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Impacts of topography change on saltwater intrusion over the past decade in the Changjiang Estuary

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Abstract

Saltwater intrusion in estuaries is mainly controlled by tides and river discharge, as well as by topography and other factors. The Changjiang estuary has been seen a significant change in its topography from the data obtained in 2007 and 2017. In this study, a well-validated 3D numerical model was used to simulate and analyze the residual water and salt transport, water diversion ratio (WDR) in bifurcated channels and water resources in the Changjiang Estuary in 2007 and 2017. The comparisons of the model results showed that due to the North Branch becoming much shallower and narrower over the period from 2007 to 2017, the overall salinity in the North Branch decreased and the intensity of saltwater spillover (SSO) from the North Branch into the South Branch weakened. In the North Channel, the simulated residual or net transection water flux (NTWF) and WDR decreased during spring tides, resulting in increased saltwater intrusion. During neap tides, the saltwater intrusion was weakened despite the decreased NTWF and WDR because the water depth at the river mouth became shallower. The changes of topography during that period also resulted in changes of DWR, NTWF, salt transport across the tidal flats and dykes in the North Passage, South Passage and the South Channel, as well as overall dynamic mechanism. The results indicated that the salinity at the water intakes of the three reservoirs in the estuary slightly decreased, indicating that the time that reservoirs can take water from the estuary become longer in dry seasons. In the scenario of complete silt-up of the North Branch, the saltwater intrusion was weakened in the South Branch because of the disappearance of the SSO, which was favorable for the utilization of freshwater resources, but enhanced in the North Channel, North and South Passages. The overall influence from the topographic change over the period is that the saltwater intrusion is weakened in the North Branch, and enhanced during spring tides and weakened during neap tides in the North

Channel, North and South Passages. Sediment accretion in the North Branch is favorable for utilization of freshwater resources.

Keywords: topography change; saltwater intrusion; freshwater resource; numerical model; Changjiang Estuary.

1. Introduction

Saltwater intrusion is a common phenomenon in estuaries where freshwater and saltwater converge. Saltwater intrusion can produce estuarine circulation (Pritchard, 1956) and affect stratification (Simpson et al., 1990), thereby influencing sediment transport, producing peak estuarine turbidities (Geyer, 1993), and degrading freshwater quality (Zhu et al., 2010). Estuarine saltwater intrusion is mainly controlled by tide and river runoff (Pritchard, 1956; Prandle, 1985; Shen et al., 2003), but it can also be affected by topography (Prandle, 2006), wind stress (Hansen and Rattray, 1966; Li et al., 2012), and vertical mixing (Ippen and Harleman, 1961; Simpson and Hunter, 1974; Prandle and Lane, 2015). Prandle (2006) presented the relation between the estuarine morphological development and the forcing parameters such as tide range and river flow with the data from 80 UK estuaries. It can be well explained from these theoretically derived relationships and indicated that estuarine topography evolution should be considered in the determination of saline intrusion length. Estuarine topographies reflected the influences of tidal amplitude and river flow, along with some representation of alluvium (Prandle and Lane, 2015). Topography change was caused by natural evolution over long time scales and anthropogenic activities, especially in recent decades (Shen et al., 2003; Zhu and Bao, 2016).

Changjiang, also known as the Yangtze River, is one of the largest rivers in the world. The river discharges large amounts of freshwater (9.24×10^{11} m^3) into the East China Sea each year (Shen et al., 2003). The seasonal variation of river discharge ranges from a maximum monthly mean of 49,850 m^{3}s^{-1} in July to a minimum of 11,180 m^{3}s^{-1} in January (Zhu et al., 2015). The estuary has a 90-km-wide river mouth and a nearly 640-km tidal limit. The Changjiang Estuary is characterized by multiple bifurcations (Fig. 1). The estuary is first divided into the South

Branch (South Branch) and the North Branch (North Branch) by Chongming Island. The lower South Branch was then bifurcated into the South Channel (South Channel) and the North Channel (North Channel) by Changxing Island and Hengsha Island. The South Channel was again bifurcated into the South Passage and the North Passage by the Jiuduan Sandbank. In 2017, the mean water depths in the North Branch, South Branch, North Channel, South Channel, and North and South Passages were 4.27, 10.41, 8.34, 11.47, 7.22 and 5.75 m, respectively. Tides in the Changjiang Estuary are semidiurnal, and fortnightly spring-neap signals and the most energetic source of water movement, which are close to a mesoscale. The maximum spring tide range was 3.38 m and the minimum neap tide range was 0.64 m at the Baozhen hydrological station (Fig. 1b) (Zhu, et al., 2015). The maximum tidal current amplitudes reached approximately 2.0 m/s at the river mouth during spring tide. The prevailing monsoon climate resulted in a stronger northerly wind of 5.5 m/s during winter and a southeasterly wind of 5.0 m/s during summer (Zhu, et al., 2015). The northerly wind produced a southward current along the Jiangsu coast in winter, which resulted in a higher water level along the coast by the Ekman transport. So the northerly wind caused a horizontal circulation around the Changjiang Estuary, which flowed into the estuary in the North Channel and out of the estuary in the South Channel (Wu et al., 2010; Li et al., 2012).

River discharge and tides are major control factors of saltwater intrusion in the Changjiang Estuary (Li et al., 2010; Qiu et al., 2012; Shen et al., 2003; Wu et al., 2006; Zhu et al., 2010;) but is also influenced by wind (Li et al., 2012), topography (Li, et al., 2014), anthropogenic activities in the river basin and estuary (Lyu and Zhu, 2018a; Qiu and Zhu, 2013; Zhu, et al., 2006) and sea-level rise (Qiu and Zhu, 2015). The North Branch is always found to be filled with highly saline water due to a low river discharge and high tidal range. In addition, saltwater intrusion is found to be the strongest in the South Passage and the weakest in the North Channel, mainly in a landwards wedge-like manner, especially during neap tide, similar to those observed in other partially mixed estuaries (Shen et al., 2003). During the dry seasons, when the river discharge is low, the North Branch always contains highly saline water under strong tidal conditions and low river discharge. Due to the bifurcation nature of the estuary, there is a particular type of saltwater intrusion in Changjiang Estuary compared with the other estuaries in the world, which is known as saltwater spillover (SSO) from the North Branch into the South Branch, and the SSO commonly occurs during spring tides of the dry seasons (Shen et al., 2003; Wu et al., 2006; Wu and Zhu, 2007; Wu et al., 2010; Zhu et al., 2016), which are defined as the period from November to March (next year) when the river discharge is usually low. Only a small amount of the saltwater returns to the North Branch because the shoals in its upper reaches surface during ebb tides. The saline water from the SSO during spring tides is transported downstream by runoff during the subsequent middle tides and neap tides. This pattern of saltwater intrusion poses a significant threat to the security of freshwater resources stored in three reservoirs in the estuary: Qingcaosha Reservoir (QCSR), Chenhang Reservoir (CHR) and Dongfengxisha Reservoir (DFXSR) (Table 1). The capacity The QCSR is the largest among them and is located in the North Channel, along the northwestern coast of Changxing Island (shown in Fig. 1). The QCSR supplies more than 70% of the freshwater for city Shanghai. But the QCSR is frequently influenced by saltwater intrusion particularly during the dry seasons. The current regulations prevent these reservoirs from taking water from the Changjiang when the salinity is more than 0.45 psu, to meet the standard for drinking water. For convenience of understanding the more acronyms in this paper, the acronyms and their corresponding full names were listed in the Appendix 1.

Table 1

The capacity, daily supply and their feeding population of three reservoirs.

Reservoir	Capacity ($\times 10^4$ m^3)	Daily supply ($\times 10^4$ t/day)	Population ($\times 10^4$)
QCSR	52400	500	1300
CHR	956	130	300
DFXSR	976	15	82

Previous studies on the impacts of topography change on saltwater intrusion in the Changjiang Estuary include the works of Chen and Zhu (2014a) and Lyu and Zhu, 2018a. Li et al. (2014) calculated the differences in saltwater intrusion in the northern outlet of the North Channel in the Changjiang Estuary using different topographic data. Zhu and Bao (2016) calculated the evolution of saltwater intrusion in the Changjiang Estuary in 1950s, 1970s and 2010s. Despite of those studies, the impacts of topography change on saltwater intrusion in the Changjiang Estuary in the recent years have received a little attention. The aim of this study is to bridge the knowledge gap and gain further understanding of the impacts of topography change on estuarine saltwater intrusion and provide a reference to explain similar phenomena in other estuaries.

