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# Tidal dynamic response to riverbed evolution in the Yangtze River Estuary

Yufang Han[1*], Bingke Dai[2] and Hongwei Ding[1]

## Abstract

Since 1958, there have been significant changes in the Yangtze River estuary. Due to extensive reclamation and construction of ports and channels, the water area has drastically decreased, resulting in corresponding changes in hydrodynamics and riverbeds at the mouth of the river. According to the analysis of measured topographic data and Delft3D-FLOW model for seven typical historical periods since 1958 at the Yangtze River Estuary, this study investigates the characteristics of riverbed evolution and tidal flow dynamics. From 1958 to 2019, driven by strong human activities, the total area of the Yangtze River Estuary decreased from 2084 km$^2$ to 1403 km$^2$, with a decrease of 32.7%, while the total volume of the corresponding river channel changed slightly and remained stable. Compared with 1958, the volume of the Yangtze River Estuary in 2019 only increased by 345 million m$^3$, with an increase of about 4.1%. The tidal dynamic change of the Yangtze Estuary is closely related to the riverbed evolution of each reach, which not only shapes the estuary landform, but also is affected by the riverbed evolution. Tidal level, tidal range and water area change are closely related. With the decrease of water area in the Yangtze River Estuary, tidal range tends to increase. Tidal prism change is closely related to channel volume. In the past 60 years, the tidal volume at the mouth of the Yangtze River has decreased by 8%. The research findings will provide technical support for enhancing flood control and tide resistance measures at the Yangtze River Estuary, as well as formulating comprehensive management plans for estuaries, contributing to the protection and sustainable development of the Yangtze River Estuary.

**Keywords** Yangtze Estuary, Riverbed evolution, Numerical simulation, Tidal dynamic, Tidal prism

## 1 Introduction

The estuarine delta serves as both the primary habitat for human activities and the most susceptible area for Sea-Land interactions (Bianchi 2013). Over the past 30 years, the Yangtze River Estuary (YRE) has undergone intense development. The width of Xuliujing Reach has shrunk from over 10 km to 5 km due to the Reclamation of Tonghaisha and Jiangxinsha (Zhang et al. 2022). A sequence of reclamation projects have expanded the estuary enclosure zone from high beach to medium and low beach. Furthermore, the construction of the water source project in Qingcaosha has reduced the width of the North Branch by 1/3 (Li et al. 2023). The alteration of riverbed morphology due to these human activities and the significant decline in sand supply in recent years, is significantly impacting the equilibrium of estuarine water and sand transportation.

Under the strong driving force of high-intensity development at the river mouth, the sedimentation pattern of the estuary geomorphology will change, and the dynamic process of the estuary will respond to channel evolution. The impact of human activities not only increases the complexity and spatial variability of natural processes but also profoundly affects the dynamic geomorphic equilibrium pattern at the Yangtze River Estuary.

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In their study on tidal volume response and channel evolution in the Yangtze River Estuary, Min et al. (2016) established a mathematical model for hydrodynamics in this area. They quantified differences in energy between runoff and tides during flood and dry seasons to investigate seasonal variations and energy changes in tidal volume. The study explored differences between ebb-tide flow rate and storage tide volume, revealing that as runoff intensity increases, both tidal flow dynamics and flow rate decrease while tidal volume remains relatively constant under different runoff conditions. It was suggested that tidal flow seems to adjust according to changes in runoff flow to maintain a constant tidal volume. Hu K et al. (2009), through establishing a three-dimensional hydrodynamic model for the Yangtze River Estuary, investigated how deep-water navigation construction affected hydrodynamics and salinity levels in North Channel. It was found that ebb-tidal flux decreased with navigation construction while tide currents transitioned from rotational circulation to reciprocating circulation due mainly to dike construction on both sides,as water depth increased with navigation channels, saltwater intrusion worsened. Zhijun et al. (2016) conducted an analysis on bed evolution in North Branch section based on measured bathymetric data from 1950 to 2010 at Yangtze River estuary. The findings revealed significant reductions over nearly fifty years in average water depth as well as volumes for channels with depths greater than zero meters or five meters respectively, furthermore, it was identified that embankment along both sides played a primary role behind diminishing water area alongside decreasing influxes caused by tides within these channels.

Xiaohe et al. (2018) explored the relationship between tidal volume changes and riverbed evolution at the mouth of the Yangtze River by establishing a mathematical model. By studying the mutual influence between tidal flat evolution and tidal characteristics, they pointed out that there is a positive feedback relationship between the two, with their interaction dominating the morphodynamic evolution of the Yangtze River Delta. The sedimentation and expansion of shallow bars outside the estuary increase energy dissipation of tides towards the sea, resulting in a decrease in tidal volume within the estuary and weakening of tidal flow dynamics. Conversely, this weakening of tidal intensity has a counter effect on shallow bar evolution outside the estuary, promoting sediment accumulation.

The existing analysis and research on the evolution of the Yangtze River estuary's riverbed, characteristics of tidal currents and waves, and changes in tidal volume are mainly limited to specific regions within the estuary. There is a lack of systematic research on the overall evolution of the entire Yangtze River estuary. Additionally, most studies focus on topographic changes from the 1980 to 2010, lacking a comprehensive analysis of long-term variations in riverbed evolution and tidal current characteristics at the mouth of the Yangtze River. However, there is an interrelationship and mutual constraint between the dynamic characteristics of tidal currents at the mouth and its riverbed evolution. Therefore, studying how typical historical periods' tidal current characteristics respond to riverbed evolution plays a positive role in revealing dynamic geomorphic processes at the mouth of the Yangtze River and predicting future development trends.

This research will concentrate on the evolutionary traits (Yang et al. 2021) and hydrodynamic response process of the Yangtze River Estuary (YRE) due to intense human activities (Zhang et al. 2018). Several representative time periods will be examined based on an analysis of measured topographic data and hydrodynamic calculations, primarily focusing on erosion and siltation, river volume, tidal dynamics, and tidal prism.

## 2 Study area

The Yangtze Estuary, located on the north side of Shanghai, China, is about 160 km long and about 90 km at the downstream entrance. The estuary section characterized by three primary branches and four outlets to the sea (Fig. 1). Firstly, the first bifurcation divides the estuary into North and South Branches through Chongming Island. The South branch further forms North Channel and South Channel through Changxing Island and Hengsha Island respectively. The South Channel is finally divided into the North and South Passages by the JDS (Zhao et al. 2022).

The Yangtze River Estuary is a river mouth with moderate tidal range. According to the data from the Zhongjun Tidal Station near the mouth of estuary, the average tidal range is 2.67 m and the average flow velocity is 1 m/s. Based on data from the Datong Station, the annual average discharge of YRE (Yangtze River Estuary) was 28,300 $m^3$/s between 1950 and 2020, and the long-term average runoff remained relatively stable at $8977\times10^8$ $m^3$/y. However, due to various factors such as sediment retention, sand fixation and extraction, as well as upstream cascade reservoir construction, there has been a significant decrease in sediment load. From 1950 to 2020, there has been an evident three-stage gradual reduction trend at the Datong Station with an annual average sediment flux of only 133 million tons between 2003 and 2020.

