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Study on the Morphological Evolution of the Oujiang Estuary, China, in the 21st Century

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Abstract: Based on four years of spatially synchronous topographic data of the Oujiang Estuary from 2002 to 2019, the variations and physical mechanisms of estuarine evolution driven by natural conditions and human activities since the beginning of this century were analyzed. The results show that the evolution of the Oujiang Estuary has changed dramatically in the past 20 years. From 2002 to 2019, the net sediment erosion of the estuary was 163.44 million m^3, and the average bed elevation of the river-dominated section (RDS), transition section (TS) and tide-dominated section (TDS) decreased by 4.61 m, 1.30 m and 2.14 m, respectively. In addition, the pattern of the shoal channel had changed, and the river facies coefficient (width–depth ratio) decreased by 16–64%. The evolution of the Oujiang Estuary is mainly caused by human activities (such as sand mining, reclamation). Sand mining is the direct cause of riverbed undercutting, and the large undercutting of riverbed terrain causes the increase in tidal power in the estuary and further causes river channel scouring. In the last 20 years, the average annual tidal range of the estuary increased by 0.19–1.14 m, and the flood discharge increased by about 17–80%, with an average value of 58%. The impact of tidal power on the evolution and development of the estuary has increased significantly. Apart from sand mining, reclamation projects such as the Wenzhou shoal outside the mouth also cause the local velocity of the tidal current section to increase, which aggravates the scouring trend of local river sections downstream. The scouring and silting changes in the Oujiang Estuary since the beginning of this century are the result of the adjustment of the estuarine system in response to the strong intervention of human activities.

Keywords: erosion and deposition change; human activity; tidal force; Oujiang Estuary

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1. Introduction

Estuaries are geomorphologically active places which also have ecological and socio-economic significance, and many large cities are located in their vicinity. In recent decades human activities have had an unprecedented impact on the evolution of estuaries [1,2]. The pressure imposed on the basin environment by the intensive human economic activities linked by the estuary will have a profound impact on the environment of the estuary delta and its adjacent waters [3]. The study of water and sediment movement and riverbed evolution in estuaries in response to human activities has become a public concern and attracted more attention [4]. Many studies on estuarine erosion and deposition changes caused by human activities have been carried out, such as Allersma et al. [5], Wulfors [6], Carriquiry et al. [7], Sanyal et al. [8], French et al. [9], Rovira [10] and Rinaldi M [11]. The water volume, bed scouring and silting changes of rivers caused by human activities have been documented in: western Africa; San Benito River, California; Colorado River, US; Houghly River, India; Lower Tordera River, Spain; and in the Tuscany region, central Italy. Chinese scholars also conducted relevant studies on water and sediment variation and the re-balance process caused by human activities in the Yellow River [12], Yangtze River [13], Pearl River [14], Qiantang River [15] and Aojiang River [16] estuaries.

The Oujiang Estuary, located in the south of China, is the second largest river in Zhejiang Province. Over the past decades, development and beach enclosure have occurred. Those human activities changed the balance of hydrodynamic sediment in the estuary area. A number of researchers have investigated the impact of human activities on the hydrology and geomorphology of the Oujiang Estuary. Wang Shunzhong and Li Haolin [17] analyzed the impact of channel regulation on the river reach in the mouth; Xu Qun et al. [18] studied the impact of the Wenzhou shoal project on the port channel and its deposition promotion effect; Zhang Shuyu et al. [19] carried out two-dimensional numerical simulation of hydrodynamic changes in the estuary of the Oujiang Lingkun South Entrance Plugging Project; Zhang Bohu et al. [20] analyzed the tidal characteristic changes caused by artificial sand mining according to the measured hydrological data; and Liu Jing et al. [21] analyzed the evolution mechanism of the branching river channel in the Jiangxinyu Island under the joint drive of natural conditions and human activities.

However, the above studies mainly focus on the evolution of short-term scale or local river sections, and systematic study on the evolution of the whole Oujiang Estuary is rare. In this study, the morphological evolution of the whole Oujiang Estuary in the last 20 years was analyzed systematically, based on several topographical data. Combined with hydrodynamic survey data and a two-dimensional hydrodynamic mathematical model, the influence of natural factors and human activity were assessed. It is expected to provide a scientific basis for the life and health of estuaries and harbors, as well as for the study of the evolution process of water and sediment systems in similar small and medium-sized estuaries under changing environments.

2. Study Area

The Oujiang River is located in the south of Zhejiang Province, with a total length of 388 km and a drainage area of 18,000 km^2. The tidal reach at Wenxi downstream is the Oujiang Estuary. The Oujiang Estuary is filled on the basis of the drowned bay, and the fault structure along the river is developed, which has a very profound impact on the plane shape of the riverbed [22]. The Oujiang Estuary can be divided into three sections based on hydrodynamic characteristics (Figure 1). As for the river section from Wenxi to Meiao, with a length of 25 km, the riverbed is mainly formed by runoff rather than weak tide and this section is defined as the river-dominated section (RDS). In the river section from Meiao to Longwan, the riverbed has broadened and the shoal channel is subject to frequent erosion and siltation due to the interaction of runoff and tide. This section is called transition section (TS). From Longwan to Huanghua, with a length of 12 km, tidal processes dominate and this section is defined as tide-dominated section (TDS). The river mouth gradually broadens from top to bottom; the average river width of RDS is about 0.5 km, the average river width of TS is about 2.0 km, and the Huanghua at the mouth is expanded by more than 10 km. There are many shoals and islands in the Oujiang River estuary, including Tuotan, Xizhou Island, Jiangxin Island, Qidu and Lingkun Island, from top to bottom. The river channel flows into Wenzhou Bay in the form of multistage branches (Figure 1).

According to the statistics, the average annual runoff of the Oujiang River is 443 m^3/s, and the annual distribution of runoff shows obvious seasonal variations. The flow in flood season (from April to September) accounts for more than 78% of the annual water volume. As for the tide, it is a regular semi-diurnal tide, which is one of the significant strong tidal sea areas in China. The average and maximum tidal range at Longwan Station in the estuary exceed 4 m and 7 m, respectively. In addition, the ebb tide lasts longer than the flood tide. There is not much sand coming from the Oujiang River basin, and the annual average sediment transport is about 1.78 million t [23],which is concentrated in the flood season input estuary area. The estuary is dominated by marine sediment, and the continental sediment accounts for only 2% [22]. The TS and TDS are affected by the narrowness of the trumpet-shaped estuary and the convergence of tidal energy. The sediment content at the ebb and flow tide is as high as 5~7 kg/m^3. The sediment content at the RDS is low and the water is almost clear in the dry season [21]. The composition of the median particle size of the suspended sediment in the Oujiang Estuary is between 0.006 and 0.017 mm; the median particle size of the bottom material is between 0.015 and 0.390 mm [24]. Sediment is mainly involved in bed formation by bed load movement, while suspended fine sediment is mostly transported with the tide [25].

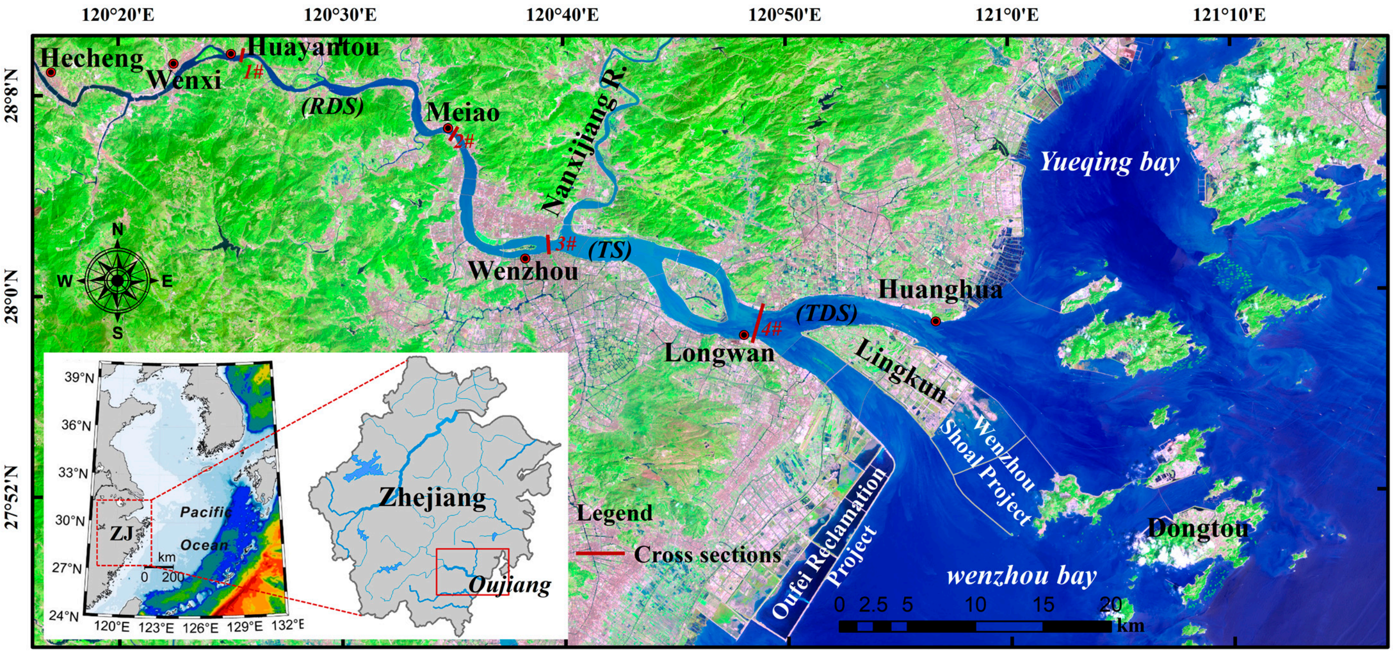


Figure 1. Remote sensing image of the study area in April 2020 based on Landsat8-OLI.

