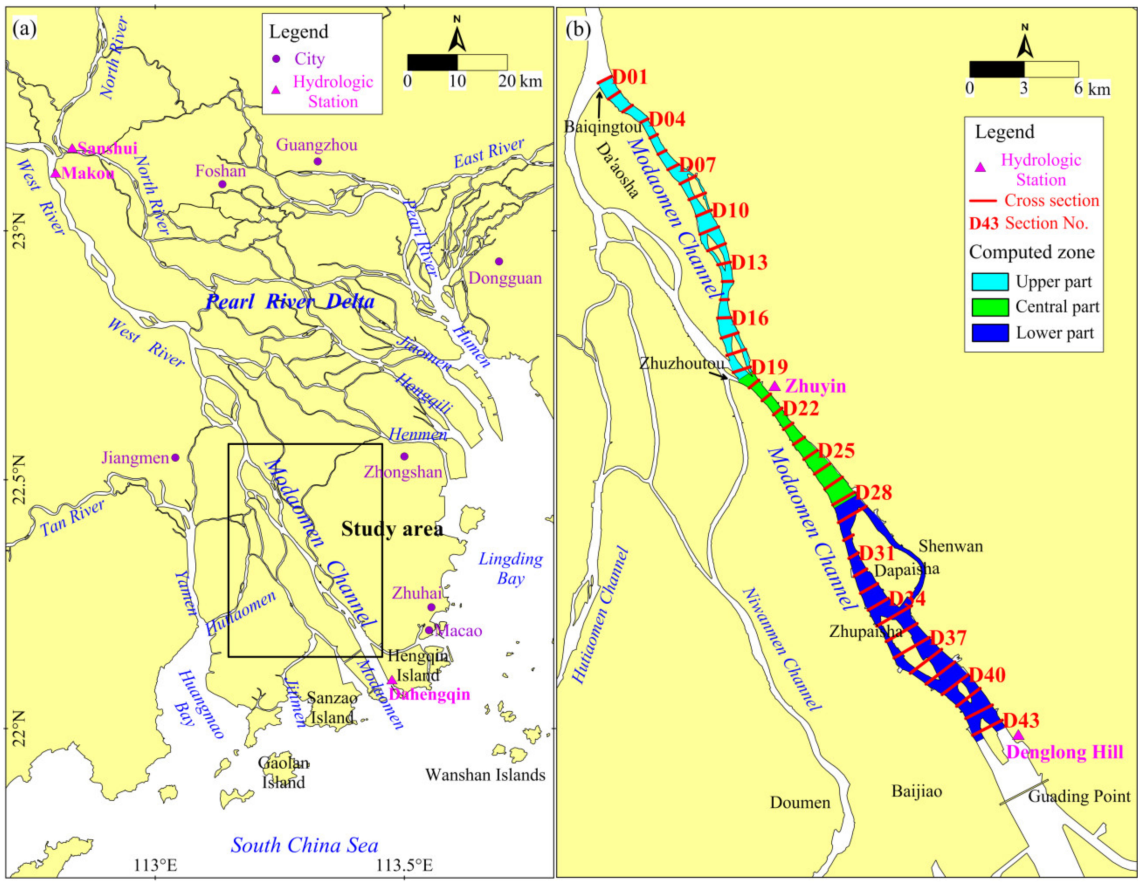

Figure 1. Sketch map of the Pearl River Delta (**a**) and Modaomen Channel (**b**), showing the cross-sections used for bathymetric analyses.

3. Data and Methods

3.1. Data

Four 1:1000-scale bathymetric datasets observed in 1962, 1977, 1999, and 2017 were collected from the Waterway Bureau of Guangdong Province. The plane coordinate system used in these datasets is the China Beijing 1954 Coordinate System with a central longitude of 114°E, and the Pearl River Datum (0.744 m above the 1985 National Height Datum) is used as the bathymetric datum. Runoff and sediment load data from Makou hydrologic station and tidal data from Zhuyin hydrologic station (see Figure 1b for the locations) were obtained from the Hydrological Bureau of Guangdong Province.

3.2. Methods

The four bathymetric data of the Modaomen Channel from 1962 to 2017 were used to generate digital elevation models (DEM) using the Kriging interpolation method with 10 m $\times$ 10 m grids. The distribution maps of scouring and silting in different periods were generated using the cut-fill tool in the ArcGIS software package [25]. The water areas below the 2 m, 5 m, 10 m, and 15 m isobaths were computed using the same method. Isobath maps of 2 m, 5 m, 10 m, and 15 m were drawn for the different years by using GIS software.

The Modaomen Channel was divided into three zones, including upper, central, and lower parts (see Figure 1), and the mean depths and volumes were calculated for each zone below the 0 m isobaths from 1962 to 2017. Forty-three cross-sections (D01–D43, Figure 1b) were established along the channel, from which the mean depth, mean width, width–depth ratio, and thalweg elevation of each section below the 0 m isobaths were calculated. Then, the long-term evolutionary characteristics of the channel were analyzed for the different years.

4. Results

Using the bathymetric data of the Modaomen Channel from 1962 to 2017, the spatiotemporal changes in the channel were analyzed, and the evolutionary characteristics of the channel were determined subsequently.

4.1. Planar Changes of the Channel

Based on the bathymetric data, the topography during different years (Figure 2) and changes in the 2 m, 5 m, 10 m, and 15 m isobaths (Figures 3 and 4) were drawn to investigate planar changes along the Modaomen Channel from 1962 to 2017.

