NUMERICAL ANALYSIS ON IMPACTS OF THE PROJECT OF NORTH BRANCH NARROWING ON SEDIMENT DISTRIBUTION

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ABSTRACT

In order to analyze the effects of middling narrowing project in the north branch plane on the sediment transport in Yangtze estuary, a two-dimensional mathematical model of average tidal current and sediment in Yangtze estuary was established. Based on the verification of the model with measured data, the hydrodynamic and suspended sediment concentration changes before and after the middling narrowing project were simulated and analyzed. The results show that after the implementation of the middling narrowing project, the flow capacity of north branch entrance declined due to the water blocking and narrowing effects caused by the project; the speed of flood/ebb tide decreased in the downstream estuary; time lags appeared for flood/ebb tide comparing with the situation before the project; moreover, the sediment concentration in the north branch river channel decreased, with section peak sediment concentration decreasing 0.0%~-14.9%. The impairing effect of this project on the intensity of sediment transport in the north branch gradually increased from downstream to upstream, while the tide level, flow velocity, and sediment concentration in the south branch were less affected by the project.

Keywords: Sedimentation; tidal current; sediment; numerical simulation

1. INTRODUCTION

The north branch of Yangtze estuary starts in the west from Chongtou(CT), the western end of Chongming Island, to the estuary Lianxinggang(LXG) in the east. With a total length of 83 km, it is a first-class branch channel of Yangtze estuary. Since 18th century, the mainstream of Yangtze River has diverted to the south branch, hence the runoff into the north branch has gradually decreased, causing an overall appearance of sedimentation and shrinkage in the north branch. The narrowest region of north branch is located around Qinglonggang(QLG), merely about 2 km of width. Aiming to delay the natural sedimentation and shrinkage in the north branch and tackle the issue of “saltwater intrusion”, as found in Yang (1993), Ding (2003), Wu (2007) or Song (2012). Shanghai and Jiangsu Province implemented a middling narrowing project in the north branch of Yangtze estuary. Figure 1 is the shoreline map before and after the implementation of the project; it illustrates significant changes of the plane shape in the north branch as the channel width of north branch has been greatly narrowed and the terrain boundary also has been changed significantly.

Previous studies about the middling narrowing project in the north branch were mainly focused on the improvement of saltwater intrusion and tidal bore and its effects on hydrodynamic environment such as tide level and flow velocity. However, less attention was paid to the effects of the project on sediment concentration and suspended sediment transport. For instance, Zekun Song (2012), Jiwei Wu et al (2006). studied the impact of the narrowing project in the north branch of Yangtze estuary on the tide level and flow velocity; Tilai Li et al. (2005) analyzed the impairing effect of Yangtze estuary comprehensive regulation project on the saltwater intrusion in Yangtze estuary. Previous studies discovered that the tidal prism and tidal range of north branch has decreased after the implementation of narrowing project in north branch, which diminished the intensity of saltwater intrusion.

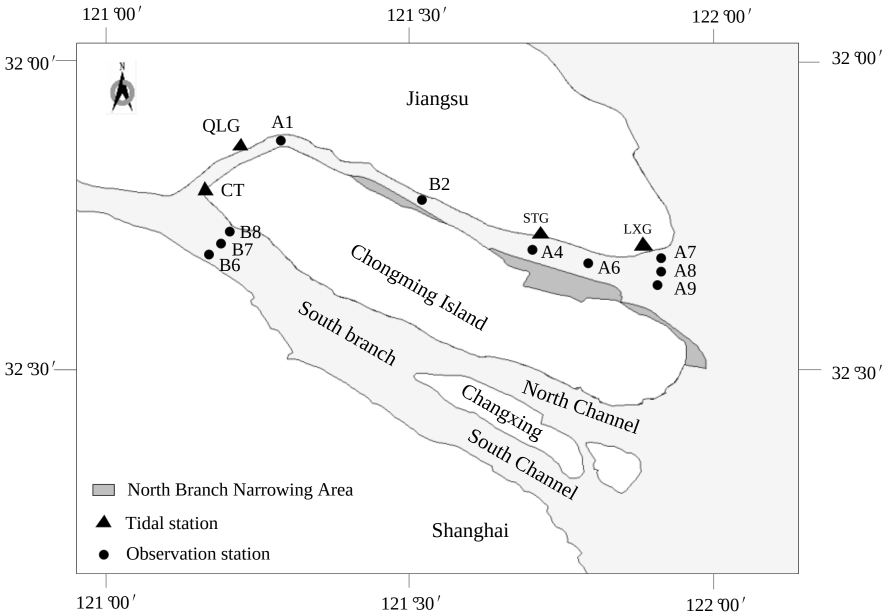


Figure 1. Yangtze estuary river map.