To study estuarine saltwater intrusion, theoretical method is commonly used to obtain analytic solutions from simplified partial differential equations, i.e., the linear momentum equation of a dynamic balance between horizontal pressure gradient and vertical turbulent viscosity stress, equations for conservation of water and salt in steady state. There are many theoretical studies on the relation between the saltwater intrusion and stratification and vertical mixing in estuaries. For example, Ippen and Harleman (1961) demonstrated that vertical mixing could be related to energy considerations and defined a stratification number that is a ratio of energy dissipation to gain potential energy. Afterwards, Ippen (1966) modified the stratification number of the available tidal energy (effective in mixing) to that required to mix river and seawater within the saline intrusion length, which is proportional to the square of the water depth. In the same year, Hansen and Rattray (1966) discussed the correlation between the vertical variations in mean velocity and salinity and the role of this correlation in maintaining the steady-state salinity distribution in estuaries where turbulent mixing results primarily from tidal currents. It indicated the variation of water depth would have significant impact on salinity vertical mixing in an estuary. Moreover, some theoretical studies showed that the variation of water depth would also affected the estuarine horizontal mixing. Ippen (1966) proposed the length of an arrested saline wedge based on residual velocity profiles for a stratified estuary, which is a function of water depth, residual velocity, difference in density between bed and surface, and a parameter that varies with river conditions. Prandle and Lane (2015) deduced an explicit expression for saline intrusion length, which shows the river mouth depth is proportional to the saline intrusion length. They also addressed the question of how tidally dominated estuaries would adapt to increases in mean sea level. It was concluded that a mean sea-level rise would have a significant impact in shallow microtidal estuaries.

Review of previous studies suggested that, the estuarine topography change would have a great influence on saltwater intrusion in the horizontal and vertical directions. Whilst the referred theoretical studies could quantify the change of saltwater intrusion in the single-channel estuaries, given that the Changjiang Estuary is a multi-bifurcated channel with complex topography and there exists the complicated SSO, it makes it much more difficult to obtain an analytic solution to reflect the real temporal and spatial variations in saltwater intrusion. Nonlinear interactions between the river discharge, tide, wind stress and topography should be included in investigating the complicated patterns of saltwater intrusion in the estuary. It therefore becomes necessary to employ and advanced 3D numerical model with the capability of solving the primitive equations in this study to simulate the impacts of topography changes from 2007 to 2017 on saltwater intrusion and water resources and capture the variation of hydrodynamics from natural forcing and human activities during this period.

In the following sections, the topography changes from 2007 to 2017, and numerical model set up and validation are described, followed by the analysis and comparisons of the water and salt transport, water diversion ratio (WDR), and saltwater intrusion in the estuary. The saltwater intrusion is also predicted under in the scenario that the North Branch is completely silt-up and the conclusions are presented finally.

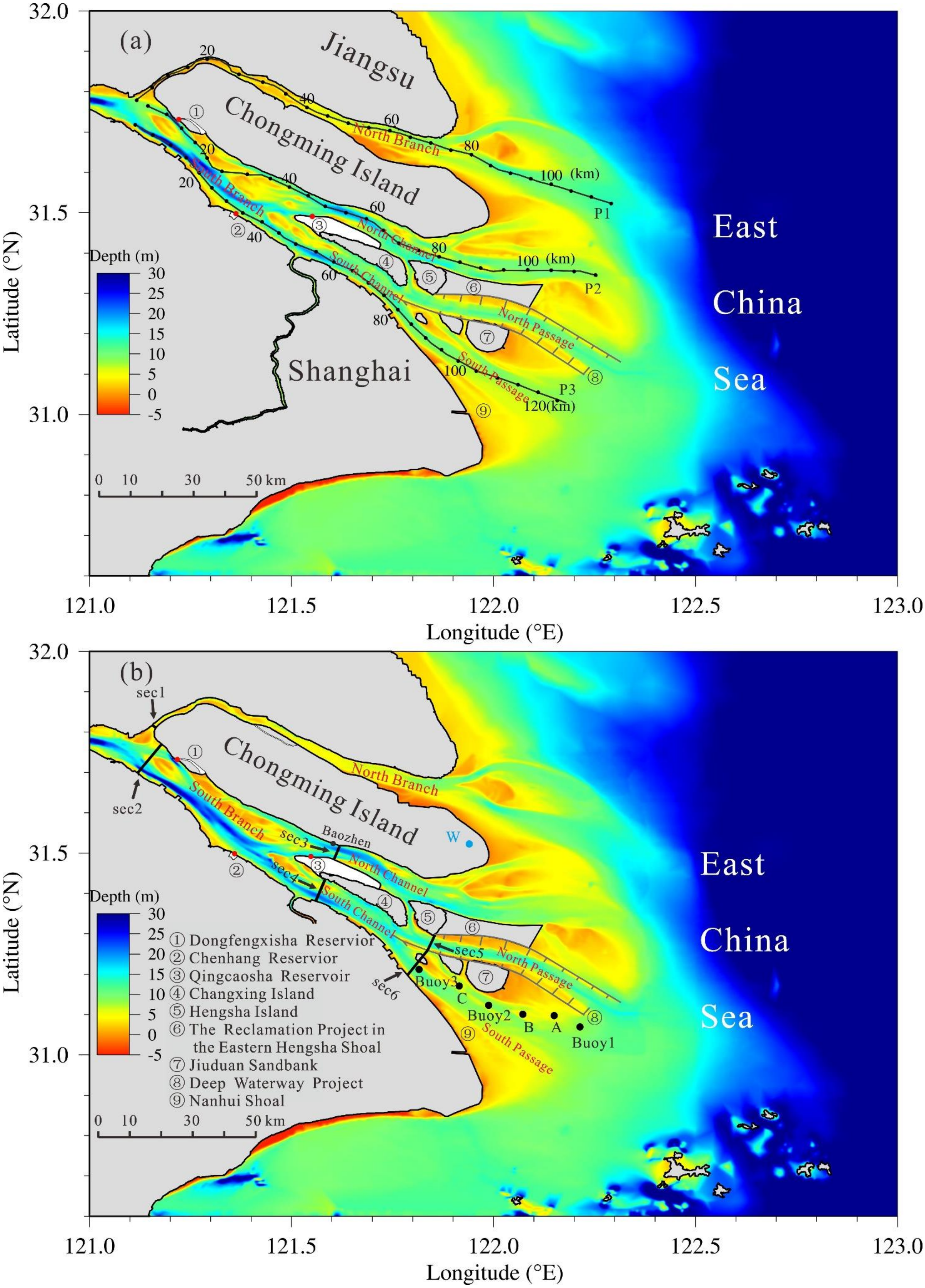

Fig. 1. The measured topographies of the Changjiang Estuary in 2007 (a) and 2017 (b), in

which: A, B and C are ship measurement sites; Buoys 1-3 are buoy measurement locations; Red dots are locations of water intakes of three reservoirs; sec1-sec6 and P1-P3 are cross-sectional longitudinal sections for saltwater intrusion analysis; and W is the location of the weather station.

2. Methods

2.1 Topographic data

In this study, the topographic data as shown in Fig. 1, was sourced from the State Key Laboratory of Estuarine and Coastal Research, surveyed in 2007 and 2017 which reflect the changes in topography over that period.

2.2 Model Setup

To investigate the impacts of topography change on saltwater intrusion in the Changjiang Estuary over period from 2007 to 2017, a well calibrated 3D numerical model was used. The numerical model was based on ECOM-si (Blumberg 1994) and later improved by Chen et al. (2001) and Zhu (2003) for studying hydrodynamics and substance transport. The HSIMT-TVD (high-order spatial interpolation at the middle temporal level coupled with a total variation diminishing scheme limiter) of the advection scheme was developed to significantly reduce the numerical diffusions with third-order accuracy (Wu and Zhu, 2010). The Mellor-Yamada 2.5 order turbulence closure module (Mellor and Yamada, 1982) with stability parameters from Kantha and Clayson (1994) was included. The model used a sigma coordinate system in the vertical direction and a curvilinear non-orthogonal grid in the horizontal direction (Chen et al., 2004). A wet/dry scheme was included to describe the intertidal area with a critical depth of 0.2 m (Zheng et al., 2003; Zheng et al., 2004).

The computational domain of the model for this study covers the Changjiang Estuary and its adjacent sea (Fig. 2), from 117.5°E to 124.9°E and from 33.7°N to 27.5°N. The model grid was composed of 337 × 225 curvilinear cells horizontally and 10 uniform σ levels vertically. The minimal grid resolution reaches nearly 100 m in the bifurcation of the South Branch and North Branch to better simulate the SSO (Fig. 2). The resolution was relaxed to ~ 10 km near the open boundary.