Since the 1950s, a series of engineering projects have been implemented in the Yangtze River Estuary (YRE) as depicted in Fig. 2. These projects can be broadly categorized into four aspects based on their different functions (Han and Dou 2020): (a) dam and seawall

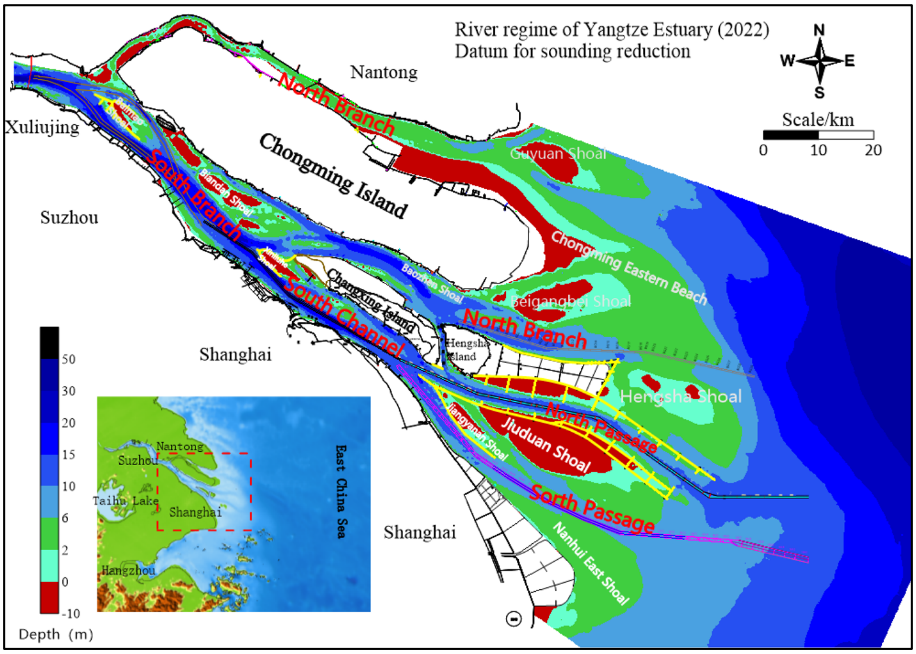


**Fig. 1** Overview of study area (Location and Bathymetry of YRE)

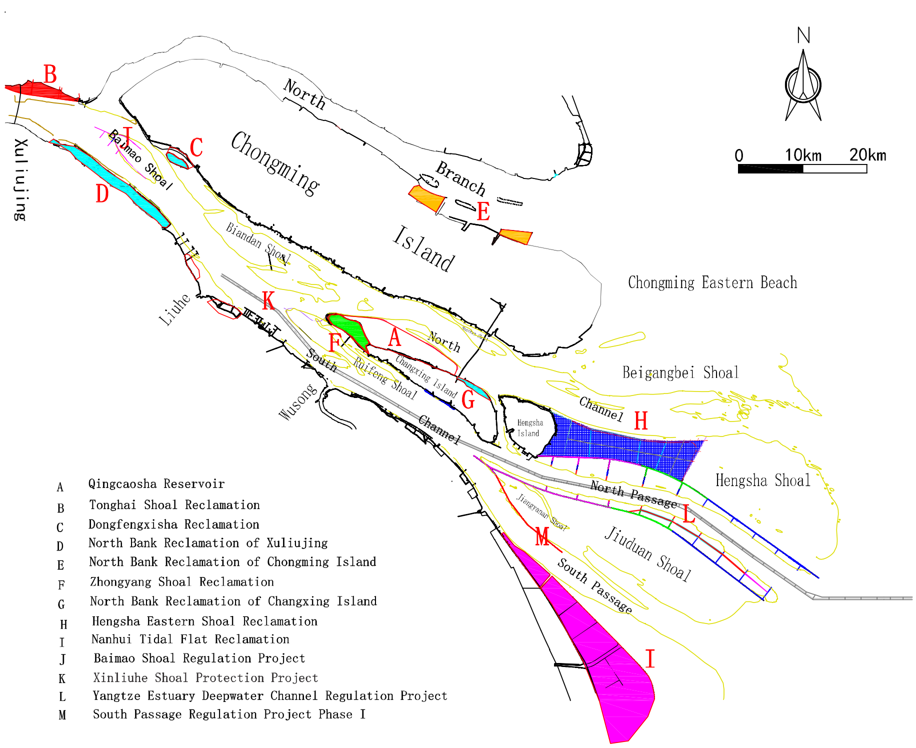


**Fig. 2** The layout of main projects (anthropogenic activities) at YRE

projects, (b) embankment projects, (c) land reclamation and shoreline stabilization projects, and (d) channel regulation and dredging works. The current pattern of the Yangtze River Estuary is the result of these four water-related projects working together.

## 3 Materials and Methods

In order to conduct a systematic study on the riverbed evolution in the Yangtze River Estuary over the past 60 years, we have collected seven topographic maps of the Yangtze River Estuary from different periods ranging from 1958 to 2019, as shown in Table 1. The reference for analyzing riverbed evolution is based on the theoretical lowest benchmark surface.

Due to its advantages of high precision, low cost, and no spatial or temporal limitations, numerical simulation has been widely used in the study of estuarine hydrodynamics. Therefore, this study adopts the state-of-the-art process-based numerical model called Delft3D. The Delft3D model solves either two-dimensional (depth-averaged) or three-dimensional unsteady shallow water equations. It has been extensively applied in various fields such as hydrodynamics, salinity dynamics, sediment dynamics, and morphodynamics in coastal and estuarine environments (Yang et al. 2021). The numerical model used in this study is two-dimensional and only includes depth-averaged processes.

The model covers the entire Yangtze River Estuary, with the upstream boundary extending to Datong and the adjacent ocean (Fig. 3). The easternmost maritime boundary is at 123.7°E, while the northern boundary is at 32.6°N, and the southern boundary is near Shengsi Islands in Hangzhou Bay (30.2°N). Six models with the same range were established in Delft3D-FLOW by using coastline and topographic data from different periods (i.e., 1958, 1973, 1989, 1998, 2010, and 2016) of YRE.

This model consists of 1118 × 130 orthogonal grid cells, with grid sizes ranging from approximately 20m at the river mouth to around 13,000m near the open sea. Additionally, in Yangtze River estuary model, structures such as docks and breakwaters are represented as overflow weirs, allowing water to flow when the water level is high enough.

The offshore boundaries were driven by 9 main astronomical tidal components (M2, S2, N2, K2, K1, O1, P1, M4 and SA). At the river boundary (Datong), the daily mean river discharge from July 10th to August 10th

**Table 1** Sources of measured data

| Period | Scale | Surveying Time | Source |
|---|---|---|---|
| 1958 | 1:25,000 | 1958.8–1958.10 | Navigation Survey Department of PLAN |
| 1973 | 1:50,000 | 1973.3–1973.11 | Shanghai Channel Bureau |
| 1989 | 1:75,000 | 1989 | Shanghai Maritime Safety Supervision Bureau |
| 1998 | 1:50,000 | 1998.06 | Yangtze Estuary Waterway Administration Bureau |
| 2010 | 1:50,000 | 2010.10 | |
| 2016 | 1:50,000 | 2016.11 | |
| 2019 | 1:50,000 | 2019.11 | |