Numerical simulation, broadly used in China and other countries, is an important method not only for studying the coast water environment of estuaries, but also for evaluating the effects of water engineering projects (reclamation, etc.) on the surrounding hydrodynamic environment (Cheng LZ et al, 2016; Zhao X, Sun Q et al., 2013; Liu GW et al., 2010). Based on the two-dimensional mathematical model of tidal current and sediment, a simulation model of sediment transport in Yangtze estuary region has been established in this paper, and the changes in sediment transport in the north branch after the implementation of the middling narrowing project have been numerically simulated and analyzed, aiming to provide scientific basis for progressing the regulation project more rationally and comprehensively.

2. MATHEMATICAL MODEL OF TIDAL CURRENT AND SEDIMENT

2.1 Calculation methods and brief introduction of the model

(1) Tidal current field numerical simulation

The plane two-dimensional flow control equation (Liu GW et al. 2010) is as follows,

Continuous equation:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=0 \tag{1}$$

Momentum equation:

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\bar{u}\bar{v}}{\partial y}=f\bar{v}h-gh\frac{\partial \zeta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial S_{xx}}{\partial x}+\frac{\partial S_{xy}}{\partial y}\right)+\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})+hu_sS \tag{2}$$

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{u}\bar{v}}{\partial x}+\frac{\partial h\bar{v}^2}{\partial y}=-f\bar{u}h-gh\frac{\partial \zeta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial S_{yx}}{\partial x}+\frac{\partial S_{yy}}{\partial y}\right)+\frac{\partial}{\partial x}(h\tau_{xy})+\frac{\partial}{\partial y}(h\tau_{yy})+hv_sS \tag{3}$$

Where x, y are space coordinates (m); t is time (s); $\zeta(x,y,t)$ is the water level (m); $h(x,y,t)$ is the total water depth (m), $h=\zeta-d$, $d(x,y,t)$ is the water level (m) below the mean sea level; $\bar{u}$ and $\bar{v}$ are the average vertical velocity (m/s) in the x and y directions respectively, $\bar{u}=\frac{1}{h}\int_{-d}^{\zeta}udz$, $\bar{v}=\frac{1}{h}\int_{-d}^{\zeta}vdz$, u and v are the velocity components (m/s) in the x and y directions of each spatial point, z is the vertical coordinate (m) of the origin at the mean sea level, with upward direction indicating positive value; $f=2\Omega\sin\varphi$ is the Coriolis force coefficient (s^{-1}), Ω is the angular velocity of earth rotation (rad/s), φ is the latitude of computational domain (rad); p_a is atmospheric pressure (kg/m/s^2); ρ_0 is water density (kg/m^3); τ_{bx} and τ_{by} are the sea-bed shear stresses (N/m^2) in the x and y directions respectively; τ_{sx} and τ_{sy} are the wind stresses (N/m^2) in the x and y directions respectively; S_{xx}, S_{xy}, and S_{yy} are the wave radiation stresses (N/m^2) and these terms are concerned with the effects of wave on tidal current; S is the source/sink flow rate (s^{-1}); u_s and v_s are the water intake and discharge flow velocity of source/sink (m/s); τ_{xx}, τ_{xy}, and τ_{yy} are the viscous stresses (N/m^2).

(2) Numerical simulation of suspended sediment movement

The diffusion equation of suspended sediment transport is as follows,

$$\frac{\partial \overline{c}}{\partial t}+\overline{u}\frac{\partial \overline{c}}{\partial x}+\overline{v}\frac{\partial \overline{c}}{\partial y}=\frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial \overline{c}}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial \overline{c}}{\partial y}\right)+\frac{1}{h}Q_LC_L-S_b \tag{4}$$

Where $\overline{c}$ is the vertical average sediment concentration (kg/m^3); D_x and D_y are the diffusion coefficients of sediment; Q_L is the source flow per unit horizontal area (m^3/s/m^2); C_L is the sediment concentration of source/sink (kg/m^3); S_b is the item concerning increase of sediment concentration or sea-bed erosion (kg/m^3/s). Equation (4) is also applicable for non-uniform sediment.