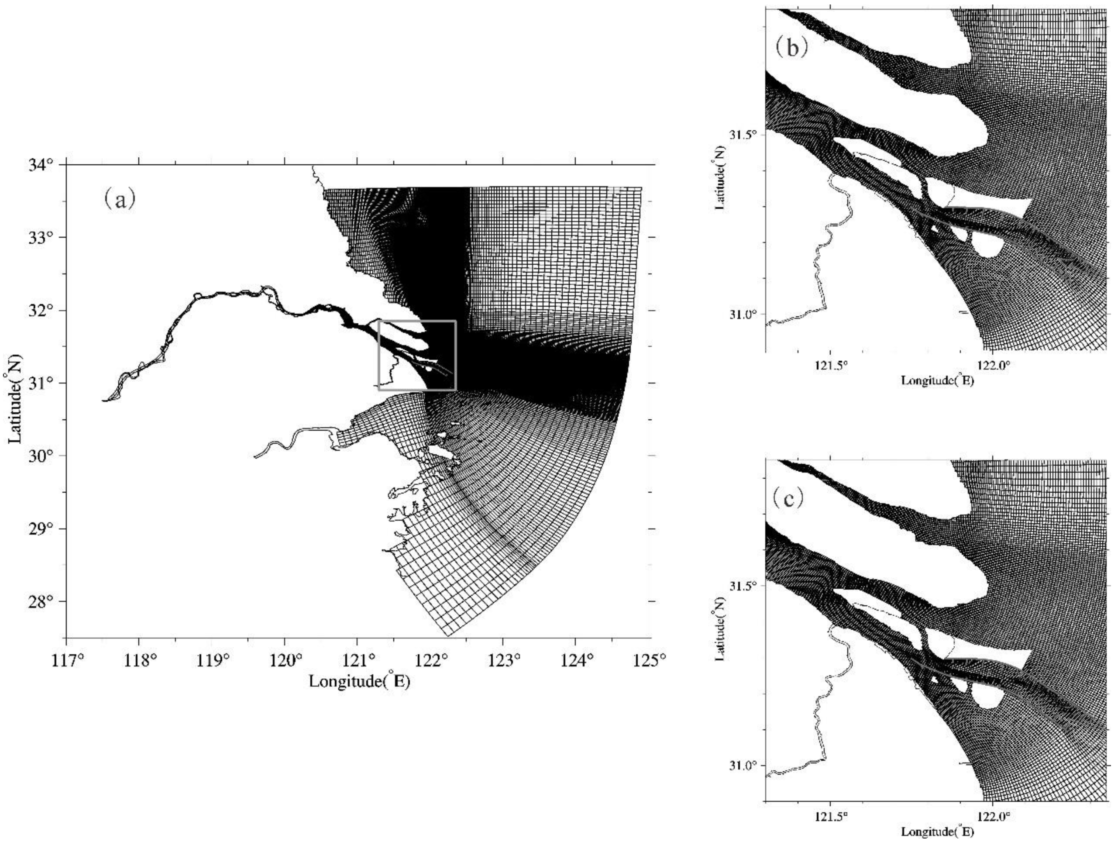

Fig. 2. Numerical model grid (a) and the detailed model grid around the Changjiang Estuary in 2007 (b) and 2017 (c)

Along the open sea boundary of the model, the tide was specified with the 16 astronomical tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, MU_2, NU_2, T_2, L_2, $2N_2$, J_1, M_1, and OO_1), derived from the NaoTide dataset (https://www.miz.nao.ac.jp/staffs/nao99/). Monthly mean river discharge recorded at the Datong hydrologic station from 1950 to 2016 (Changjiang Water Resources Commission) was used in the model as the river boundary condition. Wind data, with a resolution of 0.25°×0.25°, were adopted based on the semi-monthly mean of 10 years (2007-2017) from the NCEP (National Centers for Environmental Prediction) with a resolution of 0.25°×0.25° (https://www.ncep.noaa.gov).

For this study, two numerical experiments were conducted using the topographies measured in 2007 and 2017. However, the topography change trends of the past decade showed that the North Branch was heavily deposited and the channel became narrow (Fig.1 (a, b)). Therefore, an additional numerical experiment was conducted which made the North Branch complete silt-up on the basis of 2017 experiment. In this numerical experiment, the grids and topographies were same with the 2017 experiment but all wet grids in the North Branch were transformed into dry grids. Because the tide was just the oscillation of ocean waters under the influence of the attractive gravitational forces of the moon and the sun (Simm et al., 1996). So the differences of astronomical tides during dry season in different years were small. To make sure the tidal condition identical in three experiments, we selected the same simulation time. All model simulations covered the period from December 1, 2016 to February 28, 2017 which was the typical dry season. Because the model need 1-2 months to adjust the hydrodynamic and salinity to be stable. Therefore the model results in February were used to analyze and compare the impacts of the topography change over the past decade and the North Branch complete silt-up on residual water and salt transport, WDR, and saltwater intrusion. The monthly averaged river discharge since 1950 was 13600 m^3/s, 11100 m^3/s and 12000 m^3/s in December, January and February (dry season), and 36000 m^3/s, 45000 m^3/s and 40000 m^3/s in June, July and August (flood season), respectively. The river discharge in dry season is much lower than in flood season. The integrated time step was set to 30 s for all test cases.

To describe the water and salt transport, the residual unit width water flux (RUWF) and the residual unit width salt flux (RUSF) are defined as follows.

$$\vec{Q} = \int_{h1}^{h2} \vec{V} d\sigma \qquad (1)$$

$$RUWF = \frac{1}{T}\int_0^T \vec{Q} dt \qquad (2)$$

$$RUSF = \frac{1}{T}\int_0^T \vec{Q} s dt \qquad (3)$$

where $\vec{Q}$ is the instantaneous rate of water transport per unit width through a water column, $\vec{V}$ is the current vector, *h1, h2* is the lower and upper bound depth of a layer , and σ is the depth of layer bound. *T* is the time period (which equals one or several tidal cycles; in this study, it equals six semidiurnal tidal cycles) and is used as an averaging time window to remove the tidal signals, and *s* is salinity.

Additionally, the residual transection water flux (NTWF) is determined to calculate the WDR between channels (transection locations labeled in Fig. 1) as follows.

$$NTWF = \frac{1}{T}\int_0^T \int_{-H(x,y)}^{\zeta} \int_0^L \vec{V}_n(x,y,z,t) dldzdt \qquad (4)$$

where *T* is the same as above, ζ is the elevation, L l is the width of the transect, and $\vec{V}_n(x,y,z,t)$ is the velocity component that is vertical to the transect.

Similarly, the residual (net) transection salt flux (NTSF) is determined as follows.

$$NTSF = \frac{1}{T}\int_0^T \int_{-H(x,y)}^{\zeta} \int_0^L s\vec{V}_n(x,y,z,t) dldzdt \qquad (5)$$

where s is salinity.

2.3 Model Validation

The model has been extensively calibrated, validated and applied in a number of previous studies in the Changjiang Estuary, which have shown that the model can reproduce the observed water level, current and salinity with high simulation accuracy (Li et al. 2012; Lyu and Zhu, 2018b; Qiu, et al., 2015; Wu and Zhu 2010). In this study, we used the measured data taken in the South Passage from 9th to 19th March 2018 (three ship sites and three buoy sites shown in Fig. 1b) to further validate the model results.

The river discharge at the Datong Hydrological Station and wind data recorded by the weather station located on the east of the Chongming Island (indicate by W in Fig. 1) were adopted during the measured period to run the model. Three skill assessment indicators were used to quantify the current and salinity validation: the correlation coefficient (CC), root mean square error (RMSE), and skill score (SS). As follows,

$$CC = \frac{\sum (X_{\mathrm{mod}} - \overline{X}_{\mathrm{mod}})(X_{obs} - \overline{X}_{obs})}{[\sum (X_{\mathrm{mod}} - \overline{X}_{\mathrm{mod}})^2 \sum (X_{obs} - \overline{X}_{obs})^2]^{1/2}} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum (X_{\mathrm{mod}} - X_{obs})^2}{N}} \tag{7}$$

$$SS = 1 - \frac{\sum |X_{\mathrm{mod}} - X_{obs}|^2}{\sum (|X_{\mathrm{mod}} - \overline{X}_{obs}| + |X_{obs} - \overline{X}_{obs}|)^2} \tag{8}$$

where X_{mod} is the modeled data, X_{obs} is the observed data, and $\overline{X}$ is the mean value. SS is a statistical metric developed by Wilmott (1981) to describe the degree to which the observed deviations from the observed mean correspond to the predicted derivations from the observed mean. Perfect agreement between the model results and observations yields an SS of 1.0, whereas complete disagreement yields a value of 0. Temporal variations in the observed and modeled water velocities and salinities at ship-measured site B in the middle tide after neap tide and buoy-measured Buoy 2 were selected and shown in Fig. 3 and 4, respectively.

The assessment indicator scores of water velocity were summarized in Table 2. The values of CC at the six sites ranged from 0.63 to 0.93 in the surface layer and from 0.51 to 0.84 in the bottom layer; the RMSE ranged from 0.23 to 0.35 cm/s in the surface layer and from 0.10 to

0.21 m/s in the bottom layer; and the SS ranged from 0.79 to 0.93 in the surface layer and from 0.71 to 0.90 in the bottom layer. The mean water velocity values of CC, RMSE and SS at the surface and bottom layers at six sites were 0.77, 0.23 cm/s and 0.86, respectively.