In the Oujiang Estuary, there were limited human modifications before the 1970s. However, human activities such as channel regulation, river channel sand mining, shoreline development and beach enclosure were carried out successively after the 1970s.

(1) **Channel regulation project**

The channel regulation project mainly refers to the multi-phase regulation project implemented successively in the transition section from the 1970s to the 1980s by building spur dikes at the bifurcation to adjust the flow direction and flow pattern structure. By 2000, the impact of channel regulation on the estuary had been basically balanced after more than 30 years.

(2) **Sand mining**

The Oujiang River has a long history of sand mining, and its scale and intensity have been the largest during this century. The following will be discussed in detail through the changes of riverbed volume and elevation.

(3) **Shoreline development**

Shoreline development was mainly a flood control embankment project. During the construction of the embankment, some relatively wide river sections were moved out properly, which mainly had a certain impact on the beach channel evolution of local river sections of the project in the short term.

(4) **Tidal flat enclosure**

Tidal flat enclosure mainly refers to the implementation of the Wenzhou Shoal Project and Oufei Reclamation Project in the coastal section outside the estuary during this century. With the impact of reclamation projects, the estuary has a trend of outward development.

3. Materials and Methods

3.1. Topographic Data

The underwater terrain data used in this paper includes four years: 2002, 2005, 2014 and 2019, with a total time span of nearly 20 years. The survey scales are 1:5000 in 2014, and 1:10,000 in other years. After unifying the base plane of the topographic data of each period, with the support of ArcGIS software, the Kriging method was used to interpolate the scattered point data of the riverbed elevation of each year to a resolution of 15 m $\times$ 15 m, and a digital elevation model (DEM) was generated. The amount of riverbed erosion and deposition can be calculated quantitatively by subtracting the DEM of different years. In order to analyze the spatial difference of erosion and deposition changes, the amount of erosion and deposition were calculated according to the RDS, TS and TDS. On this basis, the characteristics of riverbed erosion and deposition change were further analyzed in combination with the longitudinal and transverse sections along the river.

The accuracy and quality of the topographic map largely depend on the number and density of the elevation points. There are about 7000 elevation points in the 1:10,000 survey map, with a relatively dense distribution of about 83 points/km^2, which is far greater than the accuracy of the survey points required by the general estuary [26]. At the same time, the water depth data are obtained using single-beam bathymetric technology and the section method. The density of the longitudinal points is about 160 m, and the density of the transverse points is about 60–80 m, To determine the characteristics of the river trend in advance, it was ensured that the survey points covered the typical deep channel position, to reflect the characteristics of the underwater beach channel. The comparison of DEM established by 1:10,000 topographic map interpolation and the 1:5000 topographic map can reflect the general law of riverbed changes. In terms of the accuracy of DEM, the Kriging interpolation technique has high precision and widely used in geographic information system (GIS) analyses of estuarine erosion and deposition changes [26,27]. After the scattered point data interpolation, the average river width of the RDS width is about 0.5 km, and the cross section also has more than 30 data points. The average river width of the TS and TDS are 2 km and more. The cross section has more than 130 data points, which can meet the requirements of analysis and calculation. At the same time, root mean square error (RMSE) is used for quantitative analysis of grid interpolation error [28], which refers to the square root of the square sum of the difference between the actual topographic survey points and the grid values. A total of 100 actual topographic observation points covering the above four years and different river sections of the estuary are selected as sample data. It was found that the RMSE is approximately 0.29 m and the average relative error is within 3%, which shows good agreement between observed and grid interpolation values.

In addition, the authors collected the tidal level data at Wenzhou and Longwan long-term tidal stations from 1960 to 2019, the daily average flow, flood elements and annual average flow data from the Hecheng Hydrologic Station (the control station of the main stream of the Oujiang River, which controls 75% of the drainage area) from 1960 to 2019. The relevant data were checked and compiled with reliable accuracy.

3.2. Two Dimensional Tidal Current Mathematical Model

On the basis of the measured data, in order to analyze the dynamic change characteristics of the low tide under the action of high-intensity human activities, the hydrodynamic (HD) module in the MIKE21 flow model (FM) developed by the Danish Hydraulic Institute (DHI) is used to establish the two-dimensional tidal current mathematical model of the Oujiang Estuary. MIKE21 FM HD is applicable to the hydrodynamic simulation of rivers, lakes, oceans and estuaries and coastal areas, and is widely used in the study of tidal currents, waves, storm surges and other hydrodynamic phenomena [29]. The model adopts triangular mesh, which is suitable for simulating coastal and estuarine environments with complex boundaries due to its flexibility. The model is solved by the finite volume method, which has the advantages of fast calculation speed, easy convergence and high calculation accuracy [30]. The model scope and grid layout are shown in Figure 2. The upper boundary is the Oujiang Qingtian Water Control Project and the Shatou dam site of Nanxijiang. The outer boundary of the sea area is the line from Kanmen to Nanjijiang (including Yueqing Bay). The differences of water flow and terrain gradient are taken into account and spur dikes at the estuary are partially densified to better reflect the change characteristics of water flow and terrain. A total of 71,724 triangular units and 38,146 effective nodes are deployed in the calculation domain. The area of the calculation domain is 2635 km^2, and the minimum spatial step of the grid is 5 m. To meet the stability requirements, the time step is taken as 30 s, and the roughness is taken as 0 01~0.03; the horizontal eddy viscosity coefficient of the model is calculated using the Smagorinsky formula [31].

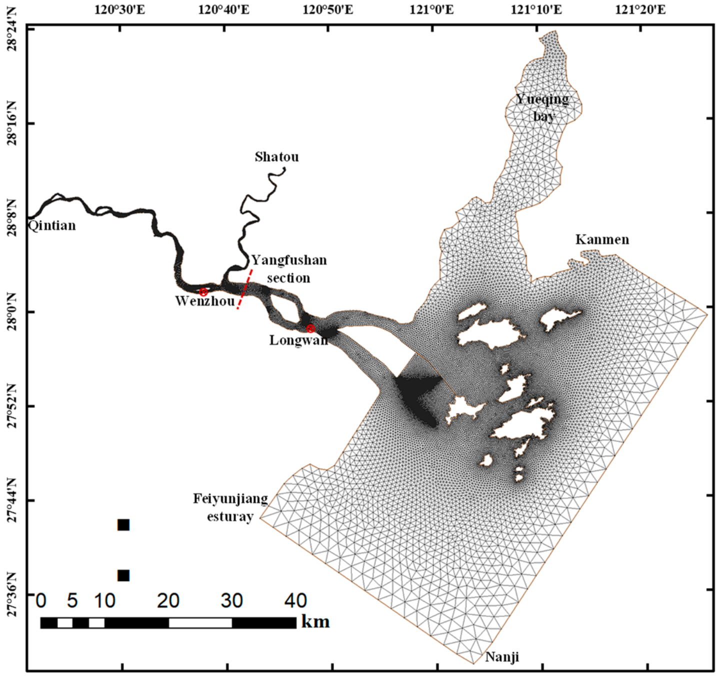
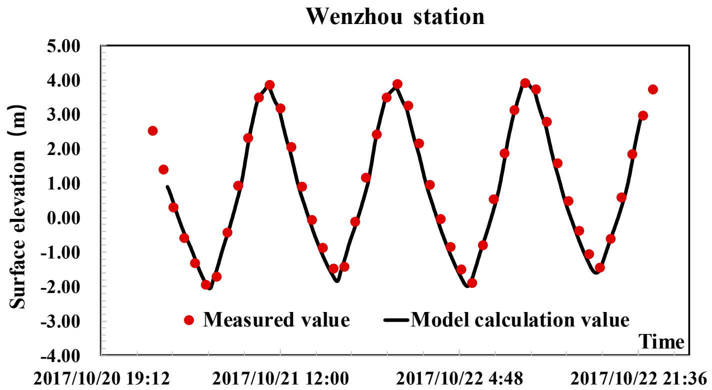
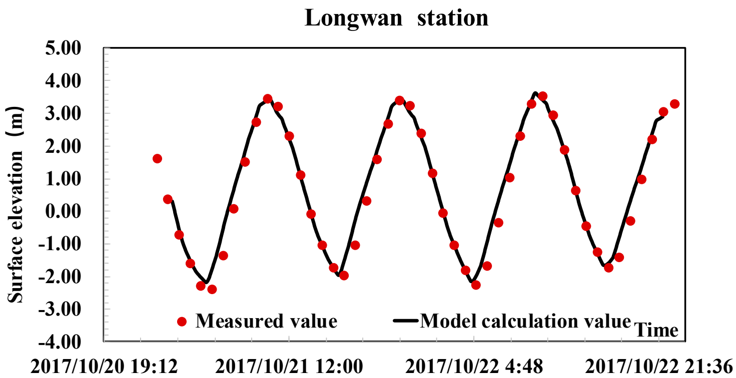