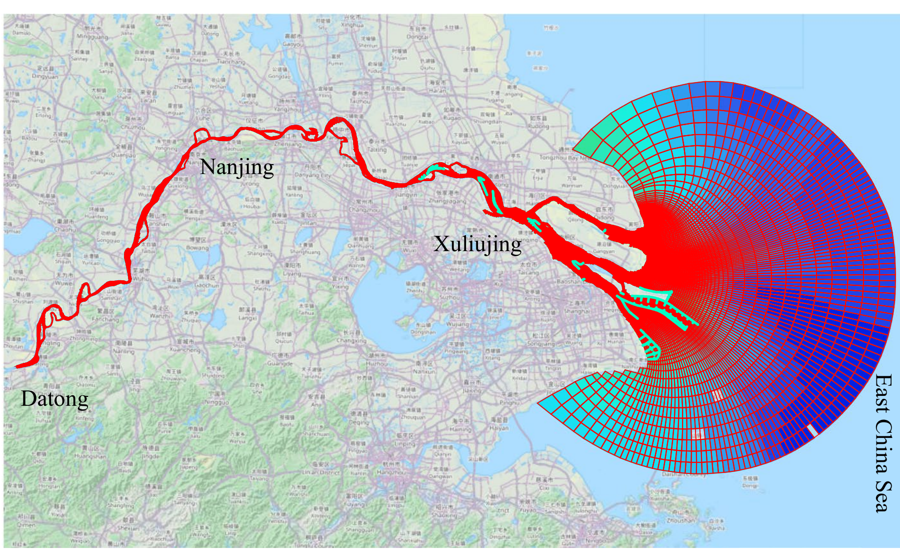


**Fig. 3** Model domain and horizontal mesh, including regulation projects (Cyan lines)

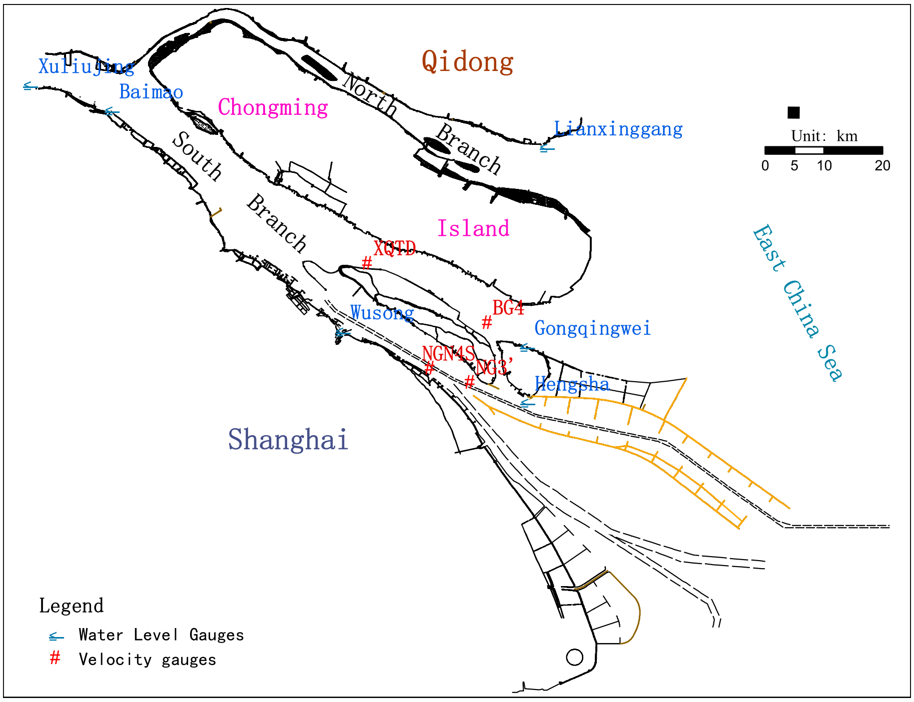


**Fig. 4** Schematic diagram of the positions of the verification points

2015 was prescribed for the model. All the control cases used the same boundary conditions.

The hydrodynamic model used in this study was based on the measured data form 2015, the positions of the verification points are shown in Fig. 4. It is suggested that the model performed well in simulation of hydrodynamics (Figs. 5 and 6).

## 4 Results

### 4.1 Shoreline and water area

In analyzing the changes in the water area of the estuary, the study area is divided into different parts based on geomorphic features, as shown in Fig. 5. It can be observed that over the past 60 years, the total water area of both the South and North Branches of the Yangtze River Estuary has decreased by 681.83 km$^2$, from 2084.36 km$^2$ to 1402.53 km$^2$. Compared to 1958, there has been a reduction of 32.71% in the overall water area of the Yangtze River Estuary. Specifically, the water area of the North branch has decreased by 414.47 km$^2$, which accounts for approximately 57.7% compared to its size in 1958. The water area of the South branch has decreased from 900.72 km$^2$ to 731.71 km$^2$, representing a decline of approximately18 0.76%. Additionally, within both North Branch and South Branch, there have been reductions in water areas for South Branch Upper section (6 0.3%) and North Branch section (32 0.28%), as detailed in Table 2.

The main reason for the decrease in water area is the impact of human activities, with reclamation projects being the main factor. From 1958 to 2019, due to the influence of reclamation construction, the shoreline at the mouth of the Yangtze River has shown a trend of extending towards inland. Typical river sections include: in Xuliuhu section, river width has narrowed from 10 to 5 km; in the middle section of North Branch, river width has decreased by more than half; and due to Qingcaosha Reservoir construction in North and South Channel section, river width has shrunk by one-third.

### 4.2 Channel volume

Statistical calculations of the riverbed volume below the reference surface were conducted on various sections of the Yangtze River Estuary (YRE), as shown in Fig. 8. The results indicate that, overall, the riverbed volume of the southern branch has increased due to erosion, but at certain stages it may decrease due to sedimentation. In contrast, the Northern Branch has significantly decreased in riverbed volume with periodic fluctuations. Since 1998, there has been a continuous increase in riverbed volume at the South Branch, South Channel and North Channel of YRE; however, there is still a decreasing trend observed at the northern branch.

The volume of the river channel in the Southn Branch increased by $16.21 \times 10^8$ m$^3$, $17.24 \times 10^8$ m$^3$, $16.61 \times 10^8$ m$^3$, and $12.16 \times 10^8$ m$^3$ below the depths of -2m, 0m,

