Exchange Mechanism of the Suspended Sediment at the Mouth of Hangzhou Bay under Coastline Changes

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Abstract. Based on FVCOM hydrodynamic numerical model and coastline topographic data in 2013, a three-dimensional numerical model of fine sediment transport in Hangzhou Bay has been established to explore the water and sediment exchange mechanism between Hangzhou Bay and the open sea at different typical sections. The results of validation with measured and satellite retrieved data show that the model can well simulate the process of water and sediment movement in Hangzhou Bay. Compared with the calculation results of the coastline topographic data of Hangzhou Bay in 1974 and 2020, the influence mechanism of shoreline change on the water and sediment exchange mechanism between Hangzhou Bay and the open sea has been studied. The results show that the sediment transport inside and outside the Hangzhou Bay is generally in the pattern of north-inflow and south-discharge. Compared with the coastline in 1974, the sediment transport from Yangshan port in the north of Hangzhou Bay and Zhoushan Islands in the middle of Hangzhou Bay increases when the coastline is pushed into the bay in 2020, while the outward sediment transport from Jintang Channel in the South decreases. The overall trend features that the sediment transport into the bay increases, with the bay mouth silting. In the three sections extending from Hangzhou Bay to the open sea, the inflowing water and sediment of the horizontal section on the north side is decreasing, while the discharged sediment from the south side and the inflowing water and discharged sediment from the vertical section at the east side are increasing.

1 Preface

Located in the north of Zhejiang Province, Hangzhou Bay is a famous strong tidal estuary with large tidal range, rapid tidal current and high suspended sediment concentration.^[1] In the north, it meets with the south of the Yangtze River; in the middle, it connects with the East China Sea through the waterways among Yangshan, Qushan, Daishan and Zhoushan Islands; in the south, it exchanges water and sediment with the open sea through Jintang waterway. Both sides of Hangzhou Bay are one of the most developed areas in China, with active and concentrated human activities, especially coastal land reclamations. The data of Zhang^[2] shows that in recent 30 years, the coastal land formation of Hangzhou Bay is 694.4km², and the land building speed is on the rise. Under the comprehensive action of various natural and human factors, the shorelines of both sides of Hangzhou Bay gradually move towards the sea area. Through the analysis of remote sensing photos, Li^[3] concluded that from 1974 to 2016, the coastline at Cao'e River Estuary in Hangzhou Bay advanced 15 km to the water area, with Jianshan coastline of nearly 7 km. The southern coastline of Hangzhou Bay is about 7 km to the water area and the coastline at Nanhui between Hangzhou Bay and Yangtze River Estuary has been broadened about 10 km.

The change of coastline will inevitably affect the tidal dynamic process, water and sediment transport process and terrain evolution in Hangzhou Bay. Guo^[4] used FVCOM to simulate the influence of reclamation project in Hangzhou Bay on storm surge caused by typhoon during 1981-2005. Lu^[5] used FVCOM to simulate the significant changes of hydrodynamic field in the South Bank of Hangzhou Bay under three different shoreline backgrounds in 1984, 2010 and 2020. Shao^[6] analyzed the influence and mechanism of shoreline change on the internal hydrodynamic process of Hangzhou Bay from 1962 to 2015 through FVCOM. However, there are few studies to analyze the influence of shoreline changes from the perspective of sediment exchange mechanism between Hangzhou Bay and the open sea.

It is of great practical significance to study the sediment exchange system of Hangzhou Bay and the open sea for the evolution of topography and beach erosion and deposition. In the last century, Cao^[7] made a preliminary analysis on the source and transport of sediment in Hangzhou Bay, and concluded that the sediment in Hangzhou Bay is mainly from the Yangtze River Estuary, and the sediment movement is mainly in the form of large inflow and large outflow and repeated transportation. Liu^[8] analyzed the sedimentary structure and sedimentary environment of Hangzhou Bay, and considered that there

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is a sediment transport route from north to south in Hangzhou Bay. Since the 21st century, many scholars have analyzed the mechanism of water and sediment exchange in the cross section of Hangzhou Bay and the open sea based on the measured water and sediment data. Zhang^[9] analyzed the water and sediment transport characteristics of the water area and the open sea based on the synchronous observation data of water and sediment at five stations in the northern sea area of Hangzhou Bay Estuary in September 2010. Based on the observation data of velocity and suspended sediment concentration in the sea area outside the central part of the mouth gate of Hangzhou Bay in September 2012, using the method of mechanism decomposition, Song^[10] calculated the characteristics of water and sediment transport flux in the Daiqu ocean and the open sea. Li^[11] analyzed the synchronous observation data of velocity and suspended sediment concentration at ten stations in Jintang waterway in autumn of 1986 and spring of 1987, and concluded that suspended sediment was exported to the open sea in the channels of spring, middle and neap tides (except the middle tide in 1986).