(3) Numerical simulation of sea-bed scouring and sedimentation

The formulas of sedimentation and resuspension are as follows,

sedimentation,
$$\frac{\partial \overline{c}}{\partial t}+\overline{u}\frac{\partial \overline{c}}{\partial x}+\overline{v}\frac{\partial \overline{c}}{\partial y}=\frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial \overline{c}}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial \overline{c}}{\partial y}\right)+\frac{1}{h}Q_LC_L-S_b \tag{5}$$

resuspernsion,
$$\frac{\partial \overline{c}}{\partial t}+\overline{u}\frac{\partial \overline{c}}{\partial x}+\overline{v}\frac{\partial \overline{c}}{\partial y}=\frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial \overline{c}}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial \overline{c}}{\partial y}\right)+\frac{1}{h}Q_LC_L-S_b \tag{6}$$

Where S is the sediment concentration; S_m is the concentration of sedimentation and resuspension; τ_b is the sea-bed shear stress; τ_{cd} is the sedimentation critical shear stress; τ_{ce} is the erosion critical shear stress; ω is the sedimentation velocity; C_b is the near-bottom sediment concentration; E is the scouring coefficient; n is the bed erosion index.

2.2 Determination of the computational domain and grid division

The layout of the computational grid should reflect the actual terrain changes as explicit as possible. The refined triangular multi-grid was constructed after comprehensive consideration. The upstream boundary of Yangtze estuary is Jiangyin, and the model computational domain included Yangtze estuary, Hangzhou Bay, and adjacent sea area: 120.75 °E to 124.8 °E; 29.3 °N to 32.5 °N. The computational domain was divided into 85470 triangular computational units with 106586 computational nodes in total; the minimum grid side length was less than 10 m; the maximum boundary length of offshore grid was 500 m; and the maximum unit area was 0.8 km^2.

The land boundary of this model was based on the coastline in 2012. The underwater topography of the north and south branches in Yangtze estuary was based on measured data in years adjacent to 2012, while the topography data of other areas was obtained from numerizing the latest nautical charts of the Navigation Guarantee Department of Chinese Navy Headquarters. The upstream flow boundary of Yangtze estuary was measured flow, and the offshore boundary was determined by calculating the harmonic constants of the 11 main partial tides (Q1, O1, P1, K1, N2, M2, S2, K4, M4, MS4, and M6).

2.3 Model validation

The model validation was performed using the measured water level, flow velocity, and sediment concentration of large and small tides in December 2012. The tide level data in the corresponding period were collected from national or local basic tide stations such as Xuliujing, Chongtou(CT), Qinglonggang(QLG), Lianxinggang(LXG), Santiaogang(STG), Nanmen, Buzhen, Shidongkou, Wusong, Gaoqiao, Changxing, Hengsha, etc.; these data were used to validate the model, and some results are illustrated in Figure 2. A1~A9 were the measuring points of the flow velocity, flow direction, and sediment concentration. Some simulation results are illustrated in Figure 3 and Figure 4. The results indicated that the simulated tide level, flow velocity and direction, and sediment concentration had good consistency with the measured data, which could truly represent the flood-ebb fluctuations of the north branch and indicate the characteristics of tide movement in Yangtze estuary. Therefore, the well-simulated hydrodynamic environment and distribution of sediment concentration in Yangtze estuary can be used to explore and study the related issues.

The influence of runoff on the north branch is decreasing, and th tidal current has a dominant influence on the north branch. The station of B2 is at the reach where the flow paths of flood current and ebb current separate, so the sediment concentration of B2 in Fig.4 is greater than other stations.