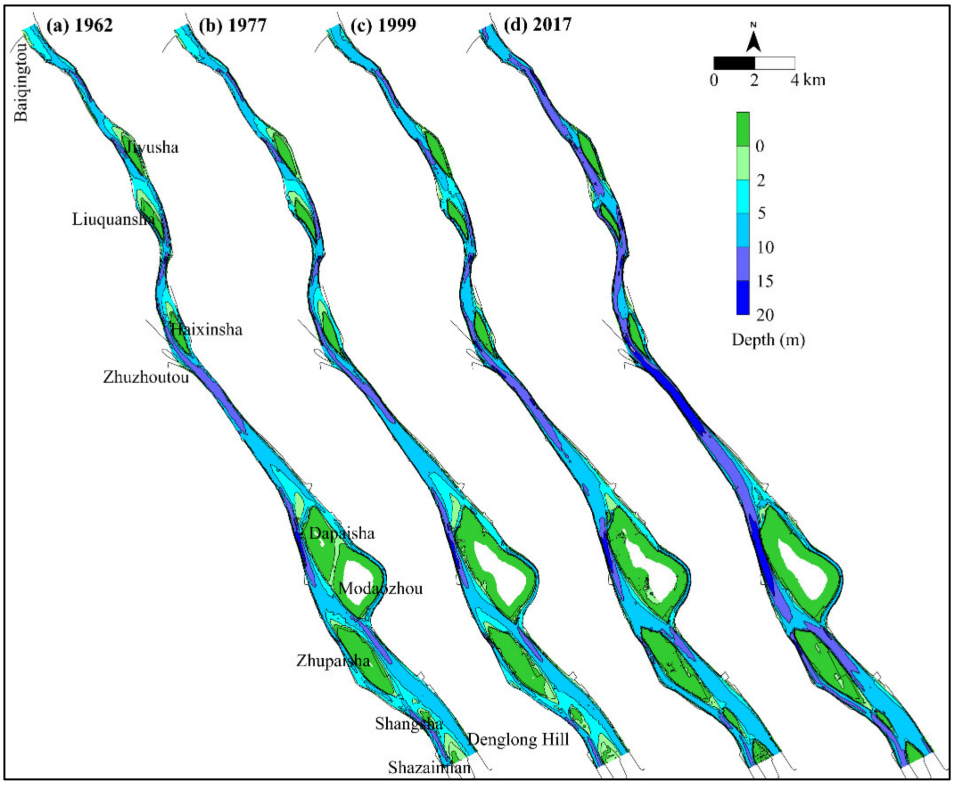

Figure 2. Bathymetry of the Modaomen Channel in (**a**) 1962, (**b**)1977, (**c**) 1999, and (**d**) 2017.

4.1.1. Planar Changes from 1962 to 1977

According to the bathymetry data from 1962 and 1977 (Figure 2a,b), several river islands were present during this period, including (from upstream to downstream) Jiyusha, Liuquansha, Haixinsha, Dapaisha, Modaozhou, Zhupaisha, Shangsha, and Shazaimian, which were distributed along the length of the channel. The river width in the channel ranged from 400 to 3800 m. The 5 m-deep trough in the upstream region was linked to the downstream trough nearly entirely, and the trough width near the river islands was narrow. Shallow water areas (water depth < 5 m) were mainly located north of the river islands, as well as to the east of Baiqingtou. The 10 m-deep troughs were located near Zhuzhoutou and Dapaisha, while some short 10 m-deep troughs were located between those in 1962.

From 1962 to 1977, the 2 m, 5 m, 10 m, and 15 m isobaths changed slightly (Figure 3). The water areas below the 2 m, 5 m, and 10 m isobaths decreased by 5–10%, while the area below the 15 m isobaths changed only slightly (Figure 4). Most of the Modaomen Channel experienced silting processes, particularly near Zhuzhoutou, Dapaisha, and Shangsha, with a silting thickness of 1–3 m. Only some local parts of the channel experienced scouring (Figure 5).

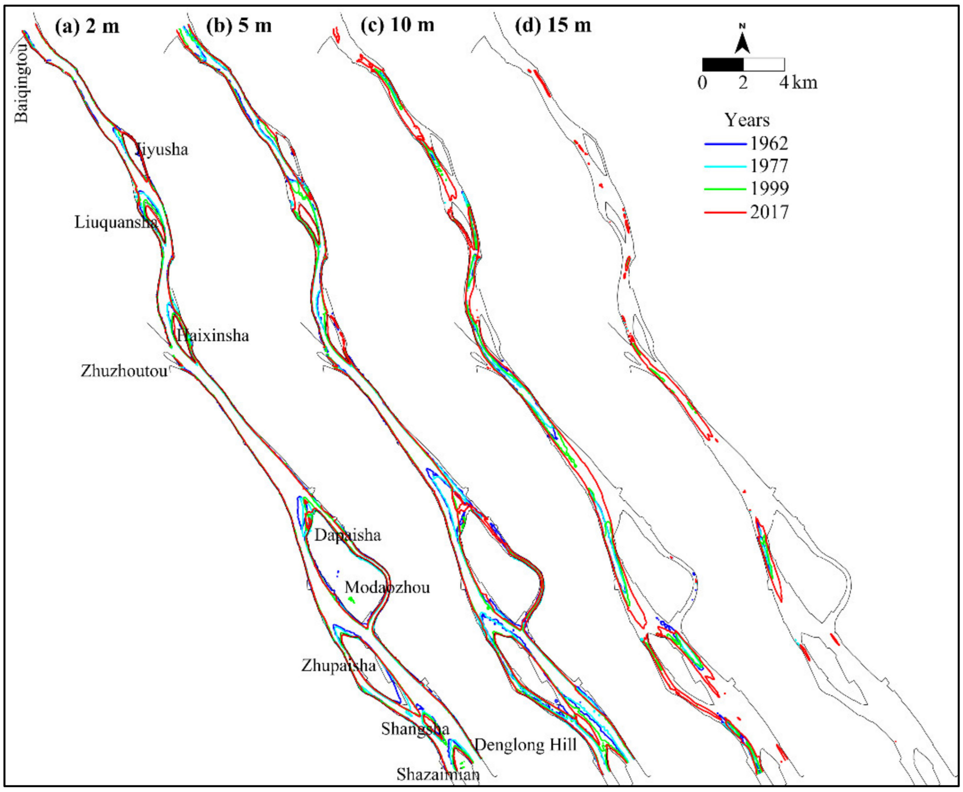

Figure 3. Planar changes in the (**a**) 2 m, (**b**) 5 m, (**c**) 10 m, and (**d**) 15 m isobaths from 1962 to 2017.

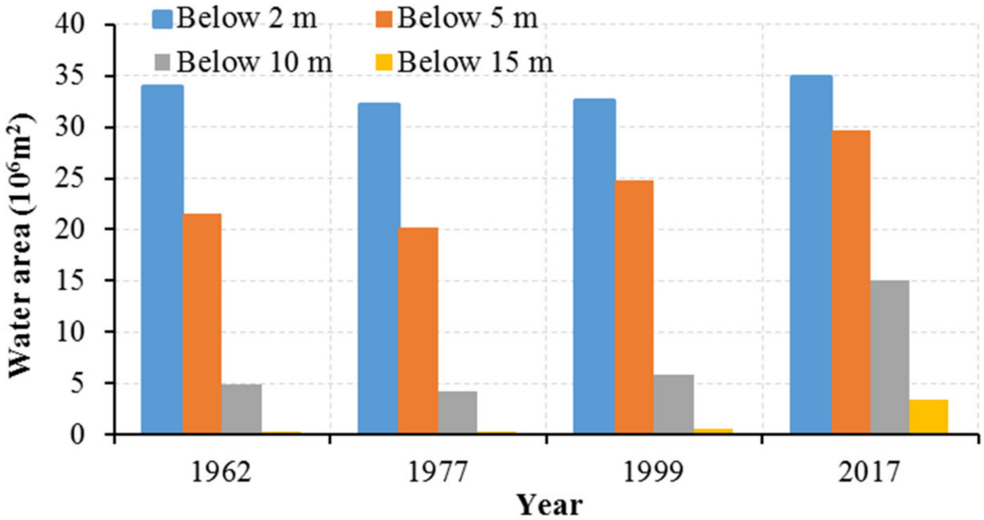

Figure 4. Changes in water area below the 2 m, 5 m, 10 m, and 15 m isobaths from 1962 to 2017.