The assessment indicator salinity scores were summarized in Table 3. The CC at the six sites ranged from 0.71 to 0.92 in the surface layer and from 0.66 to 0.90 in the bottom layer; the RMSE ranged from 0.36 to 2.49 in the surface layer and from 0.29 to 2.14 in the bottom layer; and the SS ranged from 0.80 to 0.96 in the surface layer and from 0.80 to 0.95 in the bottom layer. The mean salinity values of CC, RMSE and SS at the surface and bottom layers at the six sites were 0.83, 1.60 and 0.90, respectively. The assessment indicators indicated that the level of model performance reached a high standard.

Table 2

Values of CC, RMSE, and SS of the modeled and observed flow velocity at the surface and bottom layers at the measurement sites.

Layer	Sites	RMSE（m/s）	CC	SS
Surface	A	0.35	0.63	0.79
	B	0.23	0.93	0.89
	C	0.34	0.75	0.85
	Buoy 1	0.34	0.73	0.84
	Buoy 2	0.27	0.88	0.93
	Buoy 3	0.24	0.86	0.92
Bottom	A	0.21	0.51	0.71
	B	0.21	0.75	0.86
	C	0.18	0.73	0.84
	Buoy 1	0.11	0.78	0.87
	Buoy 2	0.12	0.84	0.90
	Buoy 3	0.10	0.80	0.88

Table 3

Values of CC, RMSE, and SS of the modeled and observed salinity at the surface and bottom layers at the measurement sites.

Layer	Sites	RMSE	CC	SS
Surface	A	1.88	0.73	0.85
	B	2.49	0.85	0.90
	C	2.24	0.71	0.80
	Buoy 1	2.33	0.87	0.93
	Buoy 2	1.73	0.92	0.96
	Buoy 3	0.36	0.83	0.89
Bottom	A	2.14	0.66	0.80
	B	1.57	0.92	0.95
	C	1.30	0.86	0.92
	Buoy 1	1.31	0.87	0.92
	Buoy 2	/	/	/
	Buoy 3	0.29	0.90	0.95

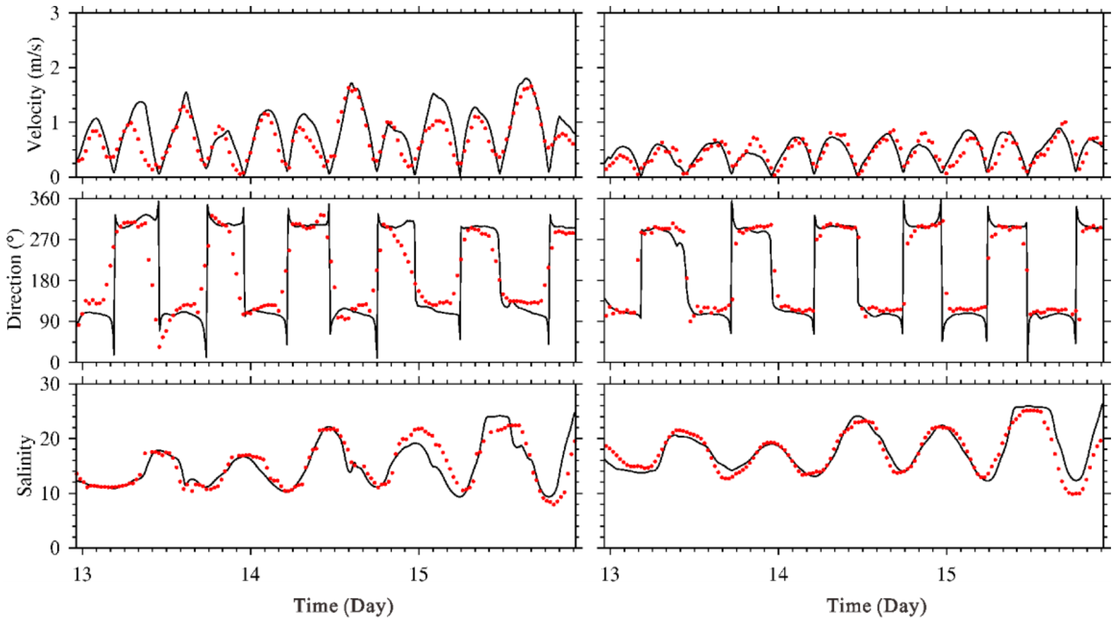

Fig. 3. Comparisons of modeled (line) and measured (dots) flow velocity/direction and salinity during neap tides at the surface layer (left panel) and bottom layer (right panel) at site B in March 2018.

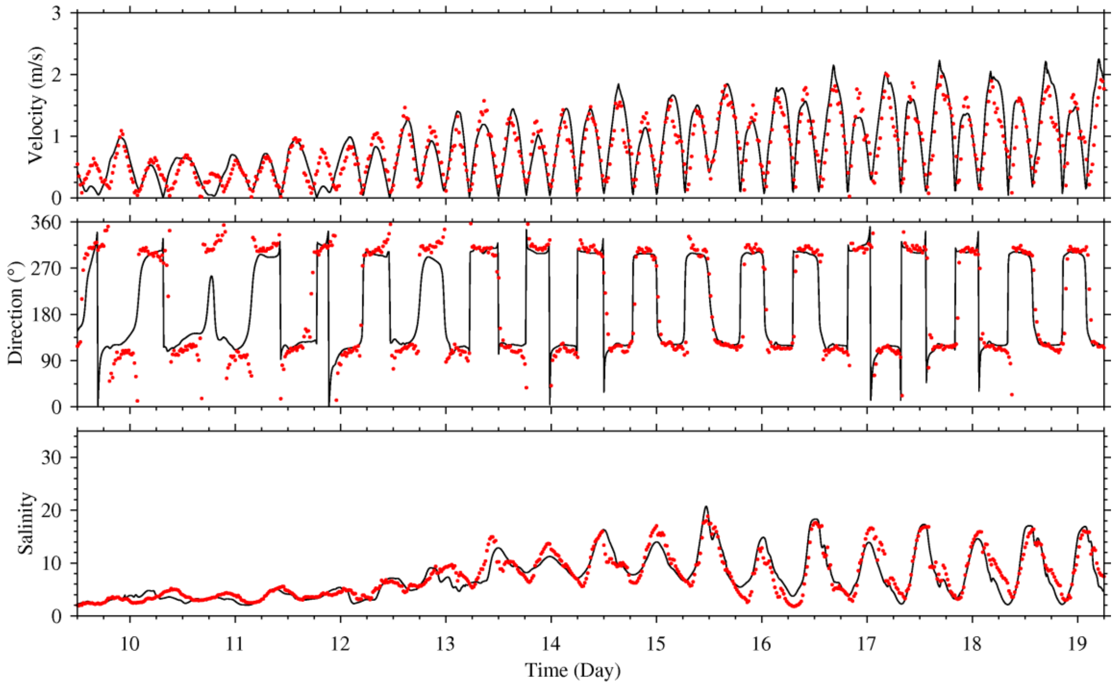

Fig. 4. Comparisons of modeled (line) and measured (dots) flow velocity/direction and salinity at the surface layer at site Buoy 2 in March 2018.

3. Results and Discussion

3.1 Topography change from 2007 to 2017

During the period from 2007 to 2017, some major reclamation projects were conducted in the Changjiang Estuary, including the reclamation projects in the Eastern Hengsha Shoal, the Qingcaosha Reservoir (shown in Fig. 1b) for the demands of land and water. These projects considerably changed the local topography and further changed the topography in the entire estuary by altering the hydrodynamic processes (Lyu and Zhu, 2018a; Zhu and Bao, 2016). Due to these anthropogenic activities, the Changjiang Estuary has undergone dramatic topography change from 2007 to 2017. Fig. 1 showed the estuarine topographies for 2007 and 2017, while the topography change in the recent decade was shown in Fig. 5. The topography was found markedly changed in some places. The topography in the lower reaches of the North Branch was deposited approximately by 2 - 4 m overall. The area in the lower reaches of the North Branch and near Chongming Island has turned into land from the tidal flat, which made it narrower and shallower. In the South Branch, the area south of Chongming Island silted severely, and the maximum value reached a thickness of 6 m, while the middle of the channel deepened. In the North Channel, the depth north of the middle and lower QCSR was heavily deposited. In contrast, the depth deepened greatly south of Chongming Island and north of the middle QCSR, in the middle of the channel and east end of the QCSR. Near the mouth of the North Channel, the depth silted overall except the area north of Hengsha Island. The area east of the reclamation project of Eastern Hengsha Shoal silted 2-4 m. In the South Channel, the depth in the upper reaches deepened by 2-4 m. The depth became shallow north of the North Passage and became deep in the main channel in a range of approximately 2 m. The depth variation in the South Passage was smaller compared with other channels in a range of approximately 1 m. And the net volume change in the North Branch, South Branch, North Channel, South Channel, North and South

Passages were -1.73×10^8, 3.24×10^8, 9.34×10^7, 2.90×10^8, -3.19×10^7 and 1.03×10^8 m^3, respectively (The negative indicates deposition). However, although the net volume changes in the North Channel indicated erosion as a whole, it was mainly eroded in the upper reaches. The lower reaches were significant deposition and net volume change in the lower reaches was -7.80 ×10^7 m^3.