Figure 2. Numerical simulation calculation range and grid layout.

The authors have carried out a lot of calibration and verification of the model by using the tide level, velocity and flow direction data measured for many years. Due to space limitations, this paper only gives the tide level process of Wenzhou (Figure 3a) and Longwan stations (Figure 3b) during October 2017 and the verification process of the Yangfushan section flow (Figure 3c). It can be seen from the figure that the calculated tide level and discharge process are in good agreement with the measured values in terms of phase and value, the error of the water level is within 5%, and the discharge is within 15%. Figure 4 shows the flow field distribution of the water area where the representative verification points were located during the spring tide in October 2017.At flow strength (Figure 4a), the tide mainly follows the north entrance of Lingkun island and enters the south and north branches of Qidu island, then goes up to the Yangfushan section. At the end of the Nanxijiang mouth, a small part flows to the Nanxijiang, and most flows to the upper reaches of the Oujiang, then divides in the Jiangxinyu section. At ebb strength (Figure 4b), the ebb tide path is basically the same as the flow tide, but the current direction is opposite. The overall flow pattern calculated by the model is consistent with the measured data and the simulation results in literature [32,33]. It can be seen that the parameters used in the model are reasonable and can reflect the flow movement characteristics of the studied river section.



(**a**)



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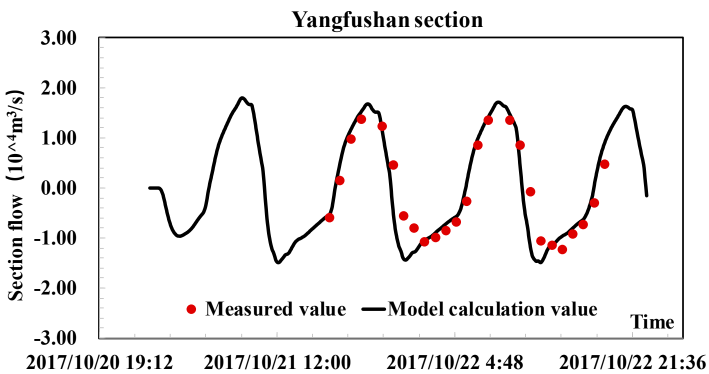
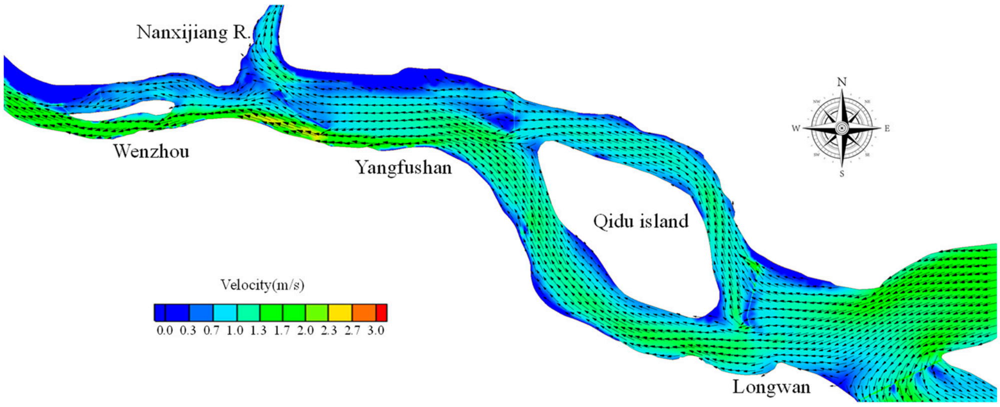


(**c**)

Figure 3. Verification of tidal level and flow process at some stations during hydrometry in October 2017: (**a**) Verification process of Wenzhou Tide Level Station; (**b**) Verification process of Longwan Tide Level Station; (**c**) Verification process of Yangfushan Section flow.



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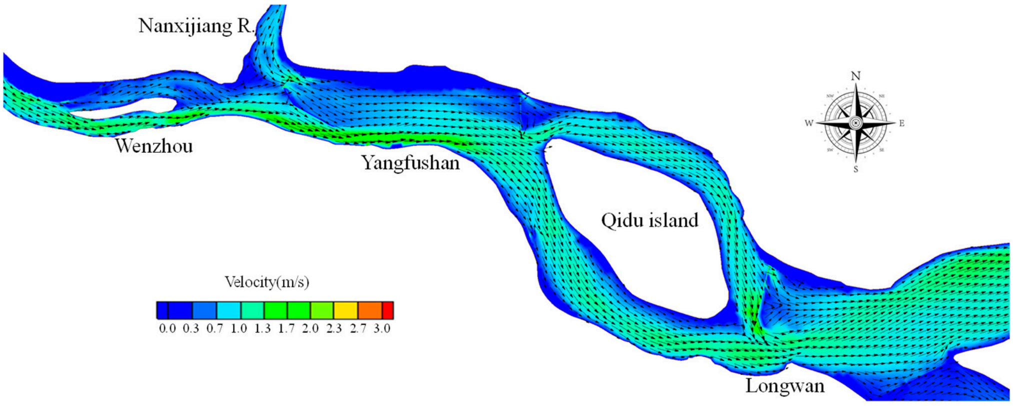


(**b**)

Figure 4. The flow field distribution during spring tide in October 2017: (**a**) Tidal current field at flow strength; (**b**) Tidal current field at ebb strength.

4. Results

4.1. Interdecadal Evolution of Oujiang Estuary

Figure 5 shows the evolution of the Oujiang Estuary in 2002–2005, 2005–2014, 2014–2019 and 2002–2019. Figure 6 shows the proportion of erosion and deposition areas at each time period. Table 1 shows the changes in net erosion and deposition (deposition minus erosion). In order to facilitate the comparison of different time periods, the latest estuarine shoreline in 2019 is taken as the boundary. It can be seen from the chart that from 2002 to 2019, the erosion area of the Oujiang Estuary was significantly larger than the deposition area, and 72% of the area was in a state of erosion with a total net erosion of 163.44 million m^3 and an average annual erosion of 9.67 million m^3. From the perspective of zoning, the average riverbed elevation of in the RDS, TS, and TDS were reduced by 4.61 m, 1.30 m, and 2.14 m respectively, and the net scouring rates were 27.1 cm/a (centimeter per annum), 7.6 cm/a, and 12.6 cm/a, respectively. The scouring rate of the RDS is obviously higher than those of the downstream TS and TDS.