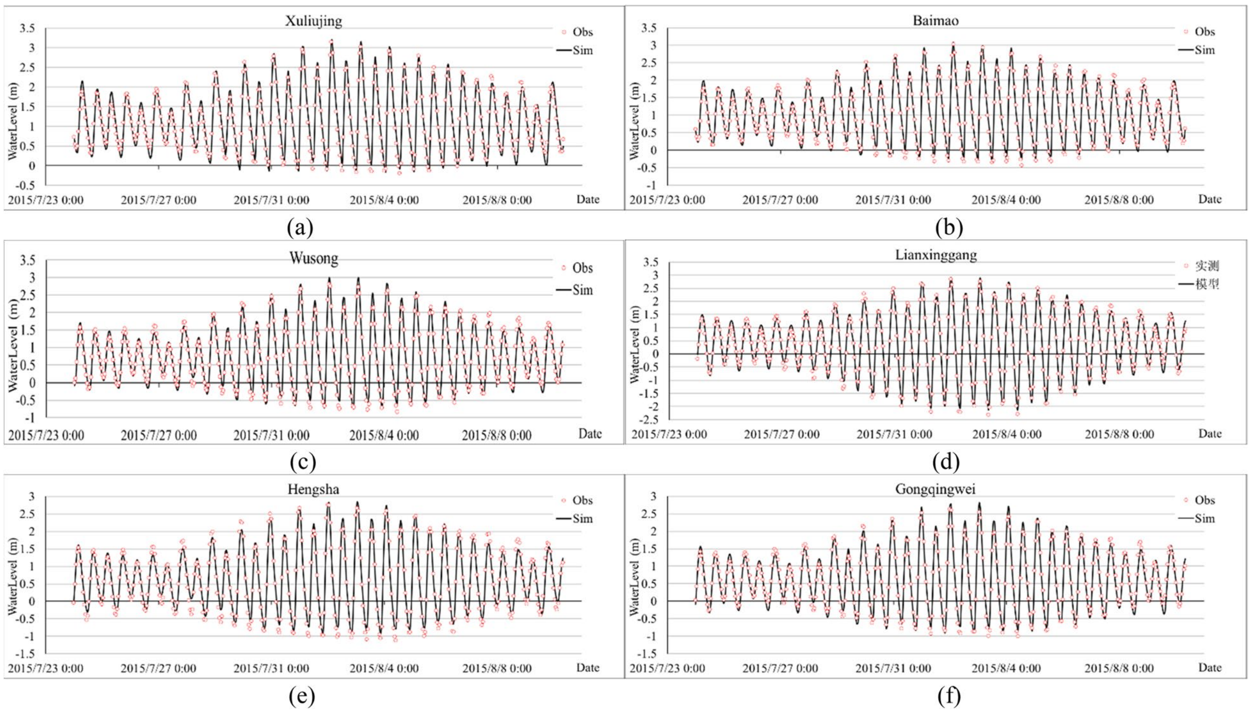


**Fig. 5** Comparison of the measured and simulated water level at YRE, from July 10th to Augest 10.th, 2015

**Table 2** The water area of each reach of YRE at different periods (km$^2$)

| Period | North Branch | South Branch | South Channel | Upper North Channel | Sum |
|---|---|---|---|---|---|
| 1958 | 718.33 | 900.72 | 199.28 | 266.03 | 2084.36 |
| 1973 | 481.05 | 824.6 | 200.05 | 234.67 | 1740.37 |
| 1989 | 443.82 | 804.03 | — | — | — |
| 1998 | 444.63 | 787.8 | 194.93 | 224.57 | 1651.93 |
| 2010 | 303.86 | 735.51 | 186.79 | 180.17 | 1406.33 |
| 2019 | 303.86 | 731.71 | 186.79 | 180.17 | 1402.53 |

-5m, and -10m respectively, with growth rates of 26.4%, 36.8%, 81.7%, and 208.2%. The total volume of the river channel below -2m showed a pattern of alternating acceleration and deceleration in growth rate, with a significant increase from 2016 to 2019 which may be related to a substantial decrease in runoff sediment since 2015. The middle and lower sections of the Southn Branch have shown continuous growth over the period from 1958 to 2019, with increases of $3.22\times10^8$ m$^3$, $5.56\times10^8$ m$^3$,and $7.43\times10^8$ m$^3$ respectively; the largest increase occurred between Liuhekou and Wusongkou section. The increase in volume below -5m and-10m is significantly greater than that in shallower water areas (below-5), indicating that deepening the estuary bed is necessary to compensate for the loss of tidal flow caused by reduced area in order to maintain relatively stable tidal discharge capacity.

The riverbed volume of South Channel at depths of 2m, 0m, -5m, and -10m increased by $4.27\times10^8$ m$^3$, $3.86\times10^8$ m$^3$, $2.09\times10^8$ m$^3$, and $0.52\times10^8$ m$^3$ respectively, with growth rates of 22.7%, 25.0%, 25.0%, and 17.8%. The riverbed volume of North Channel at depths depths of 2m, 0m, -5mand-10mincreased by $5.33\times10^8$ m$^3$, $5.54\times10^8$ m$^3$, $4.17\times10^8$ m$^3$, and $2.06\times10^8$ m$^3$ respectively, resulting in growth rates of 38 0.2%,54 0.3%,107 0.2%,and312 0.1%. Similar to South Branch, in both South Channel and North Channel sections, the increase in riverbed volume at depths below-5mand-10m is significantly greater than that in shallower areas up to -5 m.