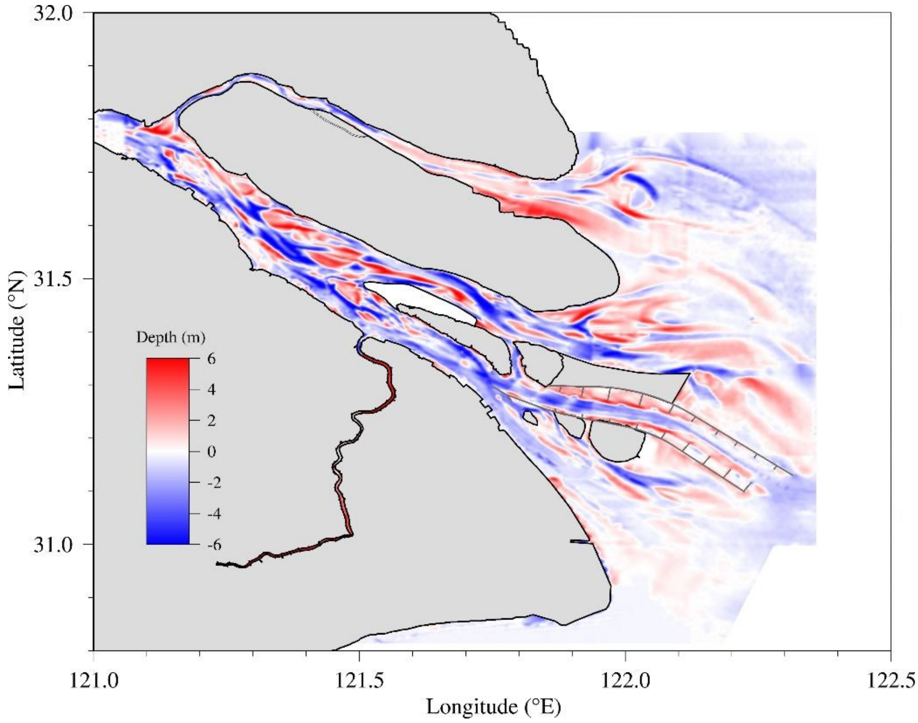

Fig. 5. Topographic changes between 2007 and 2017 indicated by water depth changes measured in 2007 in 2017 (-ve = deposition and +ve= erosion).

3.2 RUWF, RUSF, Saltwater Intrusion and WDR in 2007

Fig. 6a shows that the surface RUWF flowed seaward in the South Branch, North and South Passages during the spring tide, but the RUWF flowed into the estuary in the North Branch due to its funnel shape and tidal Stokes transport (Qiu and Zhu, 2015). This indicated that the river runoff flows into the sea mainly through the North Channel, North and South Passages. In the upper reaches of the North Branch, the NTWF and WDR were -300.1 m^3/s and

-2.6% (Table 4), respectively, where the negative sign indicated that the water was transported from the North Branch into the South Branch. Most of the river runoff (72.8%) flowed into the sea through the North Channel compared with the South Channel (Table 5). Similarly, the South Passage was the main channel (54.3%) for the river runoff into the sea compared with the North Passage (Table 6). The RUWF flowed northward east of Chongming Island due to tidal pumping transport and tidal Stokes transport (Qiu and Zhu, 2015). Additionally, the RUWF in the South Branch was seaward in both the surface and bottom layers but smaller in the bottom layer due to bottom friction (Fig. 6b). Near the river mouth, the bottom RUWF was landward, which was believed to be induced by a strong salinity front (Pritchard, 1956). The RUWF flowed seaward in the surface layer and landward bottom layers east of the Eastern Hengsha Shoal. As shown in Fig. 6(c, d), the distribution of RUSF was similar to that of RUWF. Due to high salinity around the outside of the river mouth, the magnitude of the RUSF was much larger in that area. On the northern side of the North Passage, the RUSF flowed landward, which brought high salinity into the North Channel and the area east of Chongming Island. The North Branch was occupied by the highly saline water, and the SSO was simulated, which was caused by the RUWF and RUSF flowed into the South Branch from the North Branch in the upper reaches (Fig. 6). The less saline water northeastward extended east of Chongming Island, which corresponded to the RUSF. Obviously, the saltwater intrusion in the bottom was stronger. Among each outlet in the Changjiang Estuary, the saltwater intrusion was the weakest in the North Channel and strongest in the South Passage.

During neap tide (Fig. 7), around the area outside of the river mouth, the RUWF and RUSF flowed southward because the northerly winter monsoon effect was dominant with the tide becoming weaker (Wu et al., 2014). The SSO, which occurred during spring tide, disappeared.

The NTWF became positive (93 m^3/s), and the WDR was 0.7% (Table 4). Compared with the South Channel, the North Channel was the main channel for river discharge, which accounts for 66.7% (Table 5). Compared with the South Passage, more river runoff flowed into the sea from the North Passage, accounting for 86.6% (Table 6), which was due to blocking of the stronger salinity front in the South Passage. Near the river mouth, due to a strong horizontal salinity gradient, the RUWF and RUSF in the bottom layer flow landward obviously. The saltwater induced by the SSO during spring tide has arrived at the middle reaches of the South Branch. Because the tidal mixing become weaker in neap tide than in spring tide, there existed distinct saltwater wedges near the river mouth in neap tide, resulting in high stratification, i.e., the bottom salinity was greater than the surface salinity.

Table 4

NTWF and WDR in the North and South Branches (NB and SB) during spring and neap tides in 2007 and 2017

Year	**NTWF (m^3/s)**				**WDR (%)**			
	Spring		Neap		Spring		Neap	
	NB	SB	NB	SB	NB	SB	NB	SB
2007	-300.1	11804.9	93.4	12779.8	-2.6	102.6	0.7	99.3
2017	-330.9	11842.4	199.1	12606.8	-2.9	102.9	1.6	98.4
$\Delta_{2017-2007}$	-30.8	37.5	105.7	-173.0	-0.3	0.3	0.9	-0.9

Table 5

NTWF and WDR in the North and South Channels (NC and SC) during spring and neap tides in 2007 and 2017

Year	NTWF (m^3/s)				WDR (%)			
	Spring		Neap		Spring		Neap	
	NC	SC	NC	SC	NC	SC	NC	SC
2007	8507.7	3180.4	8631.3	4303.8	72.8	27.2	66.7	33.3
2017	7655.1	4055.0	8060.2	4630.7	65.4	34.6	63.5	36.5
$\Delta_{2017-2007}$	-852.6	874.6	-571.1	326.9	-7.4	7.4	-3.2	3.2

Table 6

NTWF and WDR in the North and South Passages (NP and SP) during spring and neap tides in 2007 and 2017.

Year	NTWF (m^3/s)				WDR (%)			
	Spring		Neap		Spring		Neap	
	NP	SP	NP	SP	NP	SP	NP	SP
2007	2707.3	2282.2	5266.3	817.1	54.3	45.7	86.6	13.4
2017	3460.5	1750.9	5132.7	818.7	66.4	33.6	86.2	13.8
$\Delta_{2017-2007}$	753.2	-531.3	-133.6	1.6	12.1	-12.1	-0.4	0.4

Table 7

NTSF in the North and South Branches (NB and SB) during spring and neap tides in 2007 and 2017

Year	NTSF (t/s)			
	Spring		Neap	
	NB	SB	NB	SB
2007	-7.70	7.45	0.03	0.12
2017	-6.10	5.81	0.04	0.12
$\Delta_{2017-2007}$	1.60	-1.64	0.01	0.00