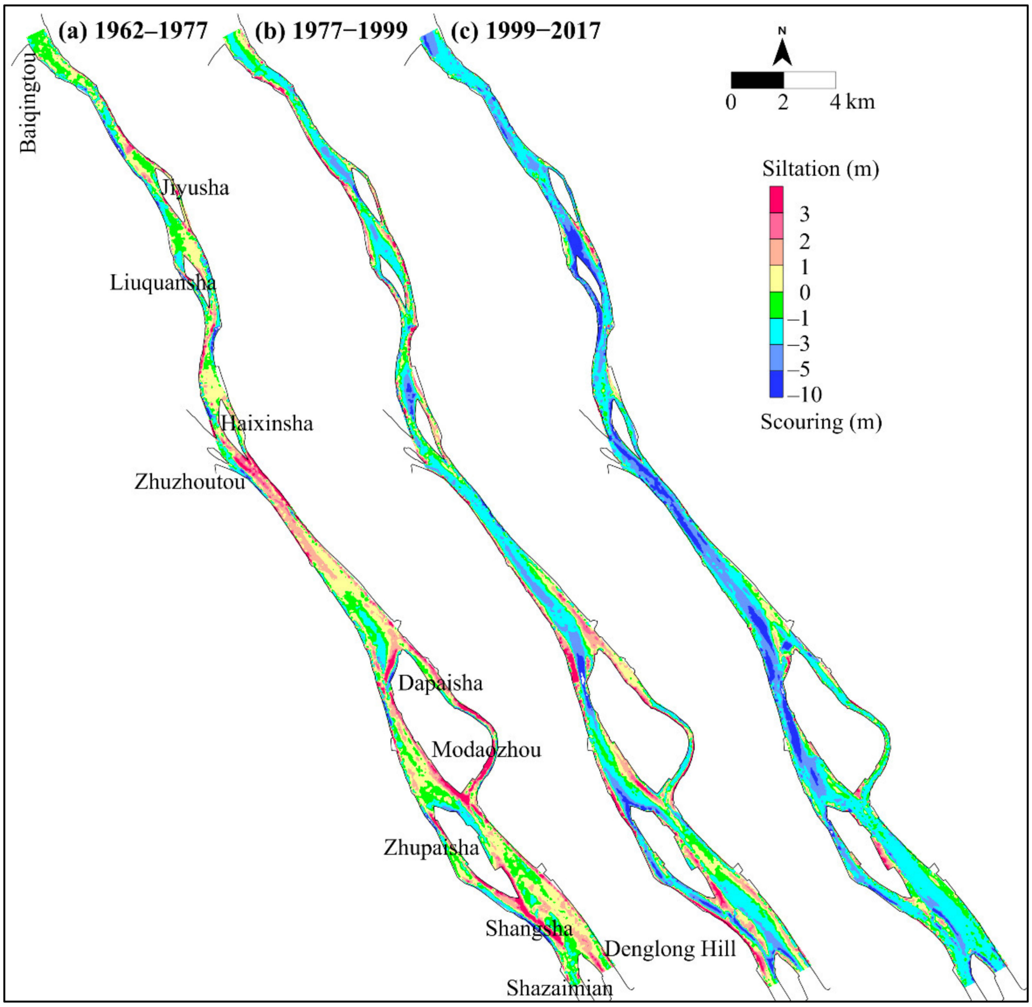

Figure 5. Maps of scouring and siltation along the channel during different decades. (**a**) 1962–1977, (**b**) 1977–1999, and (**c**) 1999–2017.

4.1.2. Planar Changes from 1977 to 1999

According to the bathymetry data from 1999 (Figure 2c), the shallow areas at the north of the river islands and to the east of Baiqingtou decreased, while the nearby 5 m-deep troughs widened. The 10 m-deep trough near Zhuzhoutou lengthened downstream, with local water depths that exceeded 15 m.

From 1977 to 1999 (Figure 3), the 2 m and 5 m isobaths at the north of the river islands retreated and exhibited an erosional trend, while these isobaths remained stable in other parts of the channel. The 10 m and 15 m isobaths near Zhuzhoutou expanded downstream, while these isobaths remained stable in the other parts of the channel. The water area below the 2 m isobaths changed slightly, while those below the 5 m and 10 m isobaths increased by ~20% and 40%, respectively. The water area below the 15 m isobaths increased by ~100% from 1977 to 1999 (Figure 4). Most of Modaomen Channel experienced considerable scouring during this period, with a scouring thickness of more than 1 m. The scouring thickness reached more than 3 m near most of the river islands (Figure 5).

4.1.3. Planar Changes from 1999 to 2017

According to the bathymetry data from 2017 (Figure 2d), the upstream 5 m-deep trough was linked completely to the downstream trough, and the width of the trough near the river islands widened substantially. The shallow areas near the river islands and Baiqingtou were nearly absent. The 10 m-deep trough near Zhuzhoutou extended upstream to Liuquansha and linked downstream with the trough near Dapaisha, the width of which also widened. A large area of deep water (>15 m) was located near Zhuzhoutou and Dapaisha. The 10 m-deep trough near Jiyusha and Zhupaisha also extended and widened.

From 1999 to 2017 (Figure 3), the 2 m and 5 m isobaths retreated at the north of Liuquansha, exhibiting an erosional trend, while those in the other parts of the channel changed only slightly. The 10 m isobaths expanded downstream and upstream near Jiyusha, Zhuzhoutou, and Dapaisha where the trough widened, producing a deep trough that was broken off near Baiqingtou, Liuquansha, Zhupaisha, and Shazaimian. The 15 m isobaths near Zhuzhoutou and Dapaisha expanded considerably upstream and downstream, and the trough widened substantially.

From 1999 to 2017 (Figure 4), the water areas below the 2 m and 5 m isobaths increased by approximately 10% and 20%, respectively, while those below the 10 m and 15 m isobaths increased by approximately 1.6- and 5.3-times, respectively. Thus, the water areas of the 10 m and 15 m isobaths in 2017 were much larger than those in previous years. During the study period (Figure 5), most of Modaomen Channel underwent scouring, with a scouring thickness of more than 1 m. In the Jiyusha–Liuquansha and Zhuzhoutou–Zhupaisha reaches, a scouring thickness of more than 3 m was observed, with some localized regions of 5 m.

Overall, the Modaomen Channel experienced slight silting from 1962 to 1977 and substantial scouring after 1977, particularly after 1999. The scouring thickness was large and the shallow areas near the river islands deepened after 1977. The water depth of the entire channel also increased after 1977.