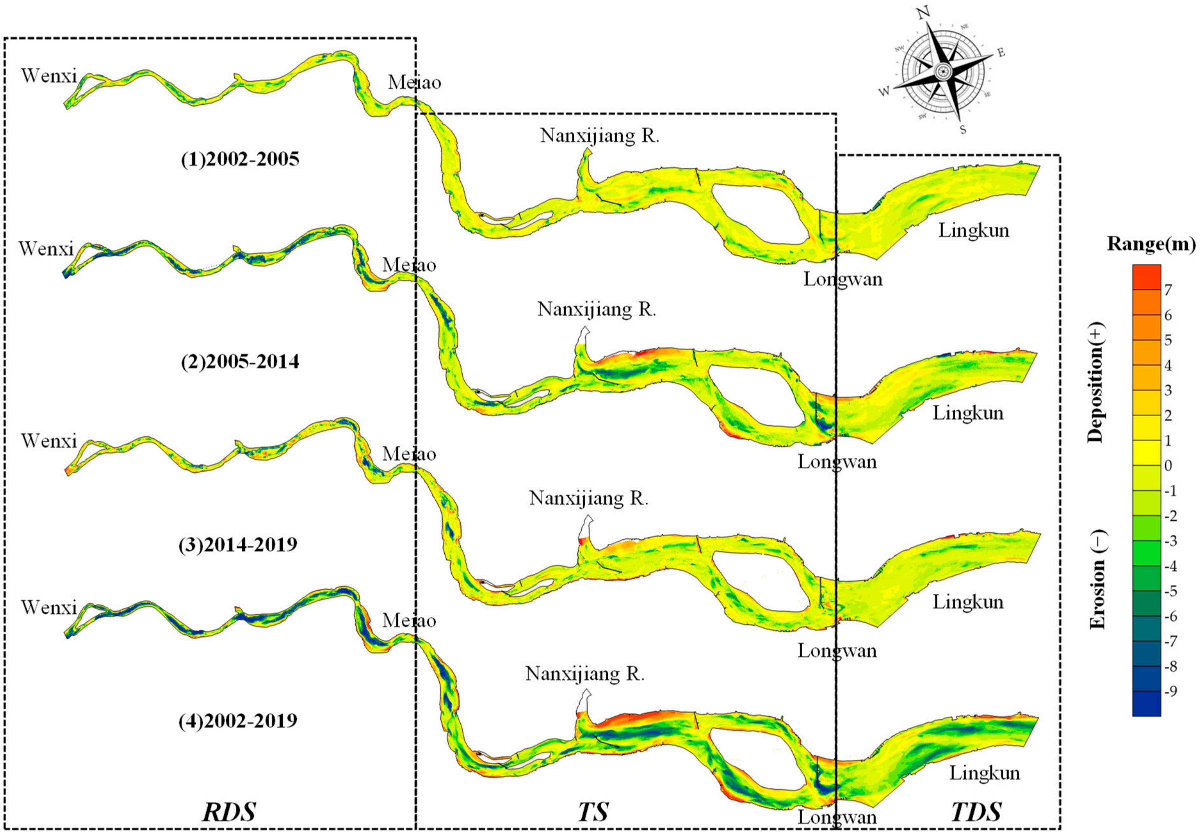


Figure 5. Interannual erosion and deposition changes of Oujiang Estuary in recent 20 years.

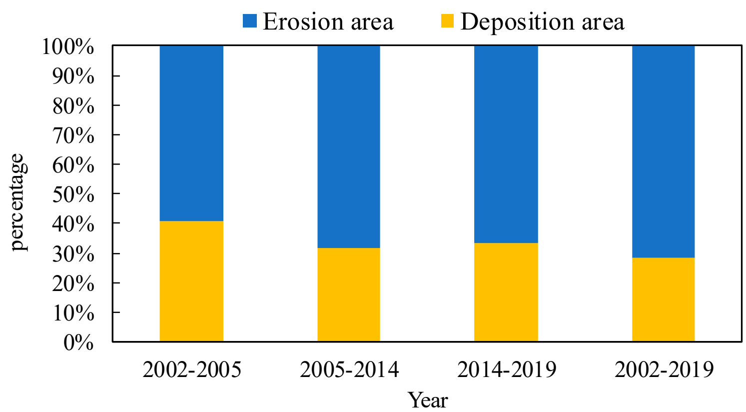


Figure 6. The proportion of erosion area and deposition area at each time period.

Table 1. Statistics of net erosion and deposition of Oujiang Estuary from 2002 to 2019.

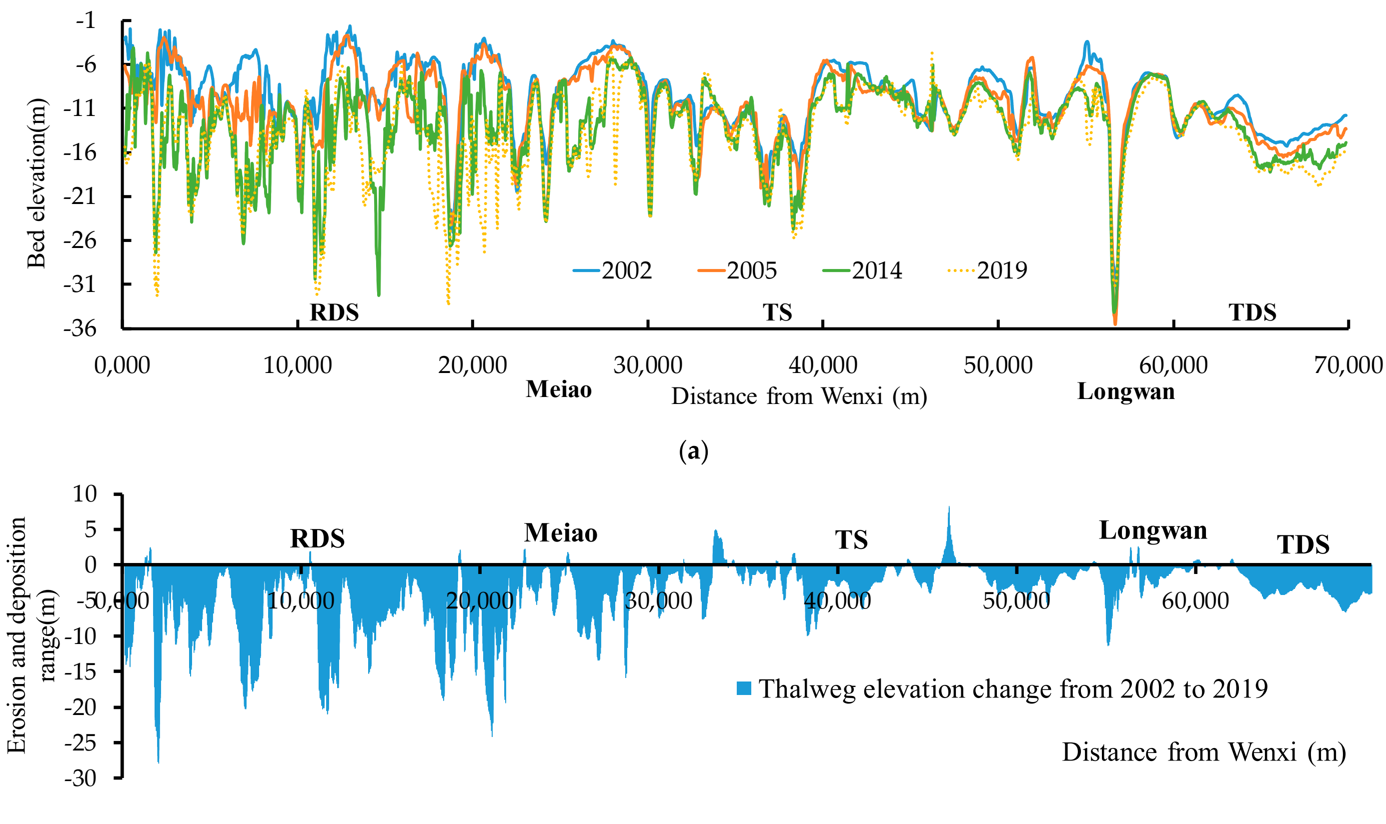
Interannual	Erosion and Deposition Amount (10^4 m^3)				Erosion and Deposition Range (m)			Average Annual Erosion and Deposition Range (cm/a)		
	RDS	*TS*	*TDS*	Total	*RDS*	*TS*	*TDS*	*RDS*	*TS*	*TDS*
2002–2005	−982	−1055	−1120	−3157	−0.94	−0.21	−0.48	−31.3	−7.0	−16.0
2005–2014	−3069	−4045	−2627	−9741	−2.93	−0.80	−1.13	−32.6	−8.9	−12.6
2014–2019	−774	−1439	−1233	−3446	−0.74	−0.29	−0.53	−14.8	−5.8	−10.6
2002–2019	−4825	−6539	−4980	−16,344	−4.61	−1.30	−2.14	−27.1	−7.6	−12.6

Note: "+" value indicates deposition and "−" value indicates erosion.

On the time scale, the scouring rate of the RDS was 31.3 cm/a from 2002 to 2005, 32.6 cm/a from 2005 to 2014, and finally decreased to 14.8 cm/a from 2014 to 2019, which was only 45% of the previous period. The scouring rate of the TS firstly increased and then decreased, with the scouring rate of 7.0 cm/a in 2002–2005, 8.9 cm/a in 2005–2014, and 5.8 cm/a in 2014–2019. The scouring rate of the TDS was 16.0 cm/a from 2002 to 2005, 12.6 cm/a from 2005 to 2014, and 12.6 cm/a from 2014 to 2019.