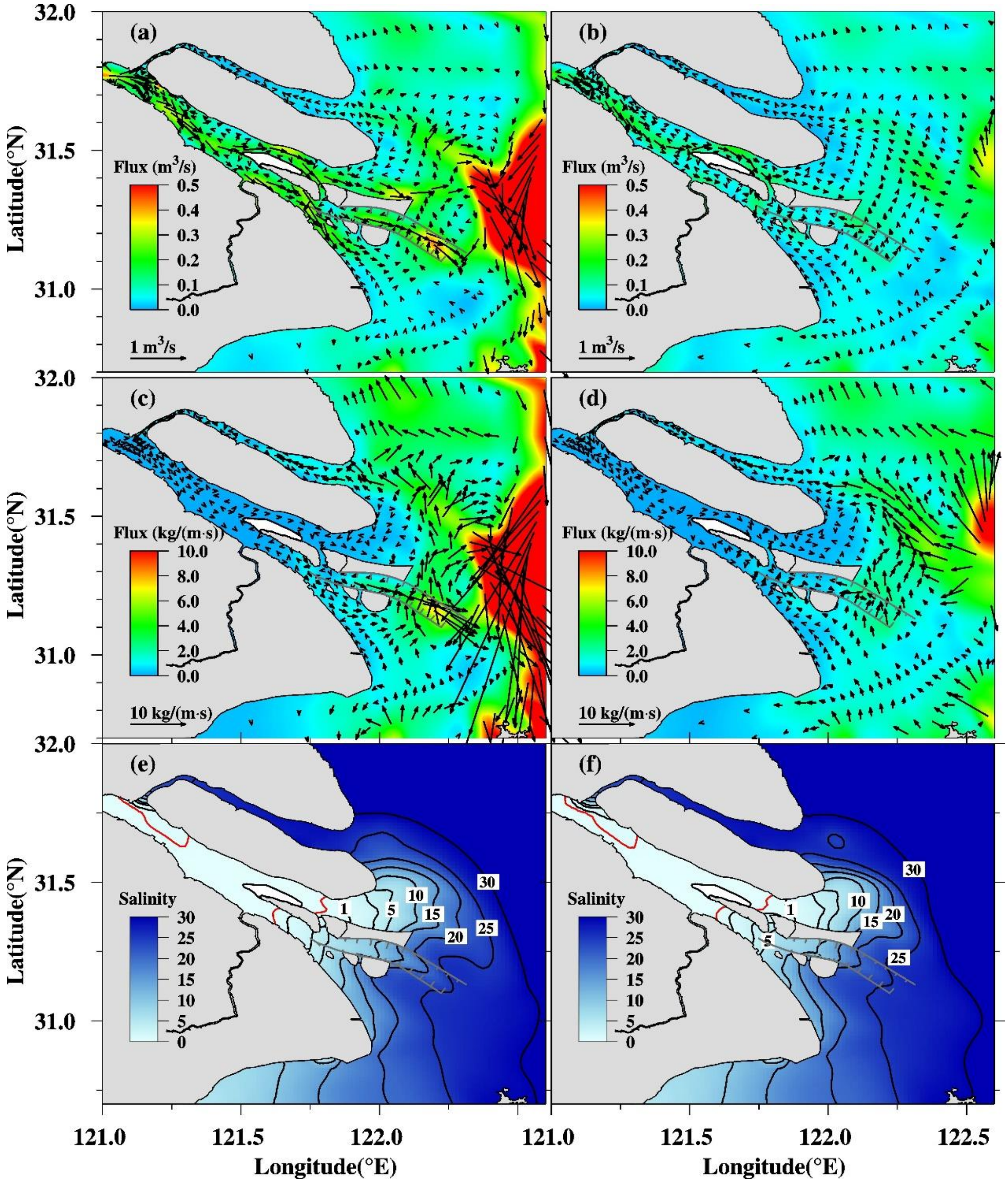

Fig. 6. Distributions of RUWF (a, b), RUSF (c, d) and salinity (e, f) in the surface (left panel) and bottom (right panel) layers during spring tides in 2007. (The red isohalines in (e, f) are 0.45, the standard salinity for drinking water).

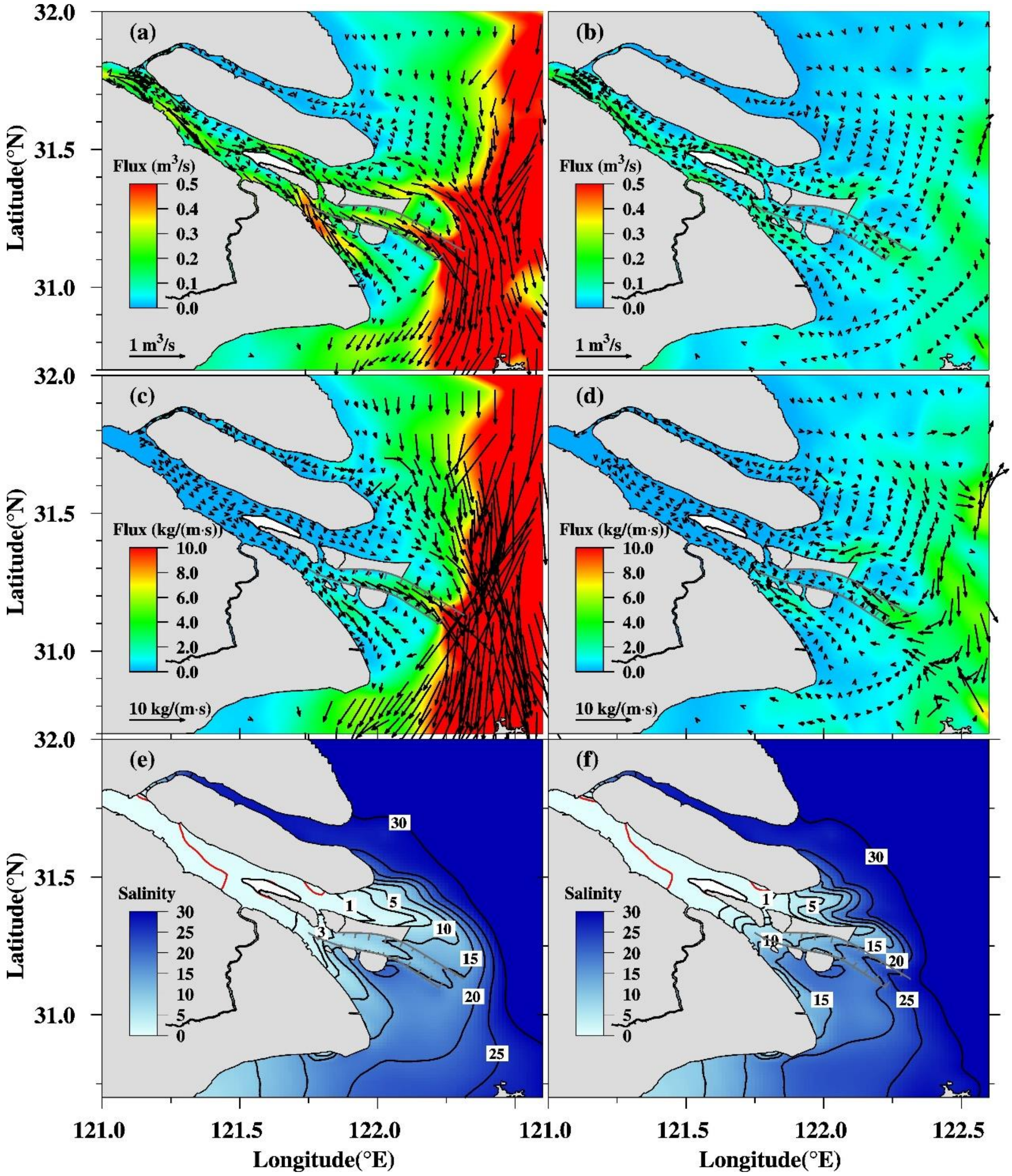

Fig. 7. Distributions of RUWF (a, b), RUSF (c, d) and salinity (e, f) in the surface (left panel) and bottom (right panel) layers during neap tides in 2007.

3.2 RUWF, RUSF, Saltwater Intrusion and WDR in 2017

The differences in distributions of the RUWF, RUSF and salinity between 2017 and 2007 in the surface and bottom layers during spring tide were shown in Fig. 8. The differences of RUWF and RUSF in the North Branch were landward, which was the same direction as RUWF and RUSF in 2007, which meant that the saline transport from the sea to the North Branch increased in 2017. However, the salinity in the North Branch decreased overall as shown in Fig. 8(e, f). This was because the topography became narrower and shallower in the middle and lower reaches of the North Branch (as shown in Fig. 1 and Fig. 5), which resulted in a decrease in the tidal volume. This could also cause the increase in the North Branch water velocity, so that the RUWF and RUSF increased. The NTWF in the North Branch was -330.9 m^3/s, which increased by 30.8 m^3/s from the North Branch to the South Branch, but the NTSF decreased 1.6 t/s (Table 7). Therefore, the SSO became weaker overall in 2017 than in 2007. The salinity in the South Branch changed little. However, Fig.5 showed that major changes in topography were detected along the Southern Branch. It can be seen from Fig. 6(e, f) and Fig. 7(e, f) that the South Branch was almost occupied by freshwater because the South Branch is the main channel for river water discharging into the sea. Therefore, though major changes in topography were detected along the Southern Branch, the salinity was very low and its change was small. However, the topography changes in the South Branch could influence the water diversion ration in the North and South Branch, which could further influence the saltwater intrusion near the river mouth where there existed salinity front. A small change of water diversion ration can cause obvious isohaline move. That is why all the changes in isohaline were noticed near the mouth and further seaward. The difference of RUWF and RUSF in the North Channel was strongly correlated with that of the topography. The RUWF and RUSF increased with the increase of water depth. Fig. 8(e, f) show that the salinity in the North Channel increased, especially in the area east of Chongming Island and Eastern Hengsha Shoal, with a maximum value of more than 4.0. The deposition in these areas was noticeable (Fig. 5), which blocked the freshwater discharge into the North Channel. The WDR in the North Channel was 65.4% in

2017, which decreased by 7.4% compared with 2007 (Table 5), resulting in an overall increase in salinity in the North Channel in 2017. Owing to the decrease in lower salinity water that flowed over the area east of the Eastern Hengsha Shoal, the amount of lower saline water that flowed cross the north dyke of the Deep Waterway to the south decreased under the action of the north winter monsoon. Therefore, the salinity near the mouth of the North and South Passages slightly increased.