4.2. Changes in Water Depth and Volume

According to the above analyses, considerable differences were observed in the morphological evolution of Modaomen Channel during different decades. Using the long-term bathymetric data, the water depth and volume below the 0 m isobaths in the different zones along the channel were calculated (see Figure 1 for location), the results of which are shown in Figure 6.

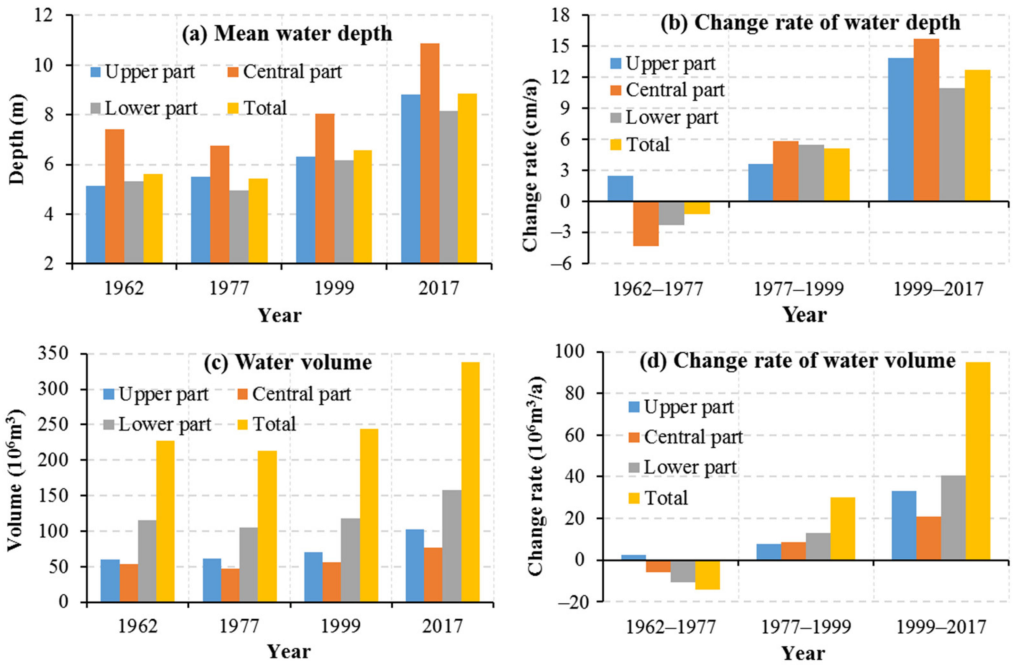

Figure 6. Changes in water depth and volume in different zones from 1962 to 2017. (**a**) Mean water depth below 0 m isobaths, (**b**) water volume below 0 m isobaths, (**c**) change rate of water depth, and (**d**) change rate of water volume.

4.2.1. Changes in Water Depth

In 1962, the mean depth in the upper, central, and lower parts of the Modaomen Channel were 5.1, 7.4, and 5.3 m, respectively, while that of the entire channel was ~5.6 m (Figure 6a). From 1962 to 1967 (Figure 6b), the mean depth in the upper part increased by 0.4 m, while that in the central and lower part decreased by 0.6 m and 0.3 m, respectively, while that of the entire channel decreased by 0.2 m, with a silting rate of 1.2 cm/a. From 1977 to 1999, the mean depths in the upper, middle, and lower parts increased by 0.8 m, 1.2 m, and 1.2 m, respectively, while that of the entire channel increased by 1.2 m with a scouring rate of 5.0 cm/a. From 1999 to 2017, the mean depth in the upper, middle, and lower parts increased by 2.5 m, 2.8 m, and 2.0 m, respectively, while that of the entire channel increased by 2.3 m with a scouring rate of 13.0 cm/a. Overall, the mean depth of the entire channel increased by 3.4 m from 1977 to 2017.

In summary, the water depth of the Modaomen Channel decreased before 1977 and increased after 1977, but these increases varied during the decades.

4.2.2. Changes in Water Volume

In 1962, the water volume in the upper, central, and lower parts of the channel were 59×10^6 m^3, 53×10^6 m^3, and 115×10^6 m^3, respectively, while that of the entire channel was ~228×10^6 m^3 (Figure 6c). From 1962 to 1967 (Figure 6d), the water volume in the upper channel increased by 3×10^6 m^3 and that in the central and lower parts of channel decreased by 6×10^6 m^3 and 10×10^6 m^3, respectively, while that of the entire channel decreased by 14×10^6 m^3 at a rate of 1.0×10^6 m^3/a. From 1977 to 1999, the water volume of the upper, central, and lower parts increased by 8×10^6 m^3, 9×10^6 m^3, and 13.2×10^6 m^3, respectively, while that of the entire channel increased by 30×10^6 m^3 at a rate of 2.0×10^6 m^3/a. From 1999 to 2017, the water volume in the upper, central, and lower parts increased by 33×10^6 m^3, 21×10^6 m^3, and 40×10^6 m^3, respectively, while that of the entire channel increased by 94×10^6 m^3 at a rate of 6×10^6 m^3/a. Overall, the water volume of the entire channel increased by 124×10^6 m^3 from 1977 to 2017.

In summary, the water volume of the Modaomen Channel was low before 1977 and increased after 1977, but the changes differed during the decades.

4.3. Changes in Cross-Sectional Shape

The section width, mean section depth, width-depth ratio ($\sqrt{width}/depth$), and thalweg elevation of the cross-sections along the Modaomen Channel are parameters that represent its cross-sectional shape. The section widths and depths, width–depth ratios, and thalweg elevations below the 0 m isobaths of the D01–D43 sections during different years are shown in Figure 7. The mean section width and depth, width–depth ratio, and thalweg elevation below the 0 m isobaths in the three parts (upper: D01–D19; central: D20–D29; lower: D30–D43) of the channel are shown in Figure 8.

The section width of all cross-sections underwent little change from 1962 to 2017. The mean section depth increased slightly in the upper part and decreased slightly in the central and lower parts from 1962 to 1977, while that increased substantially from 1977 to 2017. The width–depth ratio and thalweg elevations of the entire channel did not change substantially from 1962 to 1977, while those reduced from 1977 to 2017 substantially.

As shown in Figure 8b, the mean section depth in the upper part of the channel increased by 0.4 m, while those in the central and lower parts decreased by 0.7 m and 0.2 m, respectively, from 1962 to 1977. From 1977 to 1999, the mean section depth in the upper, central, and lower parts increased by 0.7 m, 1.4 m, and 1.4 m, respectively, while that increased by 2.4 m, 2.7 m, and 1.9 m, respectively, from 1999 to 2017.