4.2. Variation along the Longitudinal Section

On the basis of scouring and silting calculations and average riverbed evolution analysis, the variations along the thalweg elevation in each year (Figure 7a) and the scouring and silting amplitude of the thalweg elevation in 2002–2019 (Figure 7b) are plotted to further characterize the variation of the riverbed. It can be seen from the figure that the riverbed in the river section was significantly undercut. From 2002 to 2019, in the RDS, the average elevation of the thalweg dropped from −8.02 m to −15.35 m, with a range of 7.33 m, the maximum drop of 28 m, and the lowest riverbed elevation of −33 m, which was obviously not the result caused by natural scouring and silting. As for the TS, the average elevation of thalweg decreased from −9.96 m to −12.06 m, with a range of 2.1 m, and the maximum range of 15.85 m from 2002 to 2019. While the average elevation of the thalweg in the TDS decreased from −12.14 m to −15.05 m from 2002 to 2019, with a range of 2.9 m and the maximum range of 6.64 m. The change of the longitudinal profile along the route in the upstream reach is stronger than that in the downstream reach. As for the abnormal change of scour amplitude, it exceeds the scope of natural evolution, which means that the adjustment of erosion and deposition of the Oujiang Estuary riverbed has been deeply affected by human activity rather than the natural variation in flood tide during this century.



(b)

Figure 7. Thalweg elevation change along the route: (**a**) Variation along the thalweg elevation in each year; (**b**) Silting variation amplitude of the thalweg elevation in 2002–2019.

4.3. Variations of Typical Cross-Section

The variations of typical cross-sections in the Oujiang Estuary are shown in Figure 8, and the locations of the cross-sections are shown in Figure 1. Sections 1 # and 2 # are located in the RDS, and 3 # and 4 # are in the TS and TDS, respectively. The four sections are flood control sections in space. It can be seen from the figure that the beach on the south bank of Section 1 # was abnormally "undercut", and the lowest elevation reached −27 m. The underwater slope on the south bank increased from 1/20 in 2002 to 1/6 in 2019, with significant steepening. The riverbed of section 2 # tended to be uneven from 2002 to 2014, and obvious deep pits appeared in 2019, with dramatic changes in shoals and troughs. At Section 3 # the shoal channel was relatively stable. The main channel position was obviously scoured from 2002 to 2014, and the amplitude of change in other years was relatively small. Section 4 # is located at the downstream position of Longwan where, due to the widening of the riverbed and the difference between flood and ebb tides, tidal sand ridges developed in the middle of the river channel. Since 2002, the sand ridges have tended to disappear, and the riverbed has tended to be uniform on the whole.

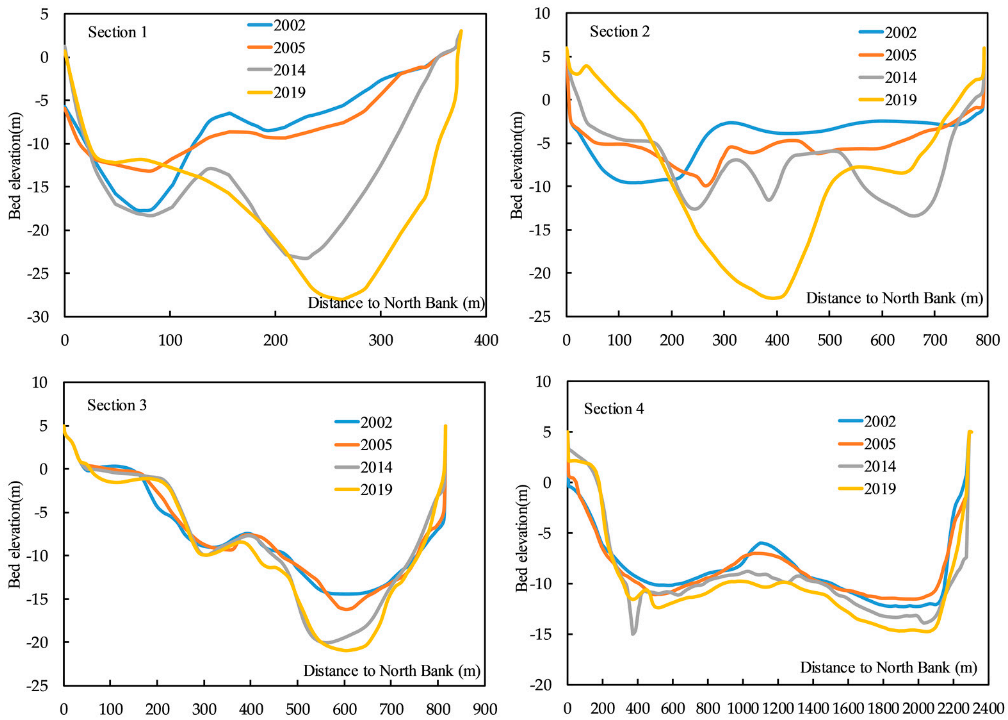


Figure 8. Erosion and deposition change of a representative section.

The river facies coefficient (width–depth ratio) is an important parameter to represent the characteristics of the river cross-section. The width–depth ratio in riverbed evolution not only reflects the width and shallowness of the riverbed shape, but is also one of the indicators of riverbed stability [34]. The formula in estuary shape is as follows [35]:

$$\xi = \sqrt{B}/H$$

where ξ is the dimensionless river facies coefficient. B and H are river width and water depth under semi-tidal water levels, respectively. Normally, the larger the river facies coefficient, the wider and shallower the riverbed is. The calculation results of the average width-depth ratio of the whole river section in the Oujiang Estuary show (Table 2) that the river facies coefficients of each section are decreasing over time. This indicates that the cross-section shape of the riverbed in the Oujiang Estuary is becoming narrower and deeper. This is mainly ascribed to the riverbed's tendency to be scoured as a whole, which is consistent with the riverbed evolution. In addition, seen from Table 2, the value ξ of each cross section decreased with different decreasing rates from 2002 to 2019 and the relative decreasing rates of section 1~4 were 49%, 64%, 16%, and 25%, respectively. The variation amplitude of the river facies coefficient of the upstream section is obviously stronger than that of the downstream section, and the change in speed of the downstream section towards the narrow depth is less significant than that of the upstream section.

Table 2. Change of average width–depth ratio of representative sections in Oujiang Estuary.

Year	Section 1	Section 2	Section 3	Section 4
2002	2.30	6.29	3.29	5.45
2005	2.27	5.39	3.31	5.36
2014	1.23	3.67	3.00	4.38
2019	1.18	2.26	2.77	4.11

5. Discussion

5.1. Influence of Natural Factors on Estuarine Erosion and Deposition

In the natural state, the aperture flow and tidal current of the Oujiang River jointly influence the riverbed. The river channel volume of the estuary is generally characterized by inter-annual flood erosion, dry deposition, annual flood erosion and tidal deposition. The flow velocity of flood tides in the dry season is often greater than that of ebb tides, and hence the sediment content of flood tides is often greater than that of ebb tides. The sediment is deposited in the riverbed during flood tides, and cannot be taken away during ebb tides. In space, it is shown as "washing down and silting up". When the flow rate of the ebb tide in the upper reaches of the river increases and the flow rate of the flood tide decreases during the flood season, the silted sediment will be flushed to the lower reaches, forming a pattern of "washing up and silting down". The dividing point of washing up and silting down will move up and down with the size of flood flow and flood volume, and also the range of scouring and silting in the riverbed during the flood season is greater than that in the dry season [36]. Although the Oujiang Estuary is a strong tidal estuary, due to the short tidal boundary, the tidal wave deformation is not severe. For example, the average tidal range at Longwan Station in the estuary is more than 4 m, the maximum tidal range is more than 7 m, the average rising tide lasts 5 h 22 min, and the average falling tide lasts 6 h 33 min. At the same time, although the flood is rapid, the sediment movement during the flood is mainly bed load movement. Under natural conditions, the interannual erosion and deposition amplitude of the riverbed and the seasonal variation within the year are not large, and the long-term erosion and deposition are in a relatively balanced state [36]. Before the 1970s, the evolution of the Oujiang River channel was completely under natural conditions. For example, 1964 was a dry year, with an annual average flow of 370 m^3/s, and 1970 was a wet year, with an annual average flow of 512 m^3/s. The volume of the riverbed under the middle tidal level in the section from Jiangxinyu to Huanghua only increased by 2.5 million m^3, and the erosion range was about 4 cm [24].