During neap tide, the patterns of difference in the distributions of the RUWF, RUSF and salinity between 2007 and 2017 in the surface and bottom layer were different from those during spring tide, and the variations were the opposite in some areas (Fig. 9). In the North Branch, the RUWF and RUSF showed little change with the weaker tide, while the WDR increased in 2017, which caused the salinity in the North Branch to decrease overall. In the South Branch, the difference in RUWF and RUSF was correlated with the difference in the topography. Similar to that in the spring tide, the salinity east of Chongming Island and Eastern Hengsha Shoal increased. However, the surface salinity near the 122.5°E area in the mouth of the North Channel and the bottom salinity north of the Eastern Hengsha Shoal decreased by more than 4.0 at its maximum. As shown in Fig. 9, the difference in the surface RUSF (Fig. 9c) was the opposite of the surface RUSF (Fig. 7c) in 2007 near the 122.5°E area in the mouth of the North Channel. This meant that the high salinity water from the north decreased. The bottom salinity decreased because the saltwater wedge weakened. The salinity variation, s', at each layer and its mean value in the water column can be estimated with a polynomial expression given by Hansen and Rattray (1966),

$$s' = \frac{H^2}{K_S}\bar{s}_x[\bar{u}(-\frac{7}{120}+\frac{1}{4}\zeta^2+\frac{1}{4}\zeta^2-\frac{1}{8}\zeta^4)+u_E(-\frac{1}{12}+\frac{1}{2}\zeta^2-\frac{3}{4}\zeta^4-\frac{2}{5}\zeta^5)] \qquad (6)$$

where s indicates the width-averaged, tidally averaged salinity, which can be divided into depth-average ($\overline{s}$) and depth-varying (s') parts. The subscript x denotes the along-channel partial derivative. K_S is the vertical eddy diffusivity; the dimensionless coordinate $\zeta = z/H$, where z indicates water depth, with $z=0$ as the surface layer and $z=-H$ as the bottom layer, and H indicates topography. River discharge is given by $\overline{u}$, $u_E = g\beta\overline{s}_x H^3/(48K_M)$, where $\beta \cong 7.7\times10^{-4}/PSU$ and K_M indicates the vertical eddy viscosity. When $z=0$ and $z=-H$, formula (6) can be written as follows:

$$\begin{cases} s' = -\dfrac{H^2}{120K_S}\overline{s}_x(7\overline{u}+10u_E) & z=0 \\ s' = \dfrac{H^2}{15K_S}\overline{s}_x(\overline{u}+u_E) & z=-H \end{cases} \tag{7}$$

It is clear that the increased H can augment the salinity variation s'. Therefore, as the depth near the mouth of the North Channel was deposited all together (as shown in Fig. 5), the decreased H reduced the variation s' near the bottom, resulting in a weaker gravitational circulation that transported less oceanic saltwater into the estuary and decreased the bottom salinity. Additionally, although the WDR in the North and South Passages had little variation, namely, approximately 0.4%, the WDR in the South Channel increased by 3.2% in 2017, resulting in a slight decrease in salinity.

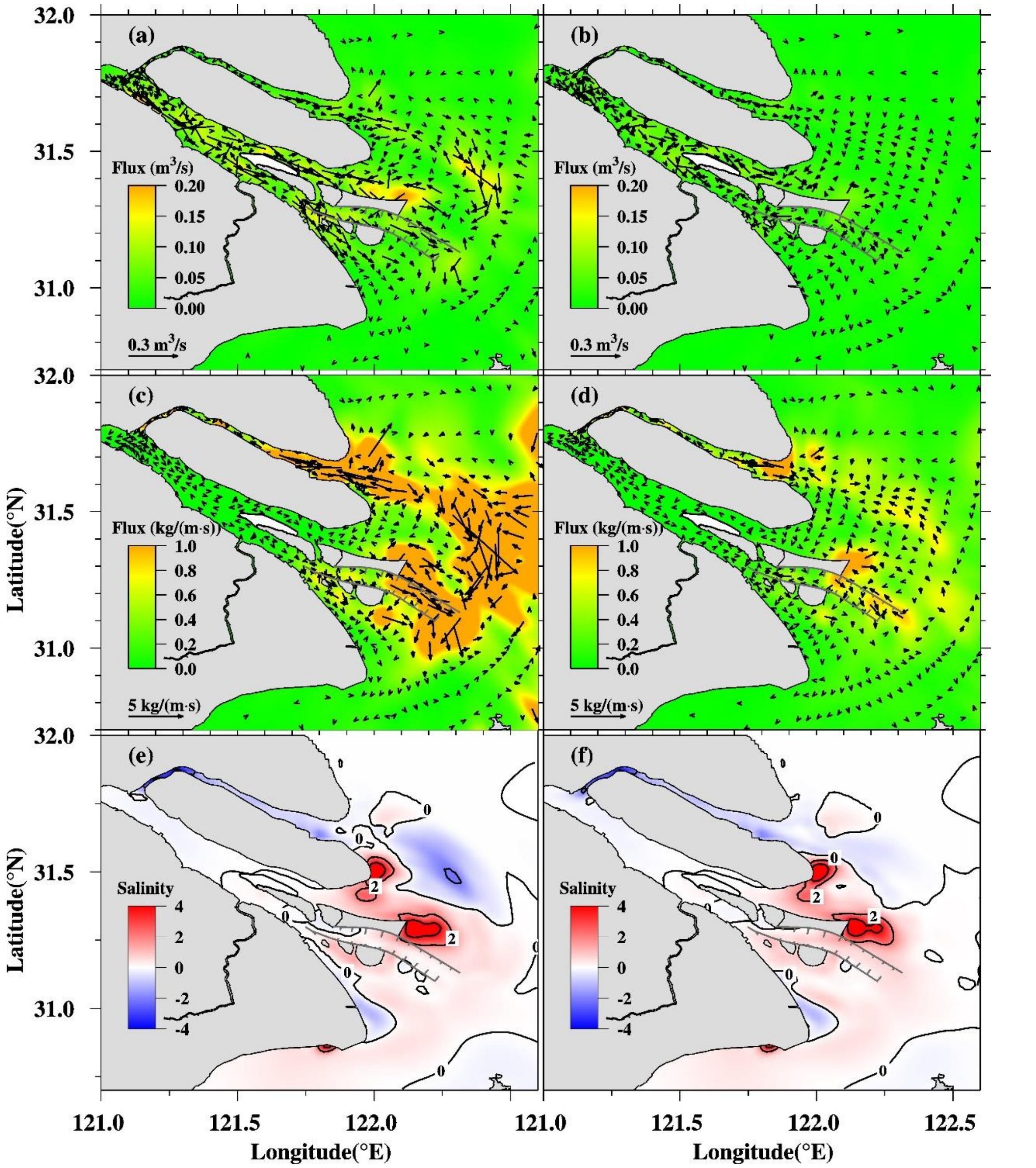

Fig. 8. Changes of RUWF (a, b), RUSF (c, d) and salinity (e, f) between 2017 and 2007 in the surface (left panel) and bottom (right panel) layers during spring tides.