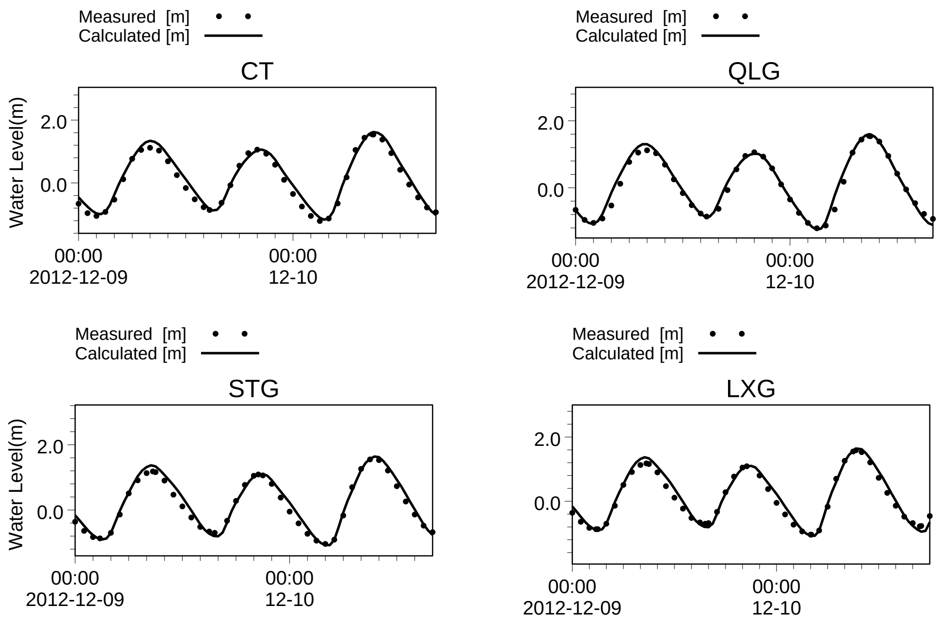


Figure 2. Tide level validation.

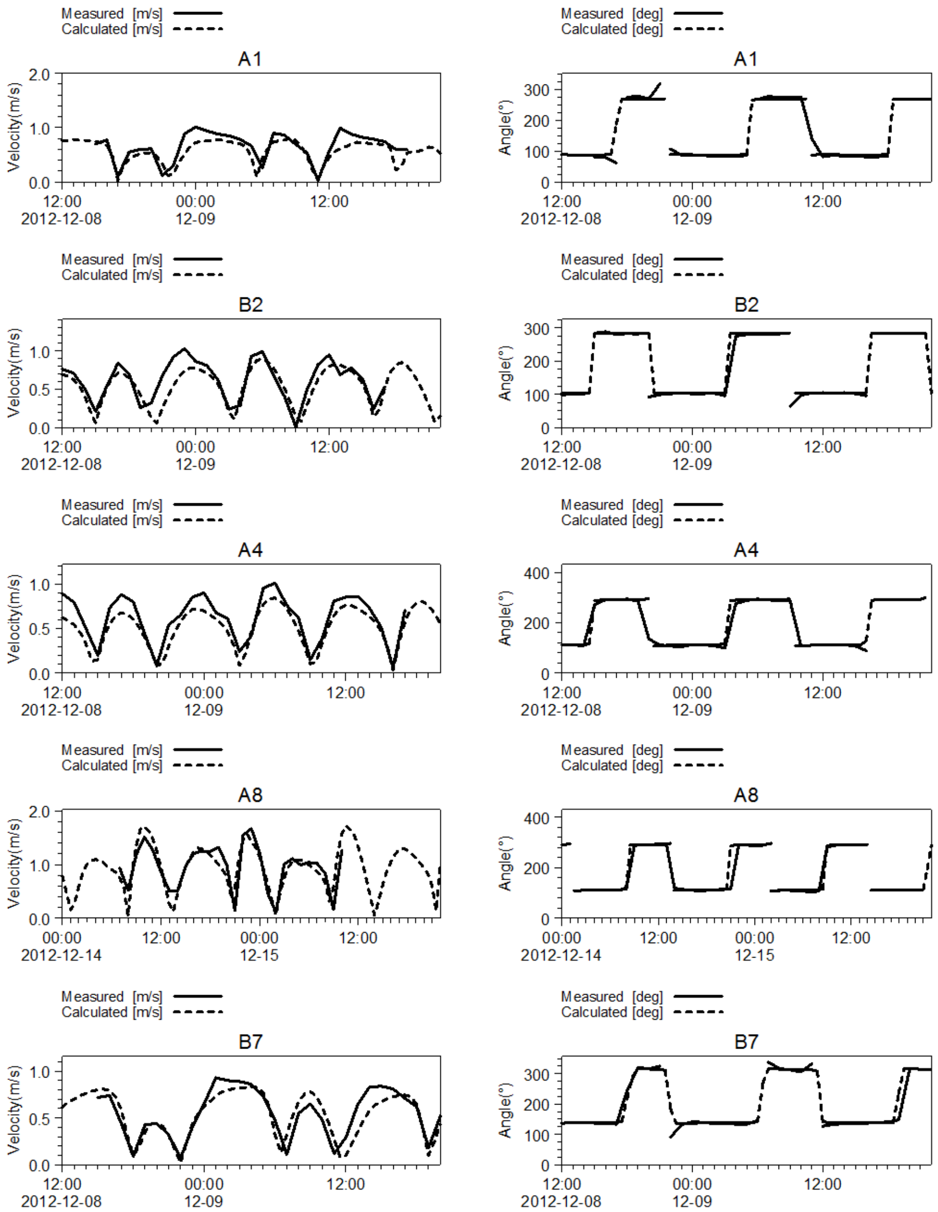


Figure 3. Flow velocity and direction validation.