Table 3 shows the annual average flow and maximum flood peak of Hecheng Hydrological Station in 2002, 2005, 2014, and 2019, the hydrological conditions in the years between the surveys, and the annual average flow from 1960 to 2019. It can be seen from the table that: the annual average flow and flood peak in 2002 were 464 m^3/s and 5180 m^3/s, respectively, and the annual average flow and flood peak in 2005 were 507 m^3/s and 13,700 m^3/s, respectively. Among them, the flood peak in 2005 was the largest flow in the last 20 years, and the riverbed was scoured in 2002–2005. The annual average flow in 2014 was 565 m^3/s, slightly higher than that in 2005. However, in terms of flood peak, the flood peak in 2014 was 10,900 m^3/s, accounting for about 80% of that in 2005. At the same time, the annual average flow and flood peak in 2006–2013 were 440 m^3/s and 8860 m^3/s, respectively, which were roughly equivalent to the multi-year average value. However, the riverbed in 2005–2014 showed a sharp downward cut, and the average decline of RDS, TS and TDS riverbeds was 2.93 m, 0.80 m, and 1.13 m, respectively. The average annual flow and flood peak in 2019 were 536 m^3/s and 8930 m^3/s, respectively, which were lower than those in 2014. The average annual flow and flood peak in 2015–2018 were 470 m^3/s and 12700 m^3/s, respectively, during which the flood peak increased by 16.5% compared with 2014. The river channel showed a trend of scouring in 2014–2019, but the scouring rate has slowed down. In addition, in terms of the annual average flow and flood peak in 2002 and 2019, 2019 is slightly larger than 2002. In general, it can be seen that during this century, the natural evolution of erosion and deposition changes in the Oujiang Estuary has coexisted with the impact of human activities, and the effect of human activities has far exceeded the natural evolution.

Table 3. Upstream water inflow in different years.

Year	Annual Average Flow (m^3/s)	Flood Peak (m^3/s)
2002	464	5180
2003–2004	296	5850
2005	507	13,700
2006–2013	440	8860
2014	565	10,900
2015–2018	470	12,700
2019	536	8930
Multi-year average (1960–2019)	443	8316

5.2. Direct Impact of Human Activities on River Bed

5.2.1. River Channel Sand Mining

The development and utilization of sand and gravel in the Oujiang River has a long history, and the amount of sand quarried was less before the 1980s and 1990s. At the end of last century, with the rapid economic development, the required amount of sand and gravel increased sharply. According to the survey data, the sand mining volume of the Oujiang River accounted for about 70% of the total volume used in Wenzhou City. From 2007 to 2009, the sand mining volume in the region reached 21.37 million m^3,and the actual annual mining capacity of the existing sand dredgers reached more than 12 million m^3 [37]. Figure 9 shows the distribution map of sand mining at the estuary from 2012 to 2019. It can be seen from the map that the sand mining areas were mainly located in the river section from Wenxi to Meiao (RDS), where the excavation amplitude was 8–18 m in Area I-II, 9–16 m in Area III-IV, 10–17 m in Area V, 9–16 m in Area VI, and 3–5 m in Areas VII and VIII of the TS [38].

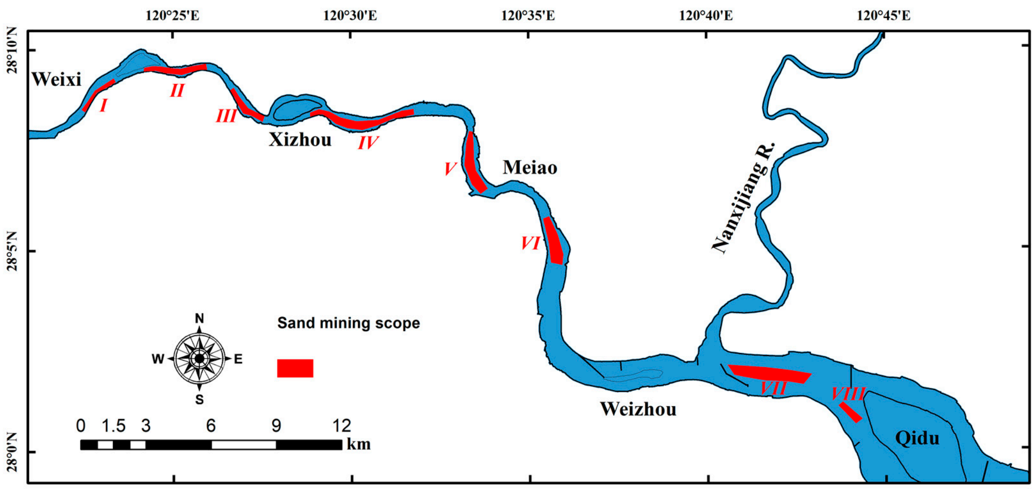


Figure 9. Distribution Map of Estuarine Sand Mining in 2012–2019.

Under the influence of high-intensity and large-scale artificial sand mining, the riverbed topography was cut down, especially in the river section above Meiao (Figure 6). The measured data show that the riverbed elevation of the river section cut down, on average, 4.61 m from 2002 to 2019, and the thalweg elevation dropped, on average, 7.33 m. At the same time, the pattern of the shoal channel changed and the shoal slope became steeper. In addition, the width–depth ratio of the riverbed decreased significantly, which had a great impact on the river regime. The scales of sand mining in TS and TDS were relatively small, and the average riverbed elevation decreased by 1.30 m and 2.14 m, respectively, from 2002 to 2019. In addition, according to the change data of the riverbed volume below the middle water level calculated by the tracking monitoring section of the estuary topography since 2012 (Figure 10), the sand mining activities in the river channel tended to slow down in recent years, which is consistent with the decreasing trend of the river channel scouring rate (Table 1). Sand mining has been prohibited in the Oujiang River estuary since May 2020.

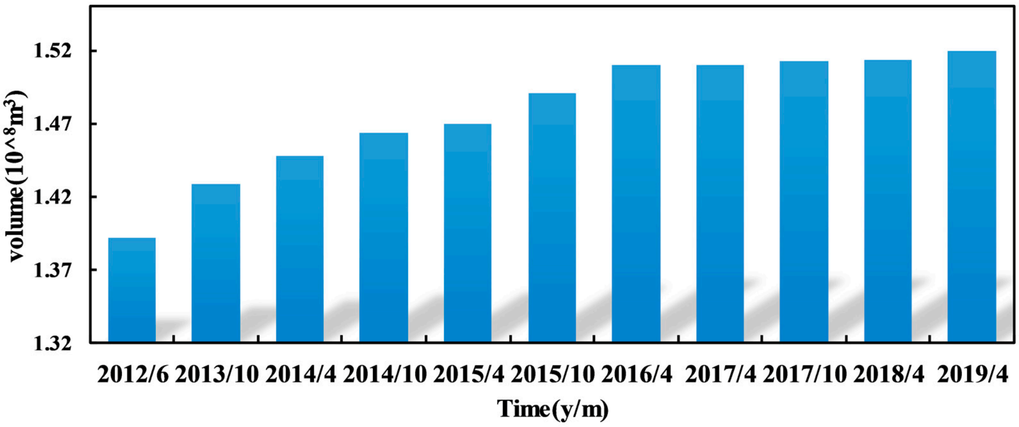


Figure 10. Statistical change of volume under middle water level in river section.

5.2.2. Impact of Reclamation Outside the Mouth

The Oujiang Estuary is developed with a relatively large beach, which is located between Lingkun Island and Niyu Island (Figure 11a). The Wenzhou Shoal Project is to build two sea levees connecting Lingkun and Niyu along the north and south sides of the shoal to artificially form the shoal into land. The first phase of the project is composed of a 15.52 km long Lingni North Dike (Figure 12) and a 5.22 km long South Dike. It was completed in 2006. The second phase of the project consists of the Lingni South Dike with a length of 8.95 km and the remaining reclamation works between the whole South Dike and the North Dike. It was started in 2013 and completed in 2016 (Figure 11b). The Oufei Reclamation Project is located in the beach area to the south of the Oujiang Estuary. At the same time, in order to promote the implementation of the Wenzhou Shoal and Oufei Reclamation Project, on the basis of the Lingkun South Entrance Submerged Dam Project built in 1979, the submerged dam was increased by 0.42 m to −0.6 m in 2000. The submerged dam project increased the diversion ratio of the north entrance, causing widespread scouring of the riverbed. According to the experience of similar regulation projects in the Oujiang Estuary, the role of bed building was most obvious in the first few years after the regulation project. The scouring and silting calculation shows that the north entrance was scoured by 16.0 cm/a from 2002 to 2005. In addition, as for the Wenzhou Shoal Project, the trend of the Lingni North Dike is basically consistent with the 0 m isobath on the north side of the Wenzhou Shoal, and the trend of the Wenzhou Shoal is basically consistent with the main direction of the two ebb and flow tides at the north and south mouth of the Oujiang Estuary, so the reclamation project has not changed the tidal current characteristics of the Oujiang Estuary area in a large range [33], but most of the tidal volume of the Wenzhou Shoal enters and exits from the waterway outside the north mouth during the flow tide, After the construction and completion of the Lingni North Dike, the tidal volume of the upper shoal on its north side was blocked, thus increasing the tidal volume entering the north entrance, causing the flow rate of the north entrance of the Oujiang River to increase, resulting in bed erosion. The north entrance was scoured 12.6 cm/a from 2005 to 2014. In addition, according to the measured velocity comparison between the adjacent stations at Lingkun North Entrance in 2005 and 2010, the hydrodynamic variation before and after the construction of the Lingni North Dike can be characterized. The relationship between the average vertical velocity at the measuring point and the Longwan tidal range is shown in Figure 13. It can be seen that the correlation between the velocity and the tidal range is good. The velocity before and after the project shows an increasing trend. The average vertical velocity at Longwan Station under the multi-year average tidal range of 4.6 m increased from 0.8 m/s in 2005 to 1.0 m/s in 2010, an increase of about 25%. In addition, after the implementation of the shoal project, the area of the shoal was reduced, which weakened the wave action in dry season. The reduction of local sediment sources also plays a role in scouring the north entrance.