However, the analysis of the sediment exchange mechanism in Hangzhou Bay and the open sea by using the observed data has great limitations both in time and space. If we want to analyze the water and sediment exchange mechanism on the whole cross-section of the intersection of Hangzhou Bay and the open sea by means of field measurement, and explore its response process under the cumulative effect of shoreline changes in decades, it requires high human and material resources. Moreover, the earlier the year, the more difficult it is to obtain the measured data, which is not conducive to the comprehensive study of sediment exchange between Hangzhou Bay and the open sea. With the development of computer technology, the application of numerical simulation technology is more and more extensive. Wu^[12] established a three-dimensional tidal current and sediment numerical model of Hangzhou Bay based on FVCOM, and initially carried out sediment simulation calculation. However, due to the limitations of the model itself, the sediment calculation results are still not very ideal. Feng^[13] established a plane two-dimensional tidal current and sediment mathematical model focusing on the study area of Luotou waterway in Zhoushan, and the simulation results were verified well with the measured data. However, the distribution characteristics of tidal current and sediment along the water depth given by the two-dimensional model are not suitable for the area with large water depth at the intersection of Hangzhou Bay and the outer sea, and cannot accurately reflect the sediment exchange mechanism between Hangzhou Bay and the open sea.

Based on FVCOM hydrodynamic numerical model, in this paper, the author considers the influence of suspended sediment concentration on water density and bottom boundary layer, and established a three-dimensional numerical model of fine sediment in Hangzhou Bay by introducing flocculation sedimentation formula. In order to study the influence of shoreline change on water and sediment transport characteristics in Hangzhou Bay, the

coastline data of Hangzhou Bay in 1974, 2013 and 2020 were collected (Figure 1). Firstly, the characteristics of water and sediment transport in the whole cross-section of the intersection of Hangzhou Bay and the open sea in 2013 are analyzed systematically. On this basis, the influence of shoreline changes on the water and sediment exchange mechanism between Hangzhou Bay and the open sea from 1974 to 2020 and its mechanism are studied, which provides reference for the planning and utilization of coastal tidal flats, and has certain scientific and engineering significance.

2 Three-Dimensional Numerical Model of Suspended Sediment

2.1 Model Introduction

Based on the unstructured grid finite volume method ocean numerical model FVCOM^[14], the model is partially modified in combination with the sediment characteristics of Hangzhou Bay. At the free surface, the net sediment concentration flux is zero; at the bottom boundary, the net sediment concentration flux is the difference between the resuspension flux and the sediment flux. The resuspension model is calculated by the formula proposed by Van Prooijen^[15]. The sediment flux is taken as the product of sediment concentration and sedimentation velocity at the bottom layer. Considering the great influence of suspended sediment concentration on the vertical distribution of density in Hangzhou Bay, the formula proposed by Winterwerp^[16] is used to calculate the water density, and the effect of suspended sediment concentration on water density is considered. The Richardson number^[17] of the turbulent closure equation is introduced into the calculation formula of the bottom friction coefficient, and the influence of suspended sediment concentration on the bottom boundary layer is considered. The settling velocity is calculated by using the settling velocity formula of suspended sediment flocculation proposed by Cao^[18].

The diffusion equation of suspended sediment concentration in the model is as follows:

$$\frac{\partial C}{\partial t} + \frac{\partial(uC)}{\partial x} + \frac{\partial(vC)}{\partial y} + \frac{\partial[(w-w_s)C]}{\partial z} = \frac{\partial}{\partial x} \left(A_H \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_h \frac{\partial C}{\partial z} \right) \quad (1)$$

Among them, x , y and z are the three-dimensional coordinates in the rectangular coordinate system, which are the east-west, north-south and vertical coordinates respectively; u , v , w are the velocity components in the x , y , z directions respectively. C is the sediment concentration. w_s is the sedimentation velocity of sediment, and downward is positive. A_H and K_h are horizontal diffusion coefficient and vertical diffusion coefficient respectively.