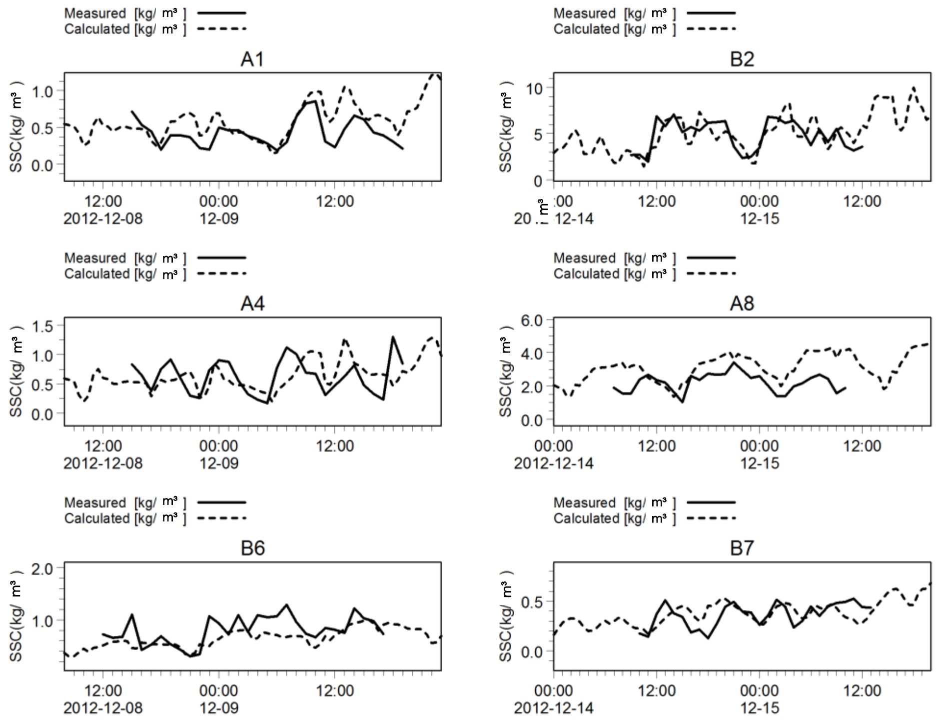


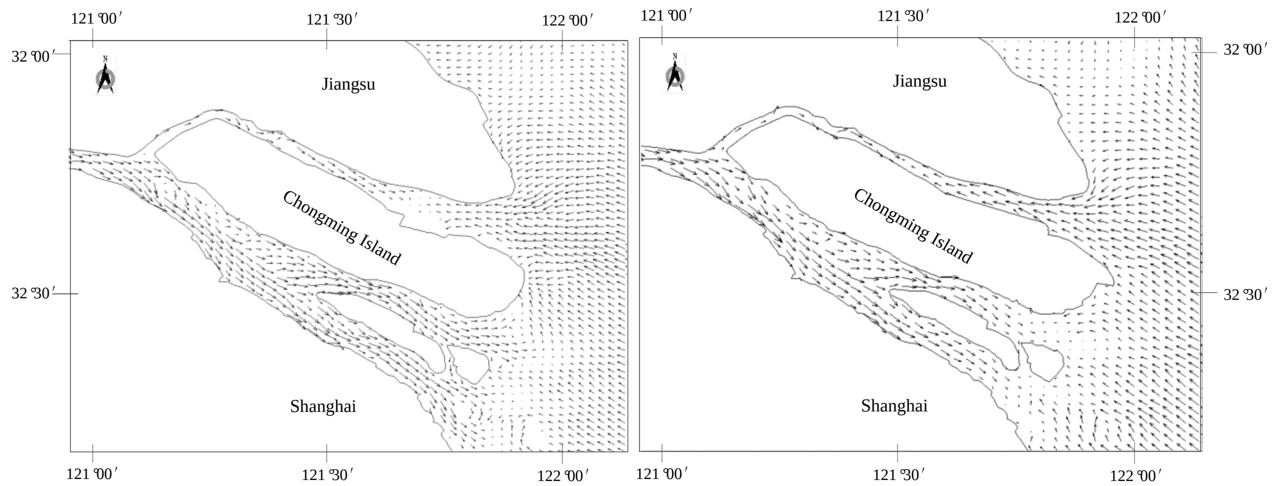
Figure 4. Sediment concentration validation.