As shown in Figure 8c, the width–depth ratio of the upper part of the channel decreased by 0.6, while those of the central and lower channel increased by 0.5 and 0.6, respectively, from 1962 to 1977. From 1977 to 1999, the width–depth ratio of the upper, central, and lower channel decreased by 0.7, 1.0, and 1.7, respectively, while that decreased by 1.2, 0.9, and 1.1, respectively, from 1999 to 2017.

As shown in Figure 8d, the thalweg elevation in the central part increased by 1.0 m, while that in the upper and lower parts decreased by 0.8 m and 0.6 m, respectively, from 1962 to 1977. From 1977 to 1999, the thalweg elevation in the upper, central, and lower parts decreased by 0.2 m, 1.5 m, and 0.1 m, respectively, while that decreased by 3.2 m, 4.3 m, and 2.8 m, respectively, from 1999 to 2017.

Overall, the Modaomen Channel became slightly shallower from 1965 to 1977, then deepened substantially from 1977 to 2017. Moreover, the change rate for the period of 1999–2017 was larger than that of 1977–1999.

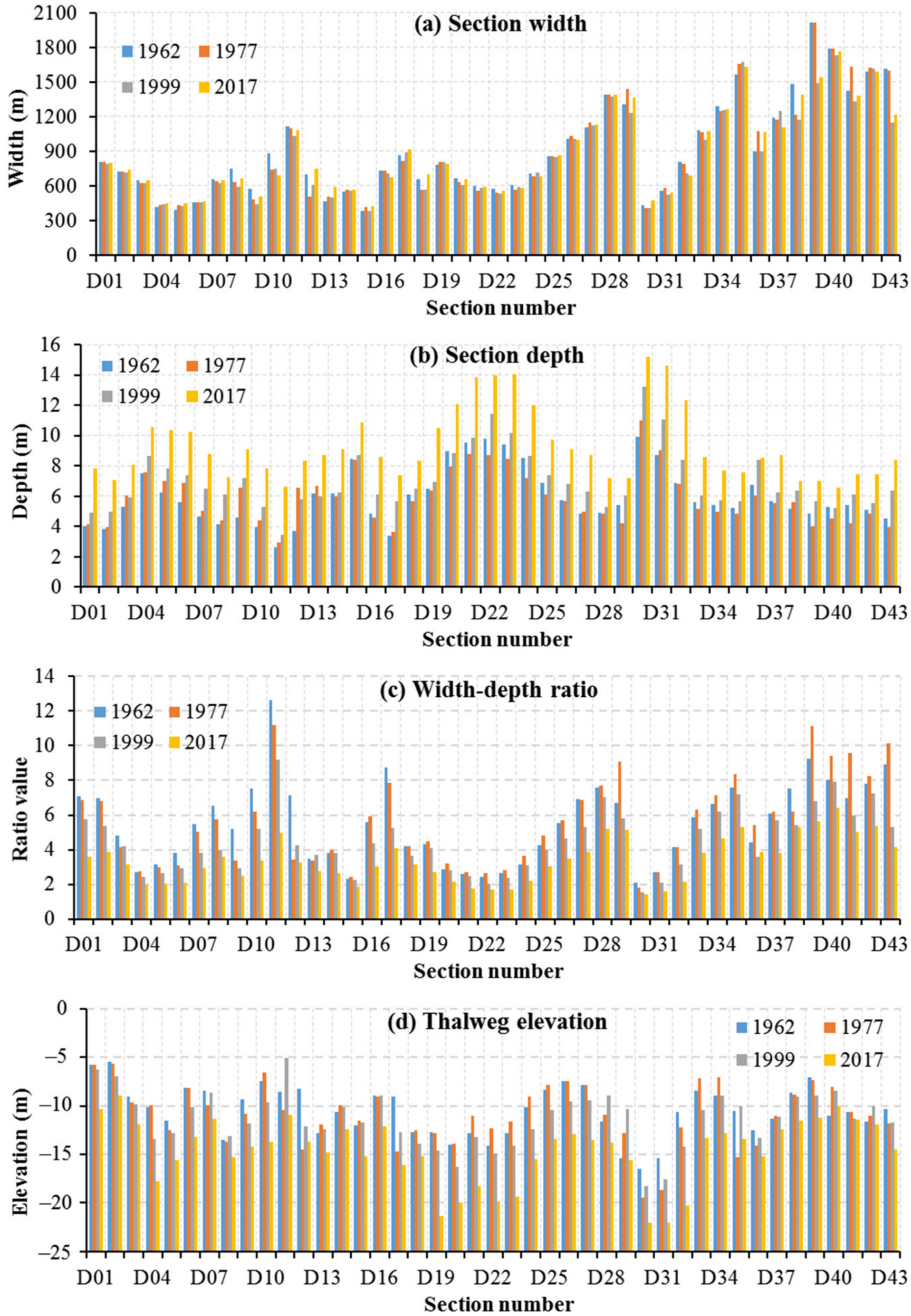

Figure 7. Section width (**a**), section depth (**b**), width-depth ratio (**c**), and thalweg elevation (**d**) of the cross-sections along the Modaomen Channel from 1962 to 2017.

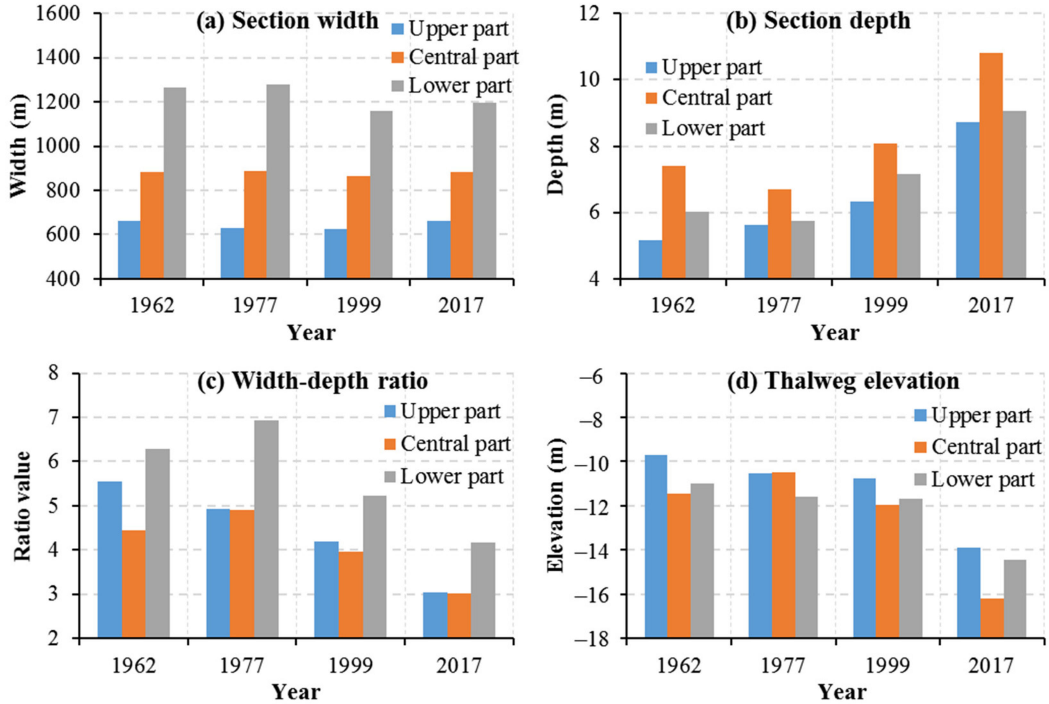

Figure 8. Mean value of section width (**a**), depth (**b**), width-depth ratio (**c**), and thalweg elevation (**d**) in the different zones from 1962 to 2017.