2.2 Model Setting

The sea area calculated in this paper is 117.5° -122.5°E, 37°-41°N (Figure 1). The minimum resolution of the model is about 100 m and the maximum resolution is about 30 km. There are 11 non-uniform σ layers in the vertical direction. The external mode time step is 0.5 s, and the internal mode time step is 5 s. The model adopts cold start mode, and the initial velocity, tide level and suspended sediment concentration are 0. Considering the influence of tidal current and runoff, only cohesive sediment is considered. Specific data sources and parameter selection can be found in the researches of Ye^[19].

Fig.1 Model grid and water depth

2.3 Working Condition Design

In order to study the influence of shoreline change on the characteristics of water and sediment exchange between the Hangzhou Bay Estuary and the open sea, the coastline data of Hangzhou Bay in 1974, 2013 and 2020 were collected (Figure 4). The coastline data of 1974 and 2013 are from Landsat satellite images. In 2020, the coastline comes from the sea use plan of marine functional zoning in Zhejiang Province.

The design of numerical experiment condition is shown in Table 1. The simulation time of condition 1 is from February 20, 2013 to April 1, 2013. The data of tide level, tidal current and suspended sediment concentration in March are selected to verify the model, and the water-and-sediment exchange mechanism at the intersections of Hangzhou Bay and Waihaikou has been analyzed. Based on the shoreline of 1974 (No.2) and 2020 (No.3), the influence of shoreline change on the characteristics of water and sediment exchange between Hangzhou Bay Estuary and the open sea during 1974-2020 is compared and analyzed.

Table.1 Experimental conditions setting

No.	Year	Grids	Nodes	Purpose
1	2013	114211	60441	model validation, analysis of water and sediment exchange mechanism
2	1974	127734	67322	analysis of the impact of shoreline changes
3	2020	112015	59306	analysis of the impact of shoreline changes

2.4 Model Validation

The accuracy of the model was evaluated by correlation coefficient (CC) and model evaluation coefficient (SS)^[20]

$$CC = \frac{1}{N} \sum_{i=1}^N \frac{(m_i - \bar{m})(O_i - \bar{O})}{S_m S_o} \quad (2)$$

$$SS = 1 - \frac{\sum_{i=1}^N (m_i - O_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (3)$$

Where, m_i and O_i are the calculated values of the model and the observed values; m and O are the average values of the calculated and observed values respectively. S_m and S_o are the standard deviations of calculated and observed values respectively. The closer the correlation coefficient is to 1, the greater the correlation between the simulated value and the measured value; when the evaluation coefficient of the model is greater than 0.2, the model has certain credibility; when the evaluation coefficient of the model is greater than 0.5, the model has a higher reliability^[21].

The measured data of tide level are from three tide stations (LCG, ZP and YG, blue points in Figure 4), and the data period is from March 1 to March 15, 2013. The results of tidal level verification are shown in Table 2. SS of Luchaogang and Zhapu is above 0.97, and CC is higher than 0.96. The SS and CC of Yanguan station are relatively low, which are 0.84 and 0.70 respectively. The main reason is that the station is located in the upper reaches of Qiantang River Estuary and is easily affected by tidal bore. On the whole, the fitting degree of tide level verification is high, which can accurately reflect the spatial and temporal distribution characteristics of actual tide level.

Table.2 Verification of tide level

Criteria	SS			CC		
Points	LCG	ZP	YG	LCG	ZP	YG
Values	0.97	0.97	0.84	0.97	0.96	0.70

The data of tidal current and suspended sediment concentration are from two stations in Zhapu water area (red dots N1 and N2 in Figure 4). The data period is from 12:00 on March 6, 2013 to 16:00 on the next day in neap tide, and from 8:00 to 9:00 on March 12, 2013 in spring tide. The verification results of current velocity and direction at each layer of N1 and N2 are good, and the corresponding average error of the two stations is shown in Table 3. During neap tide, the correlation coefficient CC and model evaluation coefficient SS of N1 and N2 are greater than 0.9, the minimum CC of current direction is 0.78, SS is greater than 0.84. During spring tide, the minimum SS is 0.82, the minimum CC is 0.75, the minimum SS is 0.84, and the minimum CC is 0.66. Therefore, the results of this model can provide reliable data for the study and analysis of current characteristics.