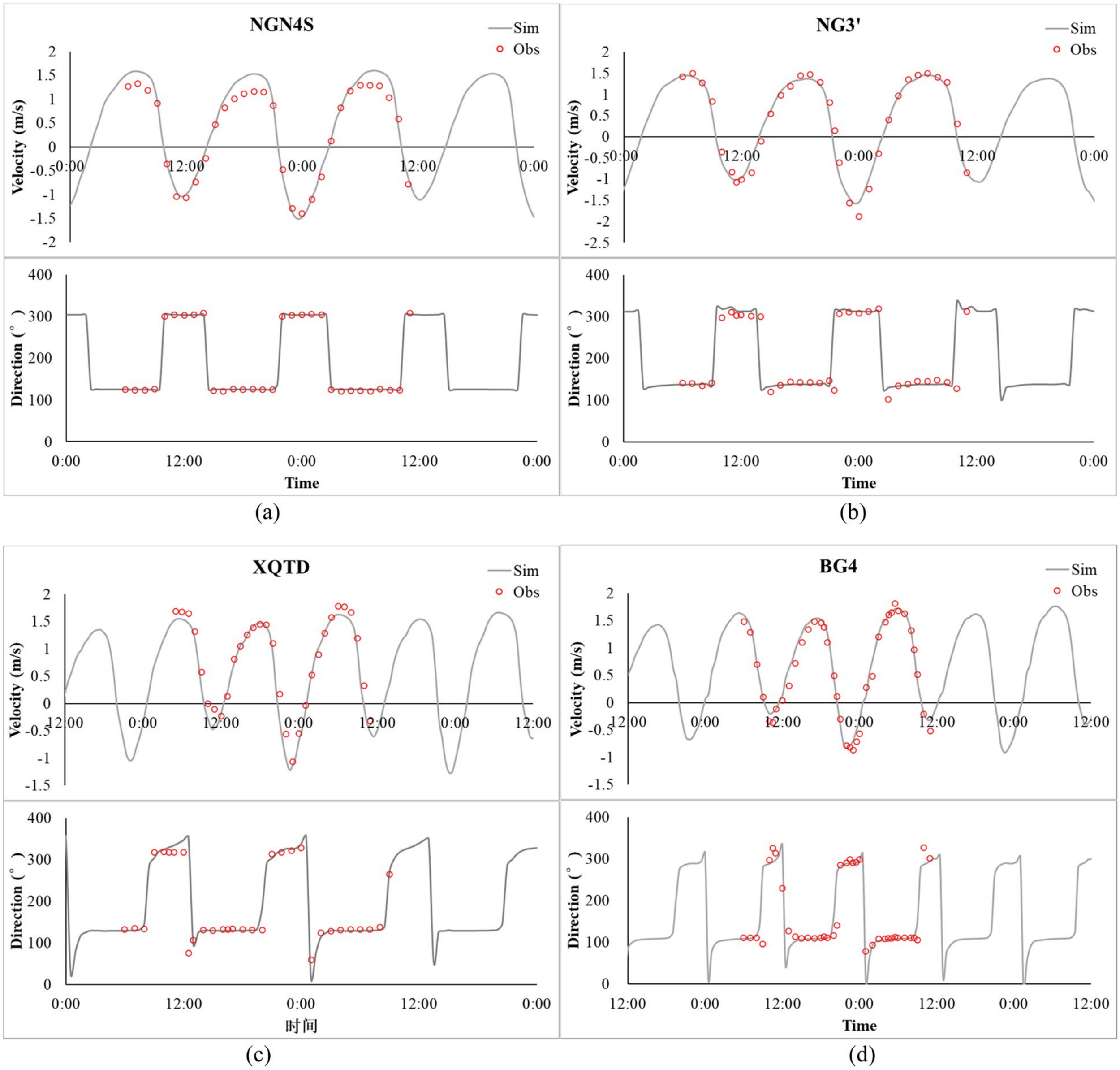


**Fig. 6** Comparison of the measured and simulated current velocity

The volume of the North Branch decreased by $12.76\times10^8$ m$^3$, $7.25\times10^8$ m$^3$, and $0.72\times10^8$ m$^3$ at depths of -2m, 0m, and -5m respectively, with reduction rates of 57.7%, 56.2%, and 66.7%. The decrease in volume below -2m exhibited a pattern of alternating acceleration and deceleration, with the fastest shrinkage rate observed between 1998 and 2010. All sections of the river experienced continuous shrinking trends, with reductions of $0.02\times10^8$ m$^3$, $0.12\times10^8$ m$^3$, $0.08\times10^8$ m$^3$ between 1958 to 2019 respectively. The largest decrease occurred in the middle section between Daxingang Port and Santiaogang Port on the North Branch.

According to the statistical data of river channel volume below 2m and 0m in the South and North Branches (Table 3), due to the gradual increase in the volume of the South Branch, while the volume of the North Branch continues to decrease, the proportion of river channel volume between these two branches is gradually increasing. The volume of river channels below 2 m changed from a ratio of 73:27 in 1958 to a ratio of 88:12 in 2019, while the volume of river channels below 0 m changed from a ratio of 78:22 in 1958 to a ratio of 92:8 in 2019. From 1958 to 2019, the overall volume of river channels below 2 m has increased by 3.45×108 m3,

**Table 3** Channel volume changes of South Branch and North Branch

| Period | Below 2 m / ($\times 10^8 m^3$) | | | | Below 0 m / ($\times 10^8 m^3$) | | | |
|---|---|---|---|---|---|---|---|---|
| | South Branch | North Branch | Sum | South:North | South Branch | North Branch | Sum | South:North |
| 1958 | 61.33 | 22.13 | 83.46 | 73:27 | 46.79 | 12.89 | 59.68 | 78:22 |
| 1973 | 65.99 | 17.83 | 83.82 | 79:21 | 51.37 | 10 | 61.37 | 84:16 |
| 1989 | 63.8 | 18.69 | 82.49 | 77:23 | 49.03 | 10.53 | 59.56 | 82:18 |
| 1998 | 70.07 | 17.35 | 87.42 | 80:20 | 55.77 | 9.31 | 65.08 | 86:14 |
| 2010 | 74.16 | 10.5 | 84.66 | 88:12 | 60.11 | 5.92 | 66.03 | 91:9 |
| 2016 | 74.69 | 10.31 | 85 | 88:12 | 61.64 | 6.34 | 67.98 | 91:9 |
| 2019 | 77.54 | 9.37 | 86.91 | 89:11 | 64.03 | 5.64 | 69.67 | 92:8 |

with a growth rate of about 4.1%, which is significantly different from the significant reduction in water area. This indicates that tidal capacity between the South and North Branches has not weakened.

### 4.3 Erosion and sedimentation

The Fig. 9 shows the changes in sedimentation and erosion of different sections of the Yangtze River estuary from 1958 to 2019. Statistical calculations of the erosion and sedimentation were conducted on various sections of the Yangtze River Estuary (YRE), as shown in Table 4.

From 1958 to 2019, the net erosion volume in the South Branch amounted to $18.13\times10^8 m^3$. The average scouring depth was 2.48m, indicating an overall trend of sediment deposition at the river mouth and channel dredging. Between 1958 and 1998, there were alternating periods of erosion and accumulation in the South Branch. However, since 1998, it has been consistently eroding. As for the north–south waterways of Baimaosha Shoal, the northern channel has been continuously silting up since 1998, while the southern channel is experiencing ongoing erosion.

The riverbeds of both the South and North Channel sections are continuously eroded, with slightly higher erosion intensity observed in the North Channel riverbed. Figure 7 illustrates the planar distribution of erosion and sedimentation in these riverbeds. In the South Channel section, there is deposition in the central area and erosion on both sides, while the North Channel section shows an overall trend of erosion.

The total sediment accumulation in the North Branch of the river is approximately $9.14\times10^8$ $m^3$, with $1.23\times10^8$ $m^3$ in the upper reach, $3.15\times10^8$ $m^3$ in the middle reach, and $4.75\times10^8$ $m^3$ in the lower reach. The average sediment thickness is 3.07m. Since 2010, there has been no significant change in the overall sedimentation trend of this river section, with slight erosion occurring in the upper reaches while continuous deposition takes place in the middle and lower reaches.

### 4.4 Influence of riverbed evolution on tidal dynamic characteristics

To analyze the impact of Yangtze River Estuary channel evolution on tidal hydrodynamic characteristics, six sets of numerical simulations were conducted. The upstream discharge condition for all simulation scenarios was set at 30,000 $m^3/s$, while the downstream water level conditions were kept consistent with those in the validation model. The validation model simulated the period from July 10th to August 10th, 2015 to ensure identical tidal conditions among the six simulation scenarios. The differences between these scenarios lie in variations in terrain data and engineering projects implemented along this river section.

**Table 4** Volume of Erotion and Sedimentation in South Branch and North Branch ("+" sedimentation, "-" erotion, $\times 10^8 m^3$)

| Period | South Branch | North Branch | South Channel | North Channel |
|---|---|---|---|---|
| 1958–1973 | -4.92 | 2.96 | 0.15 | -3.24 |
| 1973–1989 | 2.64 | -0.30 | -0.34 | 0.08 |
| 1989–1998 | -6.52 | 1.30 | | |
| 1998–2010 | -4.66 | 4.94 | -1.93 | -1.88 |
| 2010–2016 | 0.06 | 2.51 | -1.34 | -1.20 |
| 2016–2019 | -2.72 | 1.55 | -0.36 | -1.55 |
| 1958–2019 | -18.13 | 9.14 | -3.88 | -7.43 |