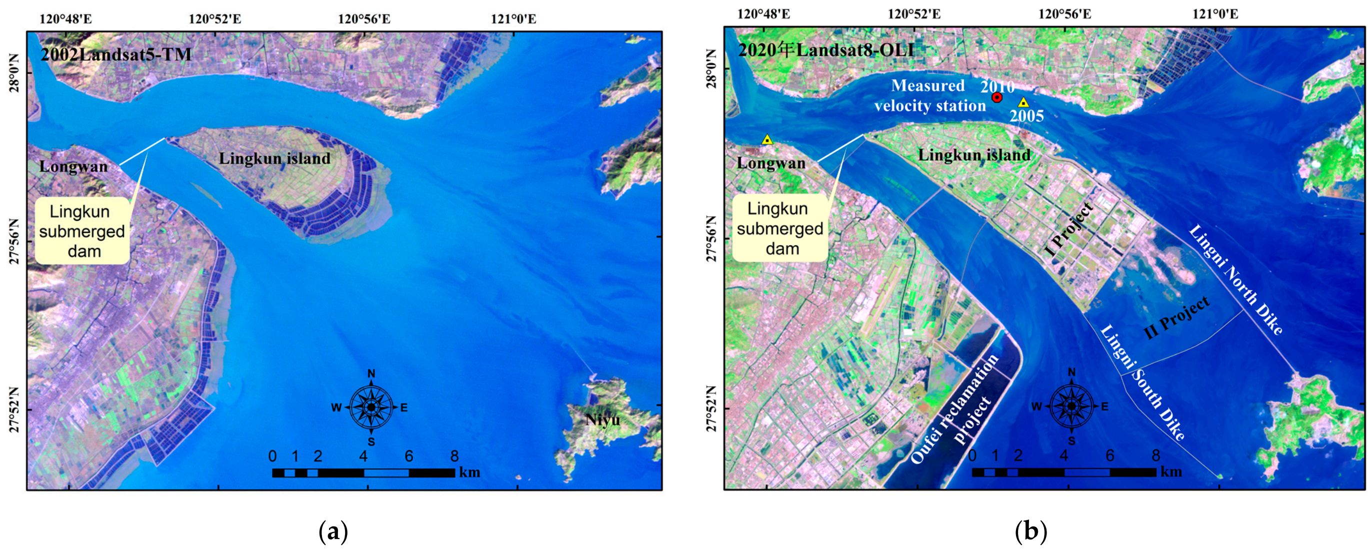


Figure 11. Remote sensing image of the Oujiang Estuary in different ages: (**a**) Landsat5-TM in 2002; (**b**) Landsat8-OLI in 2020.

Figure 12. Current situation of Lingni North Dike.

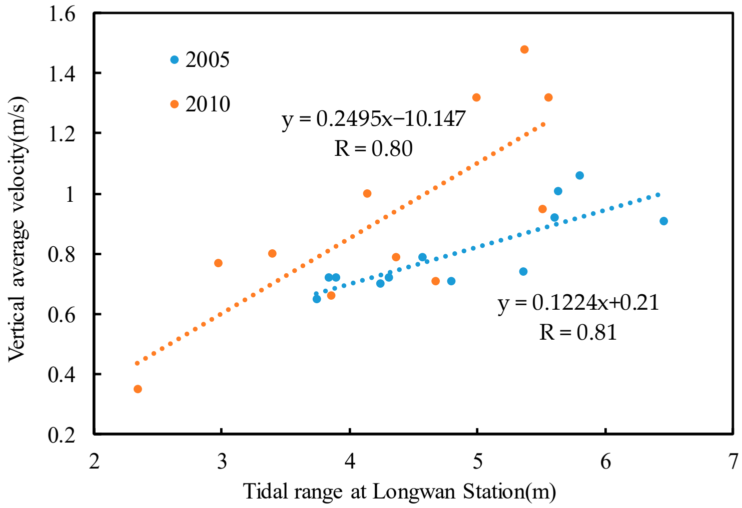
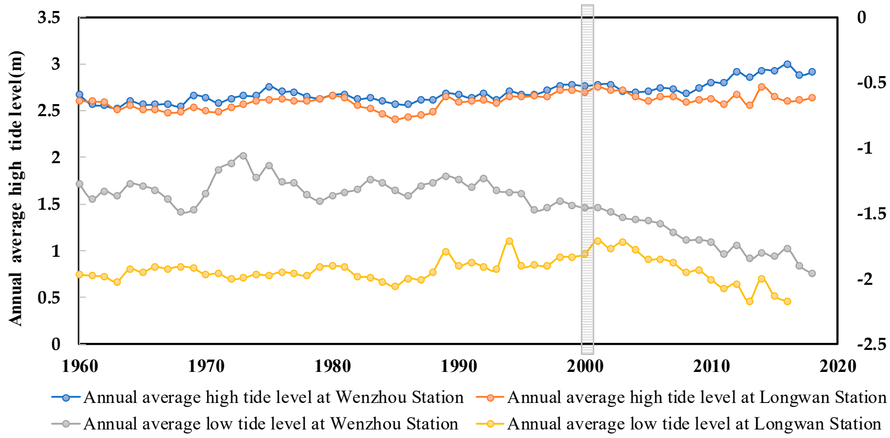


Figure 13. Correlation between tidal range and vertical average velocity at Longwan station.

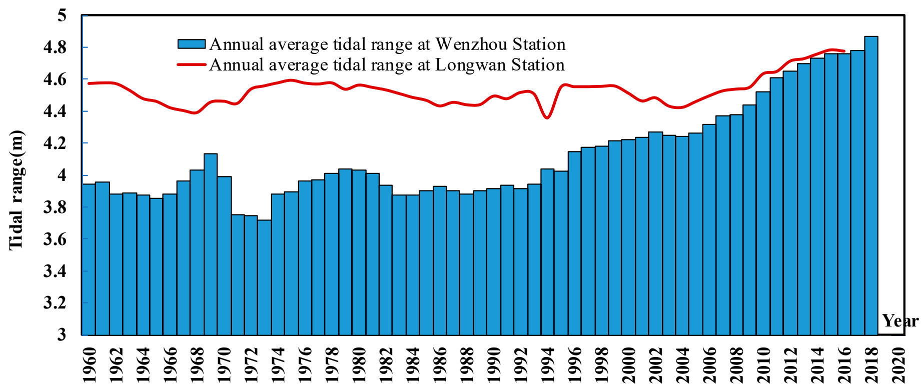
5.3. Tidal Dynamic Changes Caused by River Bed Undercutting, and Then the Impact on Deposition

High-intensity sand mining and other human activities directly lead to a significant decline in the riverbed elevation. On the other hand, the significant downward cutting of the riverbed terrain causes tidal dynamic changes and affects the scouring and silting evolution of the river channel. Tidal range is an important indicator of tidal power. Figure 14a,b show the variations of the annual average high and low tide levels and the annual average tidal range of the two long-term tide stations in Wenzhou and Longwan on the Oujiang Estuary. The estuary tide type is semi-diurnal, and the annual average high and low tide levels are the average values of the two high tide levels and low tide levels in each year. It can be seen from the figure that the change of tidal characteristics of the two stations is basically consistent. During this century, the high tide level is rising, while the low tide level is falling. Consequently, the tidal range has increased. In terms of the temporal and spatial pattern, the variation of tidal characteristics of upstream stations is greater than that of downstream stations, and the variation of low tide levels is greater than that of high tide levels.