Table.3 Error analysis of current velocity and direction

Tide condition	Position	CC		SS	
		Velocity	Direction	Velocity	Direction

Neap tide	surface	0.99	0.92	0.83	0.83
	middle	0.98	0.94	0.82	0.87
	bottom	0.97	0.85	0.85	0.70
Spring tide	surface	0.96	0.94	0.85	0.87
	middle	0.95	0.86	0.83	0.72
	bottom	0.92	0.89	0.85	0.75

The verification results of layered suspended sediment concentration(SSC) at N1 and N2 can accurately reflect the variation of SSC with time (Figure 2), and also better reflect the vertical variation of SSC. During neap tide, the CC of SSC in the middle layer and bottom layer of N1 is 0.52 and 0.80 respectively, and the SS is 0.24 and 0.59 respectively, and the error of surface verification results is slightly larger. In spring tide, the CC of SSC in surface, middle and bottom at N2 were 0.63, 0.77 and 0.68, respectively, and the corresponding SS were 0.34, 0.51 and 0.27, respectively. Therefore, the correlation between the calculated value and the measured value is high, and the credibility is general.

In order to further verify the accuracy of the model, the surface SSC calculated by the model was compared with the SSC measurement points selected on Goci satellite image (Figure 3). The results show that the variation trend and magnitude of SSC at each point are consistent with the remote sensing inversion value, so the suspended sediment model has high accuracy in the large area sea area of Hangzhou Bay.

Fig.2 Verification of SSC

Fig.3 Verification of SSC in surface

3 Research Methods

3.1 Selection of Typical Section and Analysis Period

In order to quantitatively estimate the sediment exchange fluxes between the Hangzhou Bay Estuary and the open sea, 10 sections are set up to calculate the tidal and sediment fluxes. The cross-section layout is shown in Figure 4. In order to reduce the uncertainty of the rising and falling tide periods in a single day cycle, the daily average water and sediment flux of 10 sections were calculated and analyzed by selecting three days (six semi-diurnal tides) of spring tide and spring tide in March 2013. The S1 section starts at Nanhuizui of the Yangtze River Estuary and ends at Wuguijiao, a rugged archipelago of Yangshan Harbor. The length of the section is about 26.1km, which is used to calculate the water and sediment exchange between Hangzhou Bay and the Yangtze River Estuary. S2 section is located at the entrance of the narrow sea area between Dayangshan and Xiaoyangshan, with a length of about 6.83km. Section S3 connects the sea area of Yangshan Port and Daishan, with a section length of about 32.6km; section S4 connects Daishan and Zhoushan Island, with a section length of about 16.4km; section S5 connects Zhoushan Island and Jintang, with a section length of about 15.6km. The three sections are used to analyze the water and sediment exchange characteristics between the middle part of the mouth of Hangzhou Bay and the open sea, and explore the influence of multi island topography on the sediment exchange mechanism between Hangzhou Bay and the open sea Ring. Section S6 connects Jintang and Ningbo, with a section length of 13.4 km. It is used to analyze the characteristics of water and sediment exchange between Hangzhou Bay and the open sea through Jintang waterway. S7, S8 and S9 are the north, East and South sections of Hangzhou Bay. Through these three sections, we can intuitively analyze the water and sediment exchange mechanism between the open sea and the Bay as a whole. S10 is a part of the section which has been reduced since 1974 due to the change of shoreline.

Fig. 4 Variation of coastline and distribution of measuring points and sections in Hangzhou Bay

3.2 Calculation of Tidal Flux Per Unit Width

The residual flux of a single width water body is used to characterize the water transport characteristics. Previous studies have shown that the residual flux can better reflect the material transport than the residual flow. The residual flux of single width water body is the water flux per unit length along the vertical integral in a period of time. The calculation formula is as follows:

$$F = \frac{1}{T} \int_0^T \int_{-H}^{\eta} \vec{V}_n(x, y, z, t) dz dt \quad (4)$$

Where: η is the water level, H is the water depth, L is the length of the section, $\vec{V}_n$ is the normal velocity of the section, and T is the statistical time.

3.3 Calculation of Sediment Flux Per Unit Width

The sediment flux per unit width is the sediment flux per unit length integrated vertically in a period of time. The calculation formula is as follows:

$$F = \frac{1}{T} \int_0^T \int_{-H}^{\eta} C(x, y, z, t) \vec{V}_n(x, y, z, t) dz dt \quad (5)$$

Where: C is the SSC (kg/m³), and other variables are the same as formula 4.