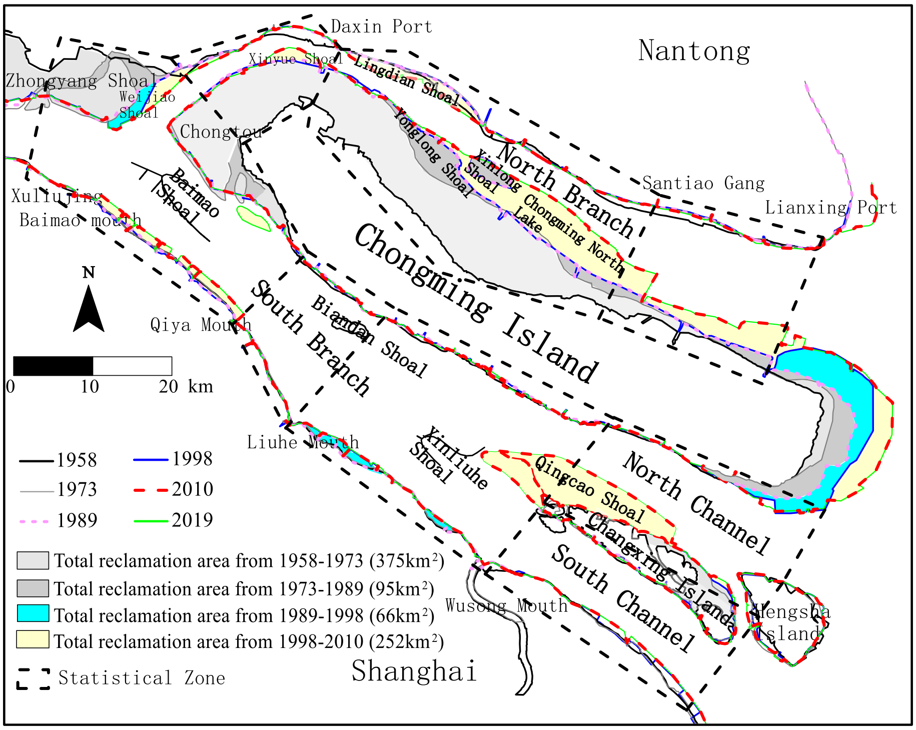


**Fig. 7** Changes in shoreline and water area from 1958 to 2019

The tidal level and tidal range of the Yangtze River Estuary (YRE) have undergone significant changes under different terrain conditions over time (Fig. 8). Since the 1950s, with the continuous reduction of the water area at the mouth of the river, the tidal range at various stations along the YRE has generally increased, while low tide levels have decreased. There are more spatial and temporal factors affecting high tide levels, with an increase in high tide levels in the North Branch and a significant rise above Qiyakou in the South Branch. However, there has been a decrease below Qiyakou.

The changes in the boundary of the Yangtze River estuary channel are closely related to the variations in high tide levels, but overall, the magnitude of change is small. In 2016, compared to 1958, the high tide level at each station did not exceed 0.4 m in South Branch. The North Branch experienced a significant uplift between 1958 and 1973, which was closely related to large-scale reclamation projects during this period. The reduction in the water area of the North Branch resulted in higher tidal levels. After 1973, there was relatively little change in the high tide level, maintaining stability.

The low tidal level and average tidal range of the spring tide show significant spatial and temporal variations. Spatially, from downstream to upstream, the water level gradually increases while the tidal difference decreases. Temporally, as the riverbed evolution, each monitoring station shows a trend of decreasing low tide levels and increasing tidal range. Additionally, the magnitude of change in the North Branch is greater than that in the South Branch. Due to riverbed erosion in the South Branch, flow velocity increases leading to a gradual decrease in low tide water levels. In contrast, due to a gradual decrease in ebb flow diversion ratio in the North Branch, ebb volume continuously decreases resulting in a gradual decrease in water levels.

The tidal prism is the amount of water that flows into and out of an estuary or bay with the flood and ebb of the tide. Normally, the calculation formula reads as follows (Petti et al. 2021):

$$P = \Delta HS = \frac{1}{2}(S_1 + S_2)(h_1 - h_2) \tag{1}$$

where $P$ is the tidal prism ($m^3$), $\Delta H$ is the average tidal range, $S$ is the average water area, $h_1$ and $h_2$ are the average high and low tide levels per tidal cycle, $S_1$ and $S_2$ are the water area corresponding to the average high and low tide levels.

The tidal prism refers to the volume of water entering and exiting a river mouth or bay with the ebb and flow of tides, calculated by the following formula (Li and Shen 2017) (4) where P represents the tidal prism ($m^3$), ΔH is the average tidal range, S is the average water area, $h_1$ and $h_2$ are respectively the average high tide level and low tide

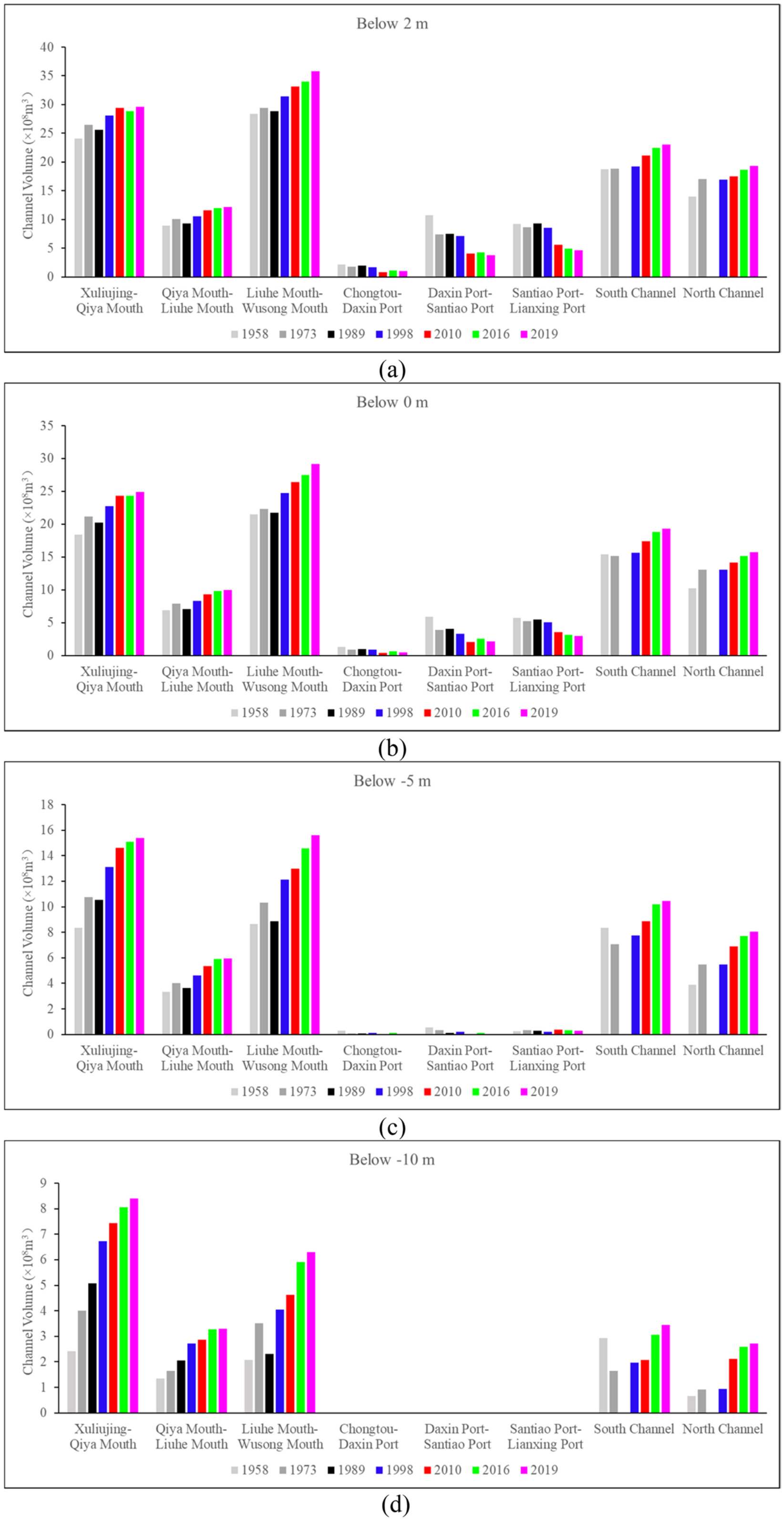


**Fig. 8** Variations of channel volume (**a**) below 2m (**b**) below 0m (**c**) below -5m (**d**) below -10m

level within each tidal cycle, and $S_1$ and $S_2$ correspond to the water areas at mean high tide and mean low tide levels.