3. RESULT AND DISCUSSION

The tidal current and suspended sediment transport in the north branch after the middling narrowing project were calculated using calibrated model parameters, then compared with the data before the project to analyze the effects of this project on the south and north branches in Yangtze estuary.

3.1 Water hydrodynamic environment changes

During the flood tide in Yangtze estuary, the tide wave first transmits from offshore to the north branch. When the flood tide begins near Lianxinggang at the entrance of the north branch, the middle and upper segments of the north branch along with the entire south branch are in ebb-tide mode. Although the flood tide in the north branch starts earlier than that in the south branch, because of the bend channel in the north branch, its flow resistance is greater than that of the south branch. Therefore, when the flood current of the south branch reaches the nearby area of south-north-branch bifurcation, Chongtou in the upper segment of north branch is still in ebb tide, and part of the flood current in the south branch merges into the north branch (see in Figure 5); hence, the area nearby Chongtou in the upper segment of the north branch is the weak-flow area, where sedimentation is prone to happen. When the south branch is in ebb tide, nearby Chongtou in the north branch is still in flood tide with water level higher than that of the south branch; hence, the flood current in the north branch flows into the south branch, which is the dynamic factor of saltwater in the north branch intruding the south branch.



(a) before narrowing project (b) after narrowing project

Figure 5. Tidal current field in the spring tide flooding period.

Table 1 exhibits the typical section peak flow change before and after middling narrowing project. After the implementation of middling narrowing project, the impacts on the measuring points in the north branch were more significant. Significant changes in the flow field also occurred in the river channel and the entrance of the north branch as the high tide level was declined and the peak flow was increased in Lianxinggang tide station. In the Chongtou section, located in the upstream of the north branch, the flood tide peak flows of spring/neap tide were increased while the ebb tide peak flows were declined; in the Santiaogang section, located in the middle-lower segment of the north branch, the flood tide peak flows of spring/neap tide were declined while the ebb tide peak flows were increased. Most of the implementation areas of middling narrowing project were point bars with relatively high elevations of the river bottom. Moreover, the progressing direction of new coastline complied with the flow direction of flood/ebb tide. All those changes narrowed the river channel of the north branch and altered the original bell-mouth shape of the north branch, which could diminish the dynamic force of tide intrusion and decline the high tide level of spring tide. Meanwhile, river channel narrowing could also constrain the water and reinforce the flow, leading to the velocity increase of flood/ebb tide.

The narrowing project didn't change the flow pattern of ebb tide in the north branch. The flow pattern of flood/ebb tide in the south and north branches were basically unchanged, so were the flow characteristics of flood/ebb tide in the south and north branches. The south branch in Yangtze estuary and the entrance area were basically unaffected with tide level and flow velocity remained unchanged in general. Also discovered in the studies by other researchers (Song ZK et al., 2012; Wu JW et al., 2006; Li TL et al., 2005), after the construction of the reclamation project in the north branch, the tide level in the lower segment of the river channel was declined overall, while the flow velocity increased significantly.

Table 1. Section peak flow changes before and after the project.

		Flood tide peak flow (10^4 m^3/s)			Ebb tide peak flow (10^4 m^3/s)		
		Before narrowing project	After narrowing project	Change	Before narrowing project	After narrowing project	Change
Chongtou section	Spring tide	1.437	1.605	11.72%	0.73	0.566	-15.05%
	Neap tide	0.768	0.790	2.94%	0.42	0.336	-3.87%
Santiaogang section	Spring tide	6.241	5.812	-6.87%	1.05	3.170	3.43%
	Neap tide	3.176	3.058	-3.70%	0.59	1.727	0.85%