3.4 Calculation of Tidal Flux and Dominant Tidal Current in Sections

The flood and ebb of the cross-section are the flood and ebb flows through a certain section in a period of time. The calculation formula is as follows:

$$Q_{f(e)} = \int_0^T \int_{-H}^{\eta} \int_0^L \vec{V}_n(x, y, z, t) dldzdt \quad (6)$$

Where: T is the duration of flood tide or ebb tide, and the other variables are the same as formula 4.

The dominant tidal volume is the ratio of ebb to the sum of ebb and ebb. The dominant tidal volume can be used as the relationship between the dynamic strength of ebb and ebb in the sea area. The calculation formula is as follows:

$$R_Q = \frac{Q_e}{Q_e + Q_f} \times 100\% \quad (7)$$

If R_Q is greater than 50%, ebb tide is the dominant current, otherwise, flood tide is the dominant current [22] [23].

3.5 Calculation of Sediment Flux and Dominant Sediment in Sections

As with the ebb and flow tides, the sediment discharge of the flood tide G_f and the ebb tide G_e in a period of time can be obtained by statistical analysis of the sediment discharge in the period of flood and ebb tide respectively.

$$G_{f(e)} = \int_0^T \int_{-H}^{\eta} \int_0^L C(x, y, z, t) \vec{V}_n(x, y, z, t) dldzdt \quad (8)$$

Among them, all variables are the same as formula 4 and equation 5.

The percentage of dominant sediment is divided by the sum of sediment discharge in ebb tide and ebb tide.

$$R_s = \frac{G_e}{G_e + G_f} \times 100\% \quad (9)$$

If R_s is greater than 50%, it is the dominant sediment of ebb tide, otherwise, it is the dominant sediment of flood tide [22] [23].

4 Results and Discussion

Based on the statistics of tidal fluxes and sediment transport during spring and neap tides, and the dominant tidal volume and dominant sediment representing the relative strength of the rising and falling tides, this paper analyzes the changes of hydrodynamic and sediment transport in typical cross-sections, and analyzes the influence of shoreline changes caused by tidal flat reclamation on the water and sediment exchange mechanism between Hangzhou Bay and the open sea. In this paper, only the calculation of the longitudinal flux of water and sediment in each section is taken into account. It is stipulated that the transport to the bay is positive and negative to the outside.

4.1 Characteristics of Water and Sediment Flux

For section S1 to S9, the water is transported from flood tide to bay and from ebb tide to bay.

From section S1 to section S6, the flow velocity of flood tide is greater than that of ebb tide, but the duration of flood tide is shorter than that of ebb tide, so the direction of net tidal flux of each section is not consistent. Generally speaking, during neap tides, all sections except S2 and S6 show that the net tidal volume points to the open sea, and the rising tide is dominant. Since S2 and S6 sections are located on the left side of the narrow channel, while the right side is narrow, the net tidal fluxes at S2 and S6 are always in the ebb direction. From neap tide to spring tide, with the increase of velocity, the amount of rising and falling tide increases. Due to the increase of ebb current

velocity and the decrease of flood duration, the advantage of ebb tide in each section is gradually enhanced. Due to the difference in the increase of the fluctuation tidal volume in different sections, except for S3, the rest sections are converted to ebb tide.

It can be seen from S7 to S9 that S7 and S8 are the channels for water delivery to the Bay. S9 section is the main channel of water delivery to the Bay, which has a pattern of north-and-east inflow and south discharge.

The suspended sediment transport direction of each section during spring and neap tides is consistent with that of tidal flux. This is because the velocity of the ebb and flow is large during the spring and neap tides, and the sediment transport mainly depends on the advection caused by the Euler residual current. In addition, under the background of higher flow velocity during spring tide, the transport effect of current on sediment is enhanced, and the concentration of suspended sediment in water body increases, resulting in the sediment transport volume of ebb and flow tide during spring tide is 5 to 10 times of that in ebb tide.

According to the net sediment discharge of each section, the sediment exchange between Hangzhou Bay and the open sea is more active in the north of Hangzhou Bay. However, in the Daiquyang sea area in the middle of Hangzhou Bay, the sediment exchange between Hangzhou Bay and the open sea is less, and the sediment transport presents a relatively balanced situation. To the Jintang sea area in the south of Hangzhou Bay, part of the sediment is transported from the sea area to the open sea.