5. Discussion

5.1. Impacts by River Flow and Sediment Discharge

River flow and sediment discharge are important inputs for deltaic evolution [1,2,6]. In recent years, due to human activities and climate change, river flow and sediment discharge have decreased sharply, then the silting rate in the deltaic regions decreased, and some regions are even at risk of erosion [2,5–7,19,26,27].

As a control station at the upstream of the Modaomen Channel, the change characteristics of the water and sediment discharges observed at Makou station can be used for the evolution analysis of the Modaomen Channel. The mean water and sediment discharges observed at Makou station were 7500 m^3/s and 2400 kg/s from the 1960s to the 1970s, 7100 m^3/s and 2200 kg/s from the 1980s to the 1990s, and 6700 m^3/s and 720 kg/s during the first two decades of the 21st Century, respectively. The annual runoff observed at Makou station changed slightly from 1960 to the present, while the mean sediment discharge changed slightly from the 1960s to the mid-1990s, then decreased by 70% from the mid-1990s to the present (Figure 9). This sharp decrease of sediment discharge was mainly caused by the construction of the reservoir in the river basin rather than by climate changes [28,29].

Since the 1990s, the sediment discharge from upstream has decreased considerably, and the flow has changed slightly, which may have altered the evolution of the channel and caused a scouring trend. However, the mean water and sediment discharges during the 1960s–1970s and the 1980s–1990s were similar, while the evolution of the channel differed widely during these periods. Thus, the recent evolution of the Modaomen Channel was not dominated by sharp decreases in sediment discharged from upstream regions.

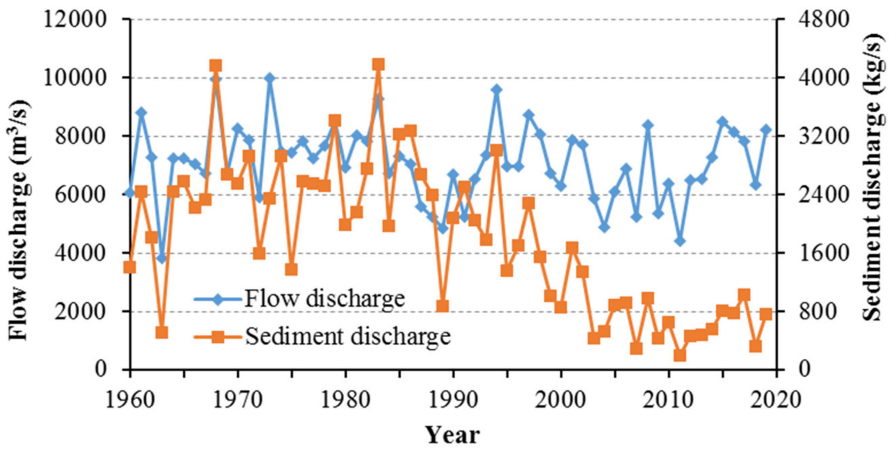

Figure 9. Annual mean value of flow and sediment discharges observed at Makou station since 1960.

5.2. Impact from Human Activities

Intense human activities occur frequently in estuarine regions, including estuarine reclamation, port and channel construction, sand mining, and bridge construction, all of which can change the estuarine boundaries and bathymetry and can even affect the morphological evolution of estuarine regions [3–6,11,19,21,29,30]. In recent decades, the main human activities in the PRD have been those related to estuarine reclamation, channel regulation, and sand mining [3,4,11,22–24,31–34].

Prior to the 1980s, the river mouth of Modaomen Channel was located at Guading Point (see Figure 1b). A shallow sea was located at the south of Guading Point and covered by some rocky islands. From the 1980s to mid-1990s, as shoal reclamation was implemented in this shallow sea, the river mouth moved from Guading Point to Shilanzhou, which is located ~16 km SE of Guading Point. Generally, as a flow passage extends into the sea, the difference of the water level between the upstream and downstream regions will decrease, which is helpful for siltation. However, the water level recorded at Dahengqing station (see Figure 1a for location) increased after the 1980s [10]. Therefore, the substantial channel scouring is likely unrelated to the shore reclamation implemented in recent decades.

The PRD contains crisscrossing channels, connecting rivers, and seas and is a key area used for inland navigation in China. There are 823 navigable channels in the PRD with a total navigable distance of 5823 km [35]. The Modaomen Channel is an important component in the high-grade waterway network in the PRD and is one of the planned main passages for connecting to the open sea. Under natural conditions, the navigation grade of the Modaomen Channel is very low, mostly due to insufficient water depth and width at some shoals. From 2015 to 2016, the regulating work for the Modaomen Channel was conducted by dredging some of the shoals. The target water depth of the channel was 4.0 m with a bottom width of 80 m, for meeting the navigation needs of 1000-ton ships. According to an analysis of the channel bathymetry in 1999, most of the water depth and width of the deep trough in the channel met these requirements, except for some shallow shoals. Therefore, the channel regulation project focused on increasing the water depth around some of the shallow shoals, thereby limiting its impact on channel evolution to local effects only.

Since the 1980s, owing to rapid economic development, large-scale sand mining activities have been conducted frequently in the PRD river network. According to previous studies, ~13,400 million m^3 of sand had been dredged throughout the entire delta, at an average of 67 million m^3 per year [31]. Sand mining focused in the central and lower channel from 1991 to 2000 reached 43.2 million m^3, with an average excavation thickness of ~1 m, which exceeds the natural annual sedimentation substantially [21]. Although "Regulations for River Sand Mining in Guangdong Province" was issued in 2005 to regulate sand mining, mining activity has been relatively frequent in the Modaomen Channel in recent years [34]. Therefore, high-intensity sand mining is likely the main cause for the scouring and undercutting of the riverbed in the Modaomen Channel in recent decades.

5.3. Impacts on Tidal Dynamics

Tidal dynamics in estuary areas are influenced by runoff and bathymetry. In recent decades, owing to the influence of human activity, estuarine topography has changed such that these regions have faced challenges related to the strengthening of tidal dynamics, coastal erosion, and saltwater intrusion, among others [3,9,24,29]. According to tidal data recorded at Zhuyin station of the Modaomen Channel since 1960, the mean high water level has changed slightly from the 1960s to the present. However, the mean low water level decreased and the mean tidal range increased synchronously (see Figure 10) after the mid-1980s. This increasing of tidal range in the channel was synchronous with the initiation of sand mining and riverbed deepening after the mid-1980s.