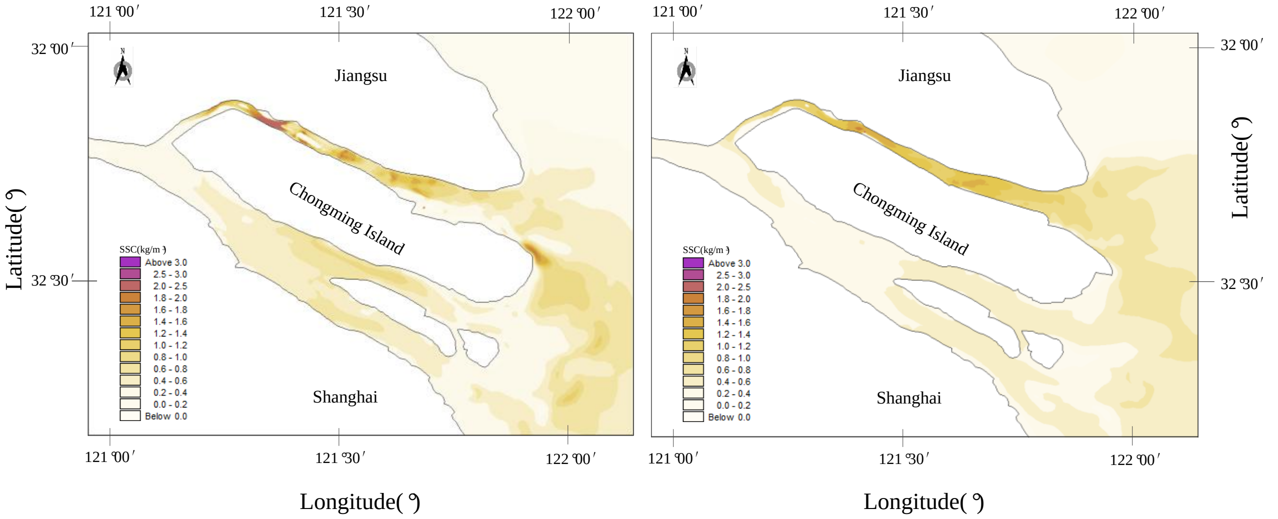
3.2 Sediment concentration changes

After the middling narrowing project, the decrease of flow capacity in the north branch estuary and the tide wave deformation in the north branch, along with other effects, would diminish the sediment transport intensity in the north branch and pose secondary effects on the sediment transportation in the south branch, which would change the peak value of the section sediment concentration hydrograph along the river channel in Yangtze estuary. Table 2 exhibits the peak sediment concentration change in the typical monitoring sections under spring/neap tide conditions before and after the project. As indicated by this table, after the implementation of middling narrowing project, the peak sediment concentration appeared a decreasing trend with a change between 0.0%~-14.9%. In the middle-later stage of flood tide, nearby the Santiaogang section, the flow was in a period with low sediment concentration due to the gradual exhaustion of flood tide momentum.

Table 2. Section peak flow changes before and after the project.

		Flood tide peak sediment concentration (10^4 kg/s)			Ebb tide peak sediment concentration (10^4 kg/s)		
		Before narrowing project	After narrowing project	Change	Before narrowing project	After narrowing project	Change
Chongtou section	Spring tide	0.872	0.742	-14.84%	1.126	0.958	-14.86%
	Neap tide	0.848	0.720	-15.01%	0.434	0.357	-17.54%
Santiaogang section	Spring tide	1.795	1.894	5.52%	3.081	2.747	-10.83%
	Neap tide	1.746	1.585	-9.17%	1.166	1.002	-14.01%

Figure 6 illustrates the sediment concentration field after the narrowing in the north branch. The narrowing in the river channel of the north branch reduced the amount of sediment toward upstream in flood tide, which facilitated the decrease of sediment concentration in the river channel of the north branch. Nonetheless, the north branch is still the high-concentration region of sediment in Yangtze estuary.



(a) before narrowing project (b) after narrowing project

Figure 6. Sediment concentration distribution after middling narowing project.

Figure 7 illustrates the sediment concentration change at some measuring points in the north branch, and it indicates that the sediment concentration at different measurement points decreased in different degrees after the project; this was because that the middling narrowing project in the north branch changed the river channel of the north branch to a great extent, leading to narrowing of the river channel and the decrease of sediment concentration in the north branch water area. Meanwhile, after the implementation of the project, the tide level in the north branch declined, leading to the decrease in the sediment transporting amount of the tidal current to the north branch; however, the flow velocity did not increase significantly; this was also one reason for the decrease of the sediment concentration in the north branch. Moreover, the river channel narrowing in the north branch caused decline of the tide level and decrease in the intrusion amount of the sediment-bearing tide water offshore. These situations all contributed to the decrease in sediment concentration in the river channel of the north branch. The south branch and the entrance area were basically unaffected with no significant changes in sediment concentration.