Among them, the sea area between Nanhuizui and rugged Islands (S1) and the sea area between Yangshan Port and Daishan (S3) are the main channels for sediment to enter Hangzhou Bay. The sea area is dominated by flood tide during spring and neap tides, and the net sediment discharge points to the bay. The average daily net sediment transport of the two sections is 12.643×10^6 tons during spring tide and 1.88×10^6 tons in neap tide. The contribution rate of S1 is 40.69%, and that of S3 is 59.31%. Although the port area (S2) between Dayangshan and Xiaoyangshan is located in the north of Hangzhou Bay, it is one of the main channels for the suspended sediment to export to the sea. During the spring and neap tides, the net sediment discharge to the sea reaches 2.3×10^6 million tons. According to the study on water and sediment flux of key section of Yangshan Port observed by Ying^[24] through ADCP and OBS, this section is also the main channel for sediment to enter Yangshan port area. After that, the sediment is transported to the open sea through the branches between Shuanglianshan and Dashantang, Dashantang and Dayangshan, and between Jiuzhushan and Jianggongzhu.

The sea area between Daishan island and Zhoushan Island (S4) and the sea area between Zhoushan Island and Jintang (S5) during spring and neap tides are dominated by flood tide, and the net sediment discharge points to the bay. The sediment transport at these two sections is small, which reflects the restriction of archipelago topography on water and sediment transport.

S6 connects Jintang and Ningbo. During spring and neap tides, the section is dominated by ebb tide, and the

sediment enters Jintang waterway through this section and transports suspended sediment to the sea. This conclusion is consistent with the results obtained by Li^[11] through the analysis of synchronous observation data of velocity and SSC. The cross-section is also one of the main channels of suspended sediment export to the sea in Hangzhou Bay. During the spring and neap tides, the net sediment discharge to the sea reaches 4.26×10^6 tons.

Through comparative analysis of the sections from S7 to S9, it can be seen that the water and sediment in Hangzhou Bay mainly come from the north section, that is, the intersection with the Yangtze River Estuary. The south side of Hangzhou Bay is the main channel to transport water and sediment from the bay to the open sea. In a period of rising and falling tide, the exchange of water and sediment between the open sea and the east side of Hangzhou Bay is small and relatively balanced.

According to the above analysis, the sediment transport in the mouth of Hangzhou Bay is generally in the north and out in the south. The sediment in the Yangtze River Estuary enters the bay through the sea areas on both sides of Yangshan port, and most of the sediment is transported out of the bay through the west entrance of Yangshan port. The rest of the sediment is transported back and forth with the rising and falling tide in the bay. Finally, the sediment mainly moves to the south of Hangzhou Bay, to the outside of the bay, and to the direction of current transportation bring into correspondence with. In addition, although the current will carry a large amount of suspended sediment during the ebb and flow period, the net suspended sediment transport volume always keeps a small value. This is mainly because the tidal current in Hangzhou Bay is strong, and the suspended sediment particle size is small, floating in the water body and difficult to settle. Therefore, the residual current is the decisive factor causing the net transport of suspended sediment, which reflects the characteristics of large input and output of sediment transport process and repeated transportation in Hangzhou Bay, which is consistent with the research conclusion of Cao^[7].

Table.4 Statistical analysis of tidal flux of each section during spring and neap tides

	statistical characteristics of daily average tidal flux(10^9 m ³)	flood tide	ebb tide	net tidal flux	dominant tide/%
	S1	13.67	-14.03	-0.35	50.63
	S2	2.28	-4.01	-1.73	63.80
	S3	18.96	-18.63	0.33	49.56
	S4	10.26	-12.28	-2.02	54.48
spring tide	S5	9.08	-11.04	-1.96	54.86
	S6	8.93	-9.18	-0.25	50.70
	S7	9.74	-8.39	1.35	46.29
	S8	78.12	-77.75	0.38	49.88
	S9	30.61	-37.24	-6.63	54.89

	S1	7.49	-7.17	0.32	48.91
	S2	1.41	-1.92	-0.51	57.62
	S3	8.95	-8.73	0.22	49.39
	S4	5.43	-5.36	0.07	49.65
neap tide	S5	5.11	-4.88	0.23	48.85
	S6	3.64	-4.03	-0.40	52.59
	S7	5.53	-3.71	1.82	40.18
	S8	31.56	-30.95	0.62	49.51
	S9	12.14	-14.78	-2.64	54.90