According to "Shoreline and water area" section, the South and North Branche of the river are divided into upper, middle, and lower sections as shown in Fig. 9. The tidal prism for each region under different terrains is calculated separately. The results are presented in Fig. 10. In the statistical area, the total tidal volume at the mouth of the Yangtze River decreased from $35.65\times10^8$ $m^3$ to $32.52\times10^8$ $m^3$, representing an 8.8% reduction in tidal volume overall. The distribution of tidal prisms varies slightly across different regions due to changes in terrain.

Specifically, the tidal prism for the Southern Branch increased by $0.435\times10^8$ $m^3$, which represents a growth of approximately 2.05% compared to that in 1958. Before 1998, there were slight variations in tidal prisms for different sections of the North Branch with a total increase of 5.6%. However, between 1998 and 2010, the construction project on the middle section of the North Branch resulted in a significant narrowing of the river width and led to a notable decrease in the tidal prism for

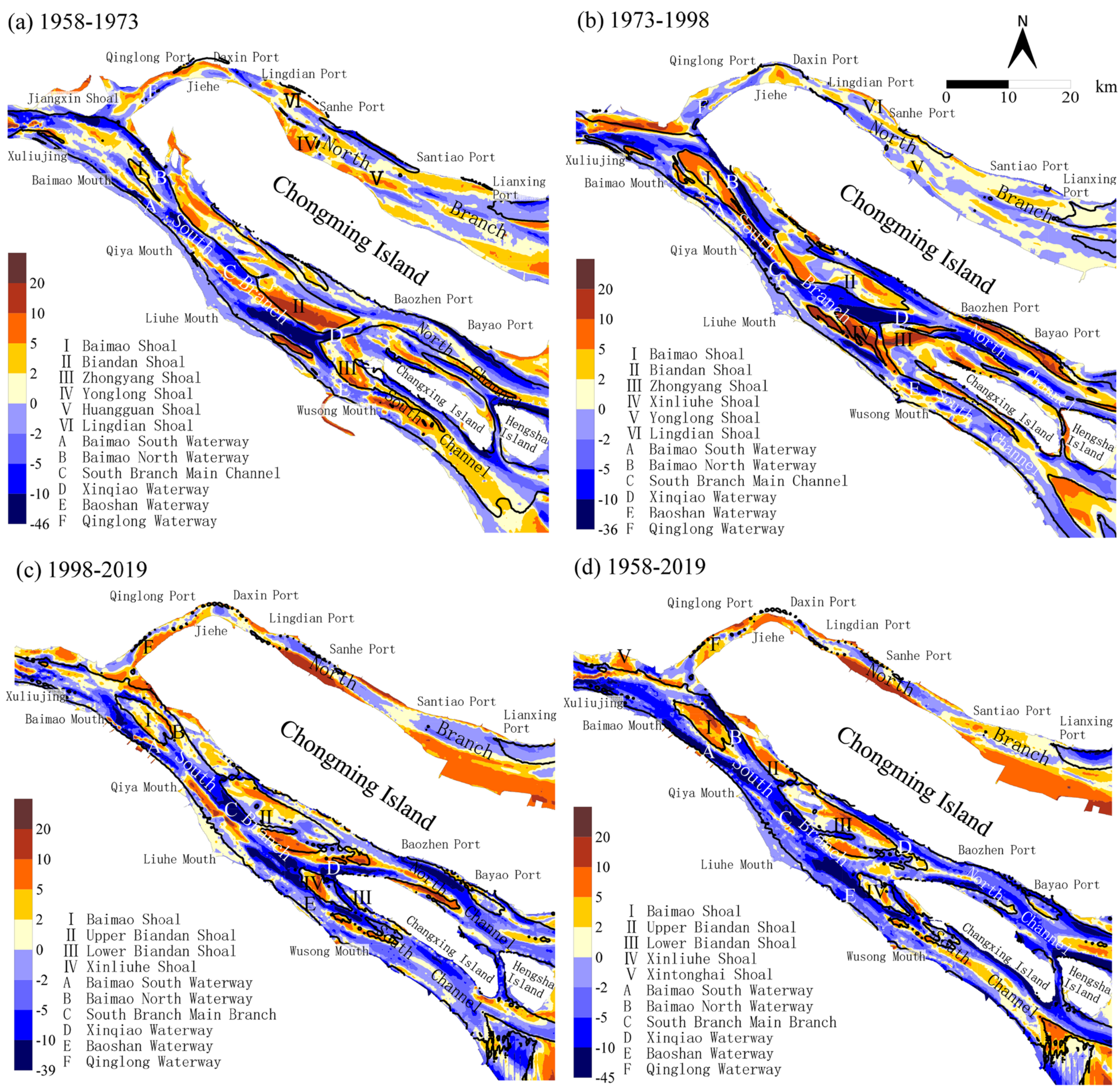


**Fig. 9** Changes of riverbed erosion and sedimentation from 1958 to 2019

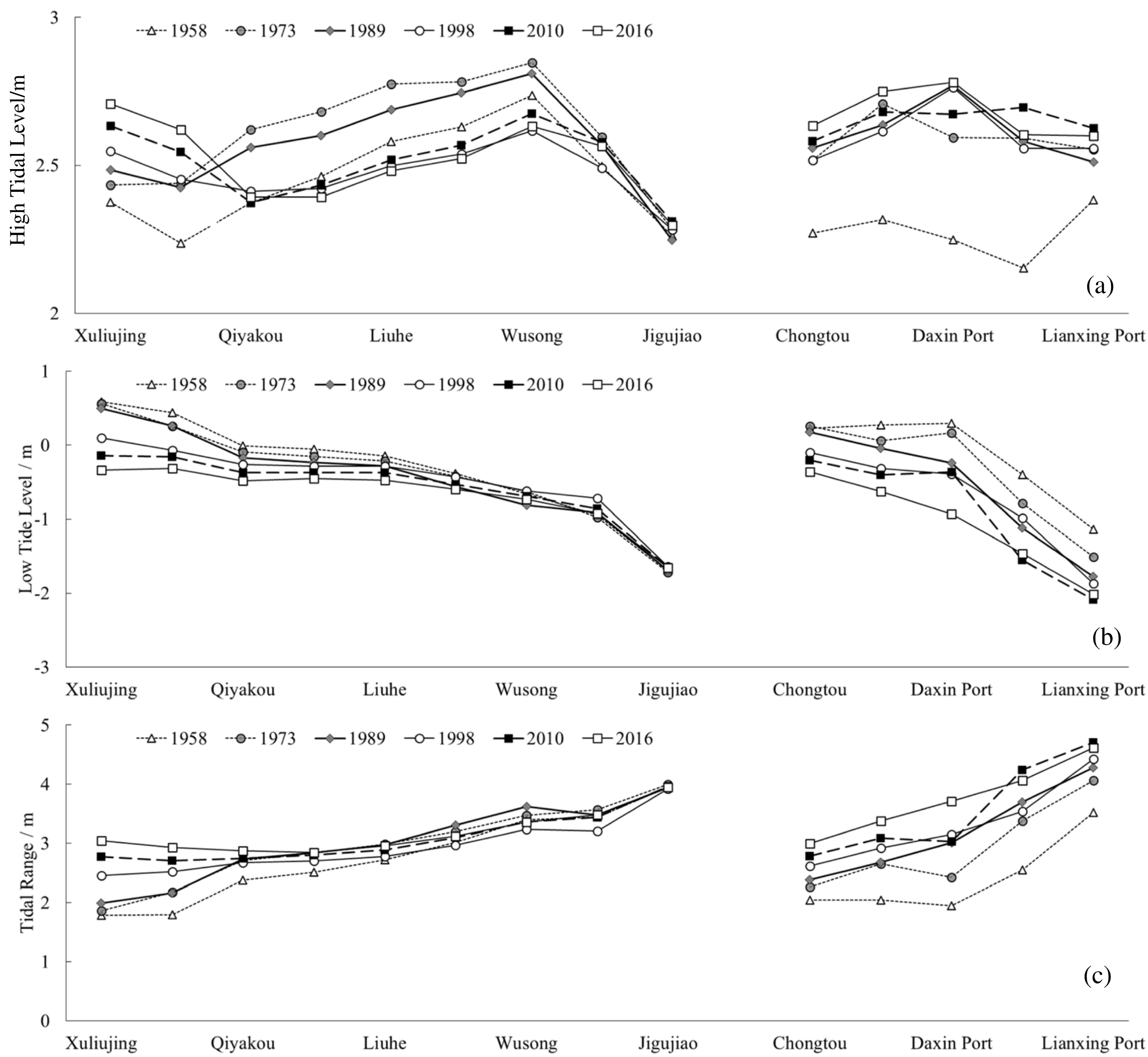


**Fig. 10** Tidal dynamics variation of all scenarios: (**a**) High tidal level (**b**) Low tidal level (**c**) Tidal range

the North Branch. In 2010, the tidal prism for the North Branch decreased by 4 $0.84\times10^8$ $m^3$ compared to 1998, representing a reduction of 31.6% (Figs. 11 and 12).

## 5 Conclusion

From 1958 to 2019, driven by intense human activities, the total water area of the Yangtze River Estuary decreased from 2084.36 $km^2$ to 1402.53 $km^2$, representing a reduction of 32.71%. However, the corresponding river channel volume experienced a relatively small change and remained largely stable. In comparison to 1958, it only increased by approximately $3.45\times10^8 m^3$ in 2019, which accounts for an approximate growth of about 4.1%. In the past 70 years, the tidal volume at the mouth of the Yangtze River in the area has decreased by 8%.