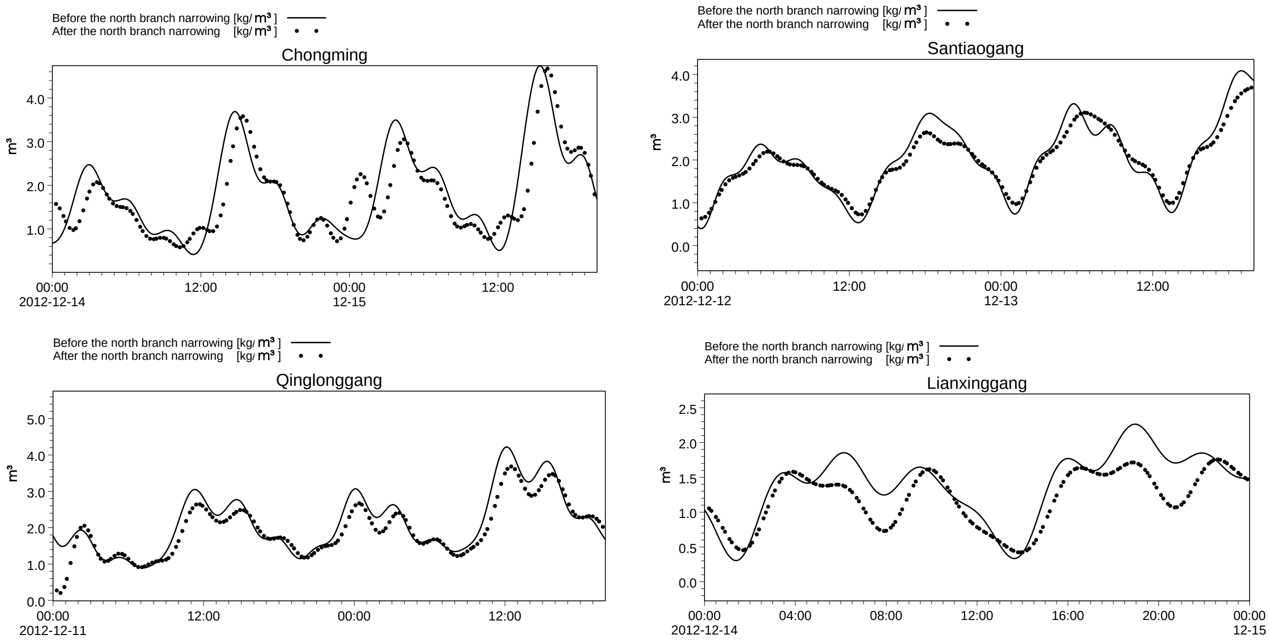


Figure 7. Comparison of sediment concentration before and after middling narrowing project.

After the middling narrowing project, the decrease in sediment concentration of flow in the north branch was in a gradual cumulative increase process; namely, from downstream to upstream, the decrease in the sediment concentration and the section sediment flux of the reach flow gradually became more significant. In addition, the impairing effect of this project on the sediment transport intensity increased gradually from downstream to upstream.

4. CONCLUSIONS

Simulation and analysis of the water-and-sediment environment before and after the middling narrowing project in the north branch of Yangtze estuary were conducted by using the two-dimensional mathematical model of average tidal current and sediment, and the following conclusions are obtained:

(1) The middling narrowing project did not change the flow pattern of flood/ebb tide, and the flow characteristics of flood/ebb tide in the south and north branches were basically unchanged.

(2) After the implementation of middling narrowing project in the north branch of Yangtze estuary, the river channel of north branch was narrowed and the dynamic force of tide intrusion was diminished, leading to the decline in the high tide level of spring tide in the north branch, which benefited the coastal protection against the tide. Meanwhile, the increase in flow velocity and the decrease in the sediment concentration were also beneficial to the sediment prevention and elimination of the river channel.

(3) After the implementation of middling narrowing project in the north branch of Yangtze estuary, the amount of suspended sediment in the north branch appeared a decreasing trend, and the decreasing trend was shown in the north branch with a change of 0.0%~-14.9%.

(4) The implementation of middling narrowing project in the north branch of Yangtze estuary had basically no effect on the tide level and sediment concentration distribution in the south branch and the entrance area.

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