Tab.5 Statistical analysis of suspended sediment discharge of each section during spring and neap tides

	statistical characteristics of daily average sediment discharge (10^9kg)	flood tide	ebb tide	net sediment discharge	dominant sediment/%
spring tide	S	31.2	-	4.84	45.80
	1	5	26.41	-2.14	59.74
	S	4.42	-6.55	7.80	44.75
	S	41.0	-	0.62	49.23
	3	9	33.29	0.09	49.82
	S	20.4	-	-3.98	55.99
	4	0	19.79	9.25	23.51
	S	12.4	-	-0.62	50.69
	5	5	12.36	-9.93	62.55
	S	14.6	-	1.07	44.66
	6	3	18.61	-0.16	54.17
	S	13.3	-4.11	0.81	45.77
	7	6	-	0.47	46.33
	S	21.9	-	0.31	46.29
	8	9	22.61	-0.28	54.05
	S	14.8	-	1.36	33.16
	9	2	24.74	0.05	49.27
neap tide	S	5.53	-4.46	-0.25	54.77
	1	0.89	-1.06		
	S	5.16	-4.36		
	3	3.47	-3.00		
	S	2.26	-1.95		
	5	1.59	-1.87		
	S	2.69	-1.34		
	7	1.77	-1.72		
	S	1.17	-1.42		

4.2 Influence of Shoreline Change on Cross Section Tidal Flux

In 1974 and 2020, the southern coastline of Hangzhou Bay pushed into the bay about 7 km as a whole, while the northern coastline was relatively small. However, the

coastline at Nanhui between Hangzhou Bay and Yangtze River Estuary advanced about 10 km. Figure 5 shows the daily average total flood volume and daily average total ebb of 9 sections from S1 to S9 during spring and neap tides in 1974 and 2020, respectively, with positive values pointing to the inside of the bay and negative values pointing to the outside of the bay.

Fig. 5 Distribution of tidal fluxes in different sections in 1974 and 2020

As the shoreline moves towards the water area, the fluctuation tidal current speed increases due to the change of shoreline, and the fluctuation tidal flux of each section also increases.

From the fluctuation range of each section, the change trend of the section close to the shoreline is obvious, which is greatly affected by the change of the coastline. The change of net tidal flux of each section is counted to analyze the influence of shoreline change on the water exchange mechanism between Hangzhou Bay and the open sea, and a sketch map is drawn according to the relative position of each section (Figure 7, the positive value of ordinate indicates the transport to the bay, and the negative value indicates the outward transport to the bay). Among them, the water delivery from Nanhui to Yangshan section and the entrance of big and small Yangshan ports increased by $0.26 \times 10^9 \text{m}^3$ and $0.14 \times 10^9 \text{m}^3$ respectively. The section from Yangshan to Daishan will be changed from water outlet to water inlet, with a change range of $0.69 \times 10^9 \text{m}^3$, which will supply water quantity in the bay to a large extent. The tidal fluxes between Daishan, Zhoushan and Jintang are relatively small, and the changes of inflow and outflow are basically balanced. The water yield of Jintang Ningbo section decreased slightly, reaching $0.34 \times 10^9 \text{m}^3$. The change of the total water transport volume of the six sections shows that the water is transported out of the bay, and the water delivery volume is reduced by $0.73 \times 10^9 \text{m}^3$. From S7 to S10, it can be seen that the change of coastline has little effect on the water exchange between the South and north sides of Hangzhou Bay and the open sea, and the water transfer from the east to the bay increases by $0.48 \times 10^9 \text{m}^3$.

Fig.6 Distribution of net tidal flux of each section in 1974 and 2020 (unit: 10^9m^3)

4.3 Influence of Shoreline Change on Cross Section Sediment Flux

The variation trend of the sediment flux in the rising and falling tides of each section is consistent with that of the ebb and flow tidal fluxes of each section, and the numerical values are increased.

Fig. 7 Distribution of suspended sediment flux at different sections in 1974 and 2020

Comparing the net sediment flux of each section in 1974 and 2020 (Figure 8, the positive value of ordinate indicates the sediment transport to the bay, and the negative value indicates the sediment transport to the bay) from Nanhuizui to Yangshan decreases by $0.38 \times 10^9 \text{kg}$, while that from Yangshan to Daishan increases by $1.88 \times 10^9 \text{kg}$. Among the two sections (S2 and S6) transporting sediment to the open sea in Hangzhou Bay, the sediment transported from the west entrance of Yangshan port to the sea increased by $0.31 \times 10^9 \text{kg}$, while that from Jintang to Ningbo decreased by $0.46 \times 10^9 \text{kg}$. The sediment transport from Daishan to Zhoushan and from Zhoushan to Jintang has little change, with an increase of $0.53 \times 10^9 \text{kg}$ in sediment inflow and $0.03 \times 10^9 \text{kg}$ in outflow, respectively. The total sediment inflow of the six sections