The changes in tidal dynamics at the mouth of the Yangtze River Estuary are closely related to the evolution of its distributary channels, shaping both the estuarine geomorphology and being influenced by channel evolution. Tidal level, tidal range, and water area show a close response. As the water area at the mouth of the Yangtze River decreases, tidal range tends to increase and tidal dynamics strengthen. The variation in sediment discharge is closely related to channel capacity. Under natural erosion and deposition conditions, there is only a small change in sediment discharge along different

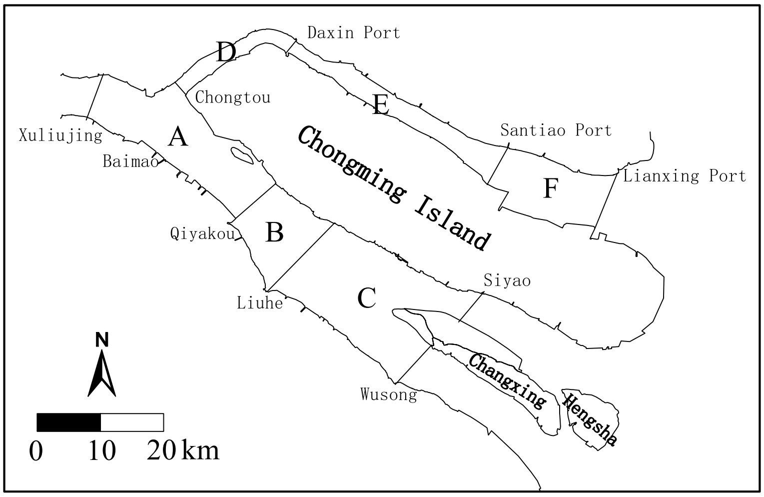


**Fig. 11** Statistical scope of tidal prisms at YRE (**A**, **B**, **C** represent the upper, middle, and lower sections of South Branch, while D, E, F represent the upper, middle, and lower sections of North Branch)

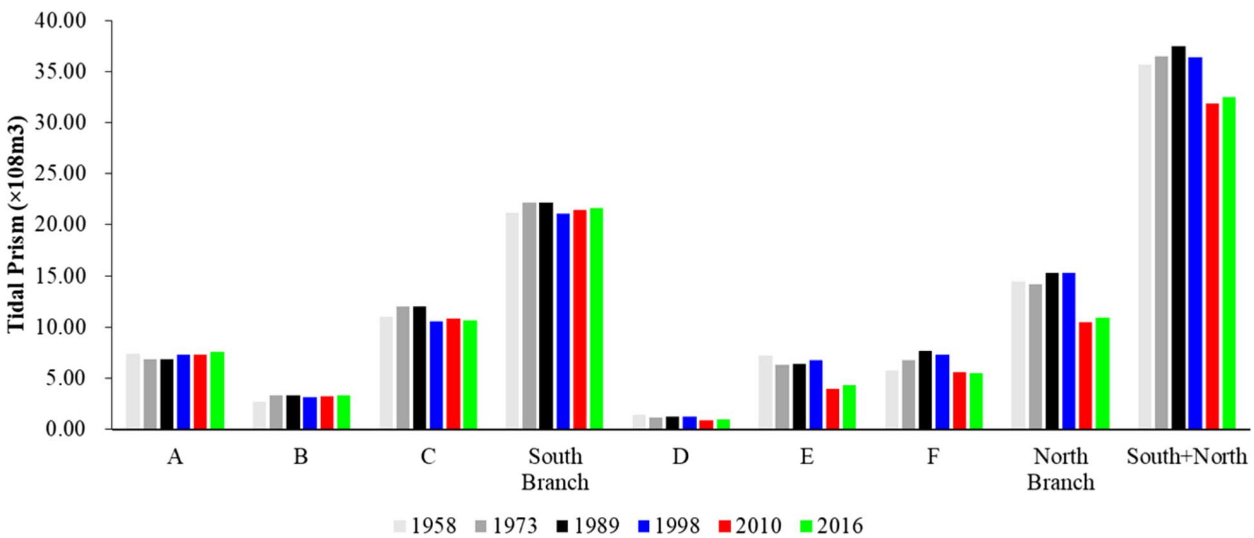


**Fig. 12** Tidal prism of all scenarios (× $10^8$ m.$^3$)

river sections over 60 years for the South Branch (with an increase of only 2.05%). However, due to construction activities on the narrow middle branch, both flood tide volume and ebb tide volume have significantly decreased with a reduction in sediment discharge by 31.6% from 1998–2010 for the North Branch.

In the past 60 years, due to a decrease in water area, the Yangtze River estuary has either maintained its health or declined, which gives us valuable insights. In the North Branch, there has been a 58% reduction in water area and it is gradually declining, while in the South Branch, although there is a decrease of 14% in water area, tidal volume remains relatively stable. In future development and management of the estuary, it is important to control land reclamation areas and provide sufficient space for tidal movement to maintain a healthy development of the river mouth.

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Not applicable.

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**Availability of data and materials**
A statement on how any datasets used can be accessed.
Not applicable.

## Declarations

**Competing interests**
Always applicable and includes interests of a financial or personal nature.
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