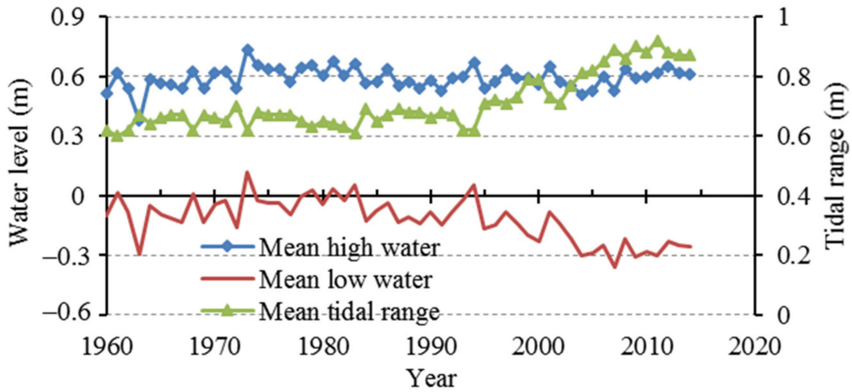

Figure 10. Water level and tidal range changes at Zhuyin station since 1960.

Large-scale sand mining activities in the Modaomen Channel and throughout the river network in the PRD led to increasing water depth and water volume, thereby decreasing the low water level and increasing the tidal prism. In addition, an increased water depth and a decreased low water level along the channel could also reduce energy consumption and increase the upstream propagation speed of tidal waves. Therefore, the tidal dynamics in the Modaomen Channel strengthened owing to the impacts of large-scale sand mining after the mid-1980s.

5.4. Implications for Estuarine Management

The Modaomen Channel is an important flow passage in the PRD and plays an important role in flood discharge, water supply, and navigation development. In recent decades, influenced by humans, the Modaomen Channel has become continuously deeper and its water volume has increased, both of which are beneficial to flood discharge and shipping. However, these changes can also cause problems, such as strengthened tidal dynamics, increased storm surge invasion, and severe saltwater intrusions [4,21–24,29].

During the 1980s, the saltwater boundary in the Modaomen Channel was located near Guading Point during the dry season. During the 1990s, the saltwater boundary gradually moved upstream past Liuquansha, finally reaching ~12 km north of Zhuzhoutou during the dry season in 1999. The maximum chloride contents of the water at Quanlu Water Plant in Zhongshan City near Liuquansha in 2006 and 2007 were 5860 and 551 mg/L, respectively, which exceed the upper limit of the national standard (250 mg/L) [21]. In recent years, the serious problems related to saltwater intrusion in Modaomen Channel have adversely affected the local water supplies and agricultural irrigation in Zhongshan, Jiangmen, Zhuhai, and Macao City. Therefore, the impacts of continued sand mining and the proposed mouth bar regulation on tidal dynamics and saltwater intrusions in the PRD require more attention in future research.

As the Modaomen Channel has gradually deepened in recent years, the stability and safety of channel embankments and bridge piers along the channel, as well as the refining of riverbed materials require further attention in order to sustainably manage the PRD. Furthermore, under the sediment discharge reduced substantially from the Pearl River and the deepening trend of the channel, the future evolution of Modaomen Channel and its impacts require further detailed investigation and research.

6. Conclusions

Determining the evolution of deltaic channels is essential to the sustainable management of flood discharge, water supply, and navigation development in estuarine regions. This research explored the long-term (1962–2017) morphological evolution of the Modaomen Channel in the PRD. The evolution of the channel since 1977 differs substantially from the period prior to 1977. Before 1977, the channel underwent natural evolution, with a low silting rate. After 1977, affected by intense human activities related to sand mining and channel regulation, the channel became deeper with the water volume increasing. Therefore, the upstream deep trough of the channel was linked completely to the downstream deep trough, which became much wider and deeper compared to that in the past. Although a deeper channel is beneficial for flood discharge and navigation development, it also causes serious environmental problems, including strengthened tidal dynamics, storm surge invasion, and saltwater intrusions, which require attention in future studies.

The PRD is located in the subtropical region, so the deltaic evolution is frequently impacted by large floods and storm surges. It is a big defect that no more flood and storm data are collected to analyze the impact of large floods and storms on the channel evolution in this paper. Furthermore, as a result of reduced sediment discharge from the Pearl River and the continued deepening of the channel, the future evolution of the Modaomen Channel and the impacts by extreme floods and storm surges require further detailed investigations and research.

Author Contributions: Writing—original draft, Z.H.; methodology, H.L. and T.X.; writing—review and editing, H.X. and S.Z.; funding acquisition, T.X. All authors have reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the National Natural Science Foundation of China (Grant No. 52171260) and the Innovation Fund of Tianjin Research Institute for Water Transport Engineering (Grant No. TKS20210111).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the editor and anonymous reviewers, whose invaluable and constructive suggestions greatly improved the scientific quality of the original manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Guillen, J.; Palanque, A. A historical perspective of the morphological evolution in the lower Ebro River. *Environ. Geol.* **1997**, *30*, 174–180. [CrossRef]
2. Giosan, L.; Syvitski, J.; Constantinescu, S.; Day, J. Protect the world's deltas. *Nature* **2014**, *516*, 31–33. [CrossRef] [PubMed]
3. Liu, F.; Yuan, L.R.; Yang, Q.S.; Ou, S.Y.; Xie, L.; Cui, X. Hydrological responses to the combined influence of diverse human activities in the Pearl River delta, China. *Catena* **2014**, *113*, 41–55. [CrossRef]
4. Tan, C.; Huang, B.S.; Liu, F.; Huang, G.L.; Qiu, J.; Chen, H.; Liu, D.; Xie, R.Y. Recent morphological changes of the mouth bar in the Modaomen Estuary of the Pearl River Delta: Causes and environmental implications. *Ocean Coast. Manag.* **2019**, *181*, 104896. [CrossRef]
5. Fanos, A.M. The impacts of human activities on the erosion and accretion of the Nile Delta coast. *J. Coast. Res.* **1995**, *11*, 821–833.
6. Komar, P.D. Coastal erosion-underlying factors and human impacts. *Shore Beach* **2000**, *68*, 3–16.