increased by $2.06 \times 10^9 \text{kg}$, and the total sediment discharge decreased by $0.15 \times 10^9 \text{kg}$. The total sediment discharge into the bay increased by $2.21 \times 10^9 \text{kg}$. The change of net sediment flux from S7 to S9 is relatively small. However, the overall change trend of the three sections is from $0.44 \times 10^9 \text{kg}$ sediment inflow to $0.11 \times 10^9 \text{kg}$ sediment discharge, which is mainly due to the extinction of S10, which leads to the decrease of $0.31 \times 10^9 \text{kg}$ sediment discharge from the north to the bay.

Fig. 8 Distribution of net suspended sediment flux at different sections in 1974 and 2020 (unit: 10^9kg)

5 Conclusion

Based on the three-dimensional suspended sediment model, the water and sediment exchange mechanism in Hangzhou Bay and its surrounding waters is simulated and analyzed. By comparing the changes of tidal flux and suspended sediment flux under the background of coastline in 1974 and 2020, the influence of shoreline change on the water and sediment exchange mechanism between Hangzhou Bay Estuary and the open sea is analyzed. The conclusions are as follows:

(1) Most of the sea area near the entrance of Hangzhou Bay is dominated by ebb tide, which is slightly different during spring and neap tides, and the sediment transport generally presents a pattern of north-inflow and south-discharge. The sea area (S1) between Nanhuizui and rugged islands in Hangzhou Bay and the sea area between Yangshan Port and Daishan (S3) are the main channels for sediment to enter Hangzhou Bay. The average daily net sediment transport during neap tide is $14.52 \times 10^9 \text{kg}$. The cross-section between Jintang and Ningbo is the main channel to transport sediment to the sea, and the net sediment transport volume reaches $4.26 \times 10^9 \text{kg}$ during spring and neap tides.

(2) Among the north, East and South sections of the cross section between the mouth of Hangzhou Bay and the open sea, the north section is the main channel for incoming water and sediment ($3.17 \times 10^9 \text{m}^3$ for inflow and $10.61 \times 10^9 \text{kg}$ for sediment inflow), and the south section

is the main channel for transporting water and sediment to the open sea ($9.27 \times 10^9 \text{ m}^3$ for outlet water and $10.18 \times 10^9 \text{ kg}$ for sediment discharge). The net water and sediment flux of the east section is relatively small ($1.00 \times 10^9 \text{ m}^3$ inflow and $0.67 \times 10^9 \text{ kg}$ sediment discharge).

(3) When the coastline is pushed into the bay, the inflow of the northern Hangzhou Bay (adjacent to the Yangtze River Estuary and Yangshan Harbor) will increase by $0.29 \times 10^9 \text{ m}^3$. Its inward sediment transport will increase by $1.19 \times 10^9 \text{ kg}$. The inflow of water and sediment will increase by $0.1 \times 10^9 \text{ m}^3$ and $0.56 \times 10^9 \text{ kg}$ respectively. In the southern sea area (Jintang Waterway Area), the outward water delivery volume will increase by $0.34 \times 10^9 \text{ m}^3$, and its outward sediment transport will decrease by $0.46 \times 10^9 \text{ kg}$. The overall trend is that the inflow increases by $0.05 \times 10^9 \text{ m}^3$, and the inward sediment transport increases by $2.21 \times 10^9 \text{ kg}$. However, the huge change of net sediment discharge has a great impact on the topography of the bay.

(4) The change of coastline from 1974 to 2020 will lead to the decrease of inflow and sediment discharge in the north section of Hangzhou (the inflow decreases by $0.25 \times 10^9 \text{ m}^3$ and the sediment inflow by $0.31 \times 10^9 \text{ kg}$), the outflow and sediment discharge of the south section increases (the water output increases by $0.12 \times 10^9 \text{ m}^3$ and the sediment discharge by $0.20 \times 10^9 \text{ kg}$), and the inflow and sediment discharge of the east section increases (the inflow increases by $0.48 \times 10^9 \text{ m}^3$ and the sediment discharge by $0.04 \times 10^9 \text{ kg}$). The change of total water volume is reflected in the increase of $0.11 \times 10^9 \text{ m}^3$ of water inflow into the bay, and the total sediment load changed from $0.44 \times 10^9 \text{ kg}$ inflow to $0.11 \times 10^9 \text{ kg}$ discharge.

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