Since Meiao Station and Huayantou Station stopped running in 1995 and 2000, respectively, this paper calculated the average annual tidal range data of Meiao Station and Huayantou Station under the average hydrological conditions through the two-dimensional tidal current mathematical model. The upper part of the model uses the average annual runoff of Hecheng Station in that year, and the lower boundary selects the tidal pattern outside the open boundary corresponding to the mid-tidal range of 50% of the cumulative frequency of Longwan Station as the average hydrological condition. The calculation shows that the variation of the tidal range in the upper reaches of the Oujiang Estuary has been more dramatic since the beginning of this century [20]. The large undercutting of the riverbed directly leads to the lowering of the low water level, which is more obvious when moving upstream. At the same time, the original longitudinal gradient of the river slows down, the energy dissipation effect of the riverbed friction on the flood tide is greatly weakened, and the high tide level is also raised, further causing the increase of the tidal range.



(**a**)



(**b**)

Figure 14. Change process of the tidal characteristic at Wenzhou and Longwan Stations: (**a**) Change process of annual average high and low tide levels; (**b**) Change process of annual average tidal range.

The increase of tidal range will enhance the tidal power of the estuary, which will inevitably break the balance of sediment transport and cause the corresponding scouring change of the riverbed. Figure 15 shows the tidal change of representative river reach calculated by a two-dimensional tidal current mathematical model under average hydrological conditions. The data show that from 2002 to 2019, the average annual tidal range of Huayantou reach (1 # section, see Figure 1 for section location) increased by 1.14 m, and the flood tide volume increased from 15 million m^3 to 27 million m^3, an increase of about 80%. The average annual tidal range of Meiao reach (section 2 #) increased by 0.91 m, and the flood tide volume increased from 36 million m^3 to 62 million m^3, an increase of about 72%. The average annual tidal range of Wenzhou reach (Section 3 #) increased by 0.60 m, and the flood tide volume increased from 121 million m^3 to 182 million m^3. The average annual tidal range of Longwan reach (Section 4 #) increased by 0.19 m, and the flood tide volume increased from 248 million m^3 to 290 million m^3, an increase of about 17%. In addition, the increase in tidal range also caused the movement of the tidal current boundary upwards. The location of the tidal current boundary was about 500 m downstream of the Hecheng Bend under the topographic conditions found in 2019, which is nearly 10 km upstream of the Oujiang Estuary tidal current boundary at the Wenxi section. In addition, it can be seen from the correlation between the width–depth ratio of the riverbed of 1–4 # representative sections and the annual average tidal range of Huayantou, Meiao, Wenzhou, and Longwan stations (Figure 16), that the width–depth ratio of the riverbed shows a significant negative correlation with the change of the tidal range. The larger the tidal power, the narrower the riverbed tends to be, and the correlation coefficients can reach 0.93, 0.98, 0.97, and 0.89, respectively, which means that the impact of tidal power on the evolution and development of the Oujiang Estuary has been significantly enhanced.

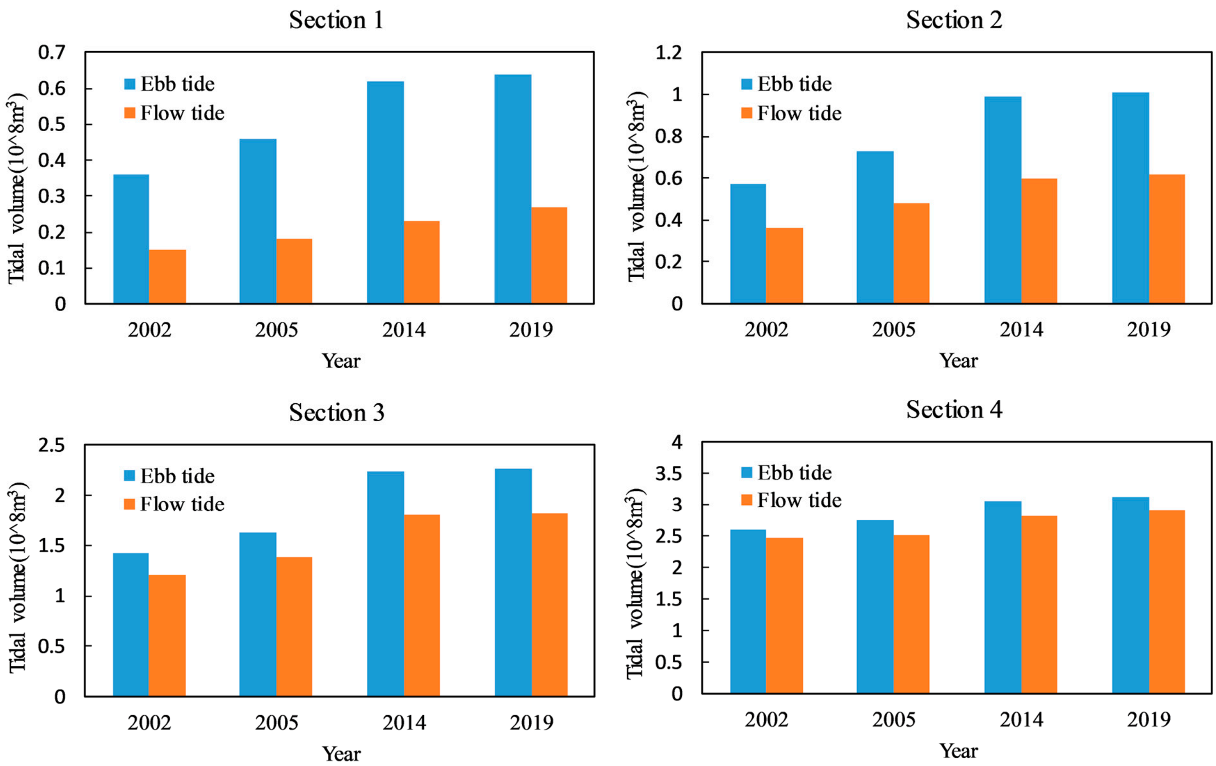


Figure 15. Tide Volume Statistics of Representative Section under Different Topographic Conditions.

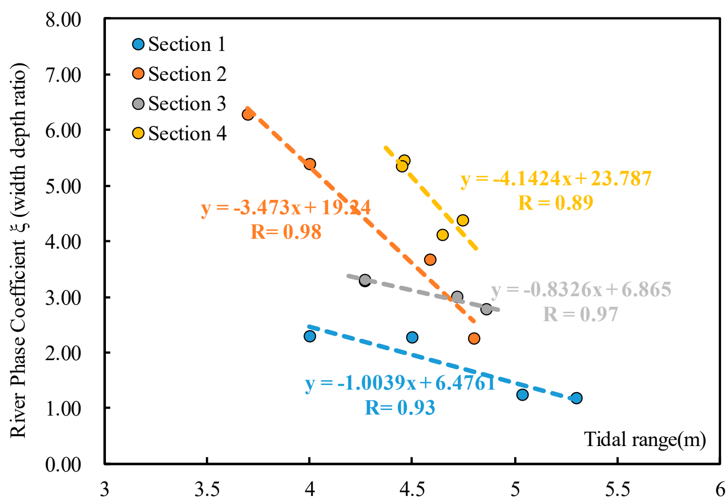


Figure 16. Average Annual Tidal Range and River Phase Coefficient ξ (width–depth ratio).

6. Conclusions

Using four years of synchronous topographic monitoring data of the Oujiang Estuary in 2002, 2005, 2014, and 2019, this paper analyzed the characteristics and physical mechanism of riverbed evolution in the Oujiang Estuary since the beginning of this century under the dual effects of high-intensity human activities and flood tide dynamics. The main understandings are as follows:

1. From 2002 to 2019, the Oujiang Estuary was generally in a scouring state, with sediment net scouring of 163.44 million m^3, and a reduction of 4.61 m, 1.30 m, and 2.14 m in RDS, TS, and TDS, respectively. In the spatial pattern, the scouring amplitude

of the upstream reach is significantly stronger than that of the downstream reach, and the scouring rate has slowed down in recent years on the time scale.
2. The pattern of shoal and channel changed obviously from 2002 to 2019. Some riverbed shoal slopes were steep and uneven. The maximum thalweg elevation could reach 28 m. The river facies coefficient (width–depth ratio) decreased by 16–64% and the riverbed tended to be narrow and deep. The evolution mechanism of estuarine erosion and deposition was driven by both natural and human activities, and the impact of human activities has been far beyond the natural evolution.
3. Sand mining in the river channel is the direct cause of riverbed undercutting, and tidal dynamic change caused by large undercutting of riverbed topography is an important factor that further affects the change of estuary scouring and silting. In the last 20 years, the average annual tidal range of the estuary increased by 0.19–1.14 m, with an average of 0.71 m. And the flood discharge increased by about 17–80%, with an average of 58%. The influence of tidal power on the evolution and development of the estuary significantly increases when the tidal current boundary moves upstream. At the same time, reclamation projects such as the Wenzhou shoal outside the mouth also cause the local velocity of the tidal current section to increase, further intensifying the scouring trend of the downstream river section. The scouring and silting change of the Oujiang Estuary in this century was the result in response to the strong intervention of human activities.

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