7. Dai, Z.J.; Liu, J.T.; Wei, W.; Chen, J.Y. Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. *Sci. Rep.* **2014**, *4*, 6600. [CrossRef]
8. Fagherazzi, S.; Edmonds, D.A.; Nardin, W.; Leonardi, N.; Canestrelli, A.; Falcini, F.; Slingerland, R.L. Dynamics of river mouth deposits. *Rev. Geophys.* **2015**, *53*, 642–672. [CrossRef]
9. Liu, F.; Xie, R.; Luo, X.X.; Yang, L.Z.; Cai, H.Y.; Yang, Q.S. Stepwise adjustment of deltaic channels in response to human interventions and its hydrological implications for sustainable water managements in the Pearl River Delta, China. *J. Hydrol.* **2019**, *573*, 194–206. [CrossRef]
10. Han, Z.; Li, H.; Xie, H.; Yan, B.; Xie, M. Long-term geomorphological evolution of the mouth bar in the Modaomen Estuary of the Pearl River over the last 55 Years (1964–2019). *Water* **2022**, *14*, 90. [CrossRef]
11. Han, Z.; Xie, H.; Li, H.; Xie, M. Morphological Evolution of the Lingding Channel in the Pearl River Estuary over the Last Decades. *J. Coast. Res.* **2020**, *37*, 104–112. [CrossRef]
12. Chen, J.Y.; Chen, S.L. Estuarine and coastal challenge in China. *Mar. Geol. Lett.* **2002**, *20*, 174–181. (In Chinese)
13. Allison, M.A. Geologic framework and environmental status of the Ganges-Brahmaputra delta. *J. Coast. Res.* **1998**, *14*, 826–836.
14. Dai, Z.J.; Liu, J.T.; Wen, W. Morphological evolution of the South Passage in the Changjiang (Yangtze River) estuary, China. *Quatern. Int.* **2015**, *380*, 314–326. [CrossRef]
15. Yang, S.L.; Zhang, J.; Zhu, J.; Smith, J.P.; Dai, S.B.; Gao, A.; Li, P. Impact of dams on Yangtze River sediment supply to the sea and delta inter-tidal wetland response. *J. Geophys. Res.* **2005**, *110*, F03006.
16. Edmonds, D.A.; Slingerland, R.L. Mechanics of river mouth bar formation: Implications for the morphodynamics of delta distributary networks. *J. Geophys. Res.* **2007**, *112*, F02034. [CrossRef]
17. Fan, H.; Huang, H.J.; Thomas, Q.Z. River mouth bar formation, riverbed aggradation and channel migration in the modern Huanghe (Yellow) River Delta, China. *Geomorphology* **2006**, *74*, 124–136. [CrossRef]
18. Mei, X.F.; Dai, Z.J.; Wei, W.; Li, W.H.; Wang, J.; Sheng, H. Secular bathymetric variations of the North Channel in the Changjiang (Yangtze) Estuary, China, 1880–2013: Causes and effects. *Geomorphology* **2018**, *303*, 30–40. [CrossRef]
19. Wei, W.; Dai, Z.J.; Mei, X.F.; Liu, J.P.; Gao, S.; Li, S.S. Shoal morphodynamics of the Changjiang (Yangtze) estuary: Influences from river damming, estuarine hydraulic engineering and reclamation projects. *Mar. Geol.* **2017**, *386*, 32–43. [CrossRef]
20. Li, C.C.; Lei, Y.P.; He, W.; Dai, Z.J. Evolutional processes of the Pearl River Estuary and its protective regulation and exploitation. *J. Sediment Res.* **2002**, *3*, 44–51. (In Chinese)
21. Han, Z.Y.; Tian, X.P.; Liu, F. Study on the causes of intensified saline water intrusion into Modaomen Estuary of the Zhujiang River in recent years. *J. Mar. Sci.* **2010**, *28*, 52–59.
22. Jia, L.W.; Pan, S.Q.; Wu, C.Y. Effects of the anthropogenic activities on the morphological evolution of the Modaomen estuary, Pearl River Delta, China. *China Ocean Eng.* **2013**, *27*, 795–808. [CrossRef]
23. Hu, D.L.; Liu, Q.H.; Wu, C.Y.; Yang, R.Q. Evolution of the Modaomen Channel of the Xijiang River based on DEM during the Last 40 Years. *Geogr. Geo-Inf. Sci.* **2009**, *25*, 55–58, 62. (In Chinese)
24. Jiang, C.J.; Zhou, J.N.; Yang, Q.S. Effects of human intervention on tidal dynamics in the Modaomen Estuary, Pearl River. *J. Trop. Oceanogr.* **2020**, *39*, 66–76. (In Chinese)
25. Milne, J.A.; Sear, D.A. Modelling River Channel Topography Using GIS. *Int. J. Geogr. Inf. Sci.* **1997**, *11*, 499–519. [CrossRef]
26. Han, Z.Y.; Li, H.Y.; Xie, H.L.; Qiang, H.Y.; Pang, Q.X. Evolution of the river mouth bar in Liaohe Estuary with RS and GIS methods. *Mar. Geol. Front.* **2018**, *34*, 53–60. (In Chinese)
27. Best, J. Anthropogenic stresses on the world's big rivers. *Nature Geosci.* **2019**, *12*, 7–21. [CrossRef]
28. Liu, F.; Hu, S.; Guo, X.J.; Cai, H.Y.; Yang, Q.S. Recent changes in the sediment regime of the Pearl River (South China): Causes and implications for the Pearl River Delta. *Hydrol. Process.* **2018**, *32*, 1771–1785. [CrossRef]
29. Monge-Ganuzas, M.; Cearreta, A.; Evans, G. Morphodynamic consequences of dredging and dumping activities along the lower Oka estuary (Urdaibai Biosphere Reserve, southeastern Bay of Biscay, Spain). *Ocean Coast. Manag.* **2013**, *77*, 40–49. [CrossRef]
30. Hoitink, A.J.F.; Jay, D.A. Tidal river dynamics: Implications for deltas. *Rev. Geophys.* **2016**, *54*, 240–272. [CrossRef]
31. Luo, X.L.; Zeng, E.Y.; Ji, R.Y.; Wang, C.P. Effects of in-channel sand excavation on the hydrology of the Pearl River Delta, China. *J. Hydrol.* **2007**, *343*, 230–239. [CrossRef]
32. Peng, X.Q.; Yuan, H.H. Innovating management system for strengthening the management of sand mining in the Pearl River Estuary. *Pearl River Water Transp.* **2012**, *14*, 47–49. (In Chinese)
33. Yue, P.J. Evolution and development trend of Lingding Bay. *J. Waterw. Harb.* **2001**, *22*, 73–79, 90. (In Chinese)
34. Hu, H.H.; Xu, Y.; Guan, M.K.; Jiang, Q.J. Analysis on morphological evolution of underwater delta in the Pearl River Estuary. *J. Waterw. Harb.* **2016**, *37*, 593–598. (In Chinese)
35. Luo, X.X. Overview of shipping planning and implementation in the Pearl River Delta. *Pearl River Water Transp.* **2002**, *4*, 24–25. (In Chinese)