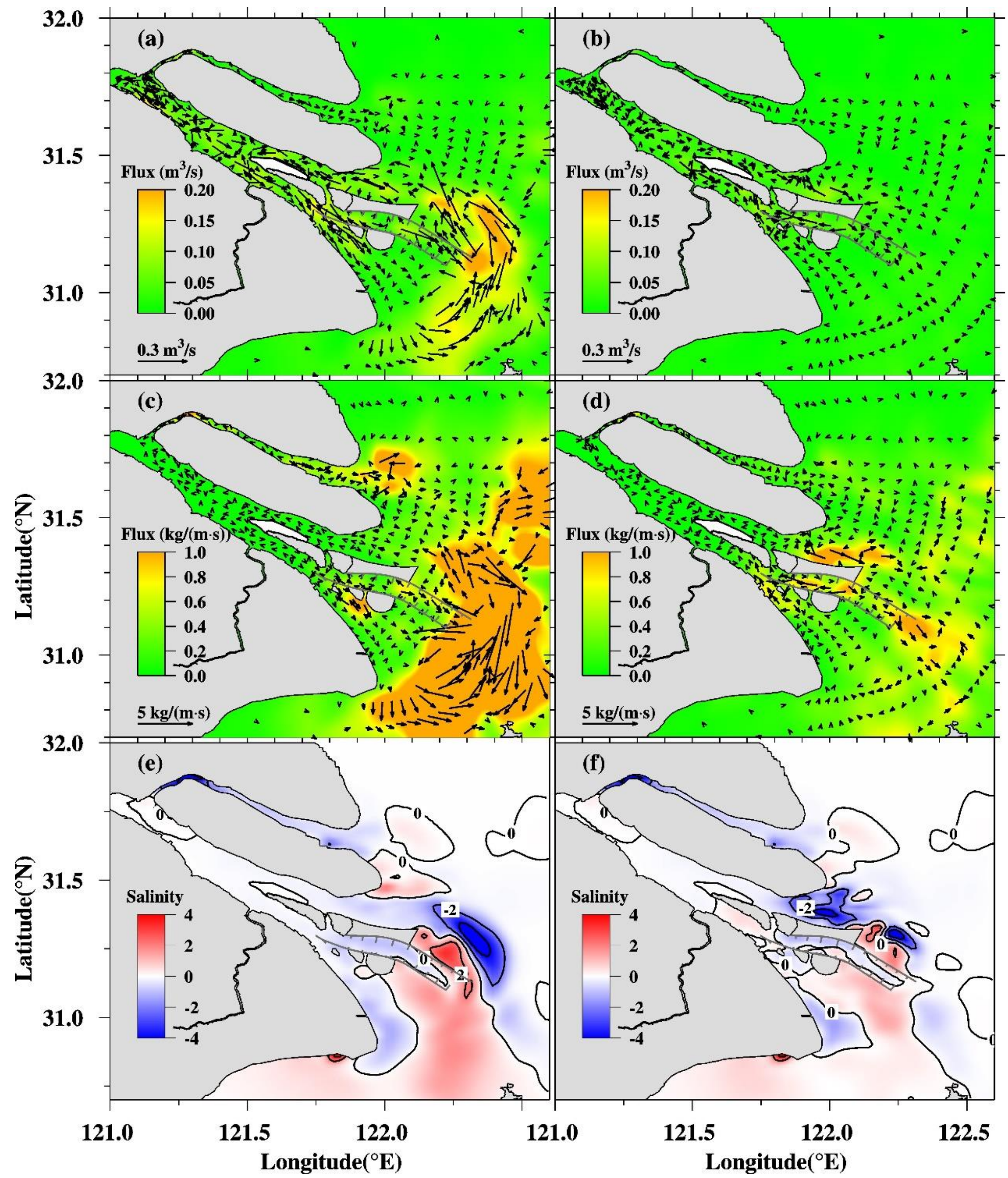

Fig. 9. Changes of RUWF (a, b), RUSF (c, d) and salinity (e, f) between 2017 and 2007 in the surface (left panel) and bottom (right panel) layers during neap tides

3.3 Variations in Vertical Salinity Distributions

The vertical distributions of salinity during spring tide along the North Branch profile (P1), South Branch-North Channel profile (P2) and South Branch-South Passage profile (P3) in 2007 and 2017 are shown in Fig. 10. It was obvious that the depth near the bifurcation of the North and South Branches became shallower. The depth at the start point of P1 was approximately 7.2 m in 2007, but it became approximately 0.3 m in 2017. Although the depth at nearly 17.5 km increased from 11.5 to 15.2 m over the ten year period, the average depth from 40 to 80 km decreased from 7.3 to 6.62 m. Therefore, it would certainly decrease the tidal volume in the North Branch. In Fig. 10a, the isohaline was densely distributed between 0 and 20 km, and the bottom salinity was higher than the surface salinity. The isohaline distribution was sparser in 2017, and the isohaline of 20 moved downstream from 10 km to 20 km. Overall, the saltwater intrusion in the North Branch became weaker in 2017 than in 2007. The vertical salinity distributions along P2 in 2007 and 2017 are shown in Fig. 10b. The water depth in 2017 became shallow overall. In the upstream and midstream areas, the depth changed slightly, except for the area near 7 km, which decreased from 52.4 to 35.4 m. The average depth in the downstream, namely, from 80 km to the end of P2, decreased from 9.9 to 9.1 m. The salinity in the upstream region was less than 0.45, indicating that freshwater existed. The intensity of SSO weakened in 2017, which could be proven by the location of the bottom isohaline being 1 in 2007. Nearly all the isohalines in the downstream moved upstream by approximately 5 km in 2017 compared to 2007. Therefore, the saltwater intrusion along the North Channel was enhanced in 2017. The vertical salinity distributions along P3 in 2007 and 2017 are shown in Fig. 10(e, f). The variation in depth was great at a distance of approximately 5 km from the start point of P3, which decreased from 53.9 to 41.8 m. Compared with the isohaline distribution in 2007, the variation was very small. In 2017, the isohalines moved upstream by approximately 1 km compared with that in 2007. The saltwater intrusion increased slightly in 2017.

During neap tide, the salinity upstream of the North Branch decreased markedly. In 2007, isohaline 0.45 appeared (Fig. 11a). Similar to that in the spring tide, the isohalines moved downstream by approximately 5 km in 2017. The saltwater intrusion in the North Branch was also weakened in 2017. However, unlike during spring tide, the saltwater intrusion in the North Channel became weaker in 2017 than that in 2007 because the main character of the saltwater intrusion during neap tide was a salt wedge (Fig. 11b). Fig. 10c shows that the bottom salinity was much greater than the surface salinity regardless of being in the North Channel or South Passage. The average depth downstream was decreased from 9.9 m in 2007 to 9.1 m in 2017, resulting in a reduction in bottom salinity. Isohaline 1 moved downstream by approximately 8 km in 2017, and isohaline 5 retreated from 82 km in 2007 to 88 km in 2017. Relative to the North Channel, the depth in the South Passage showed little change. Because the WDR in the South Channel increased from 33.3% to 36.5% over the last ten years, the saltwater intrusion was weakened in 2017.

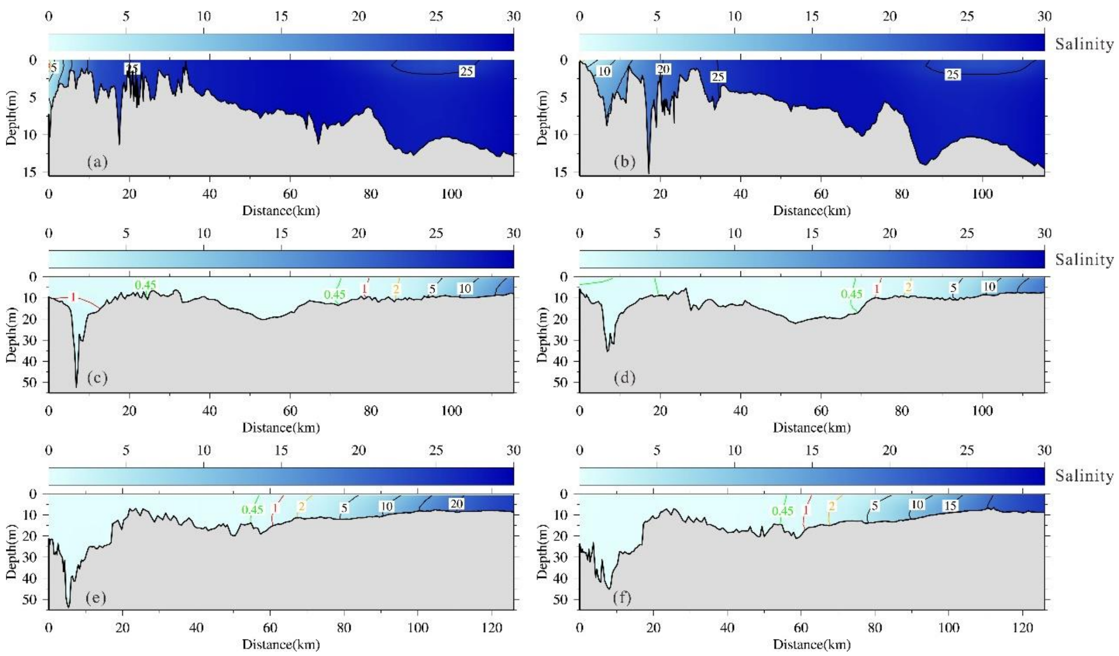

Fig. 10. Distribution of salinity along profiles P1(a, b), P2 (c, d) and P3 (e, f) during spring tides in 2007 (left panel) and 2017 (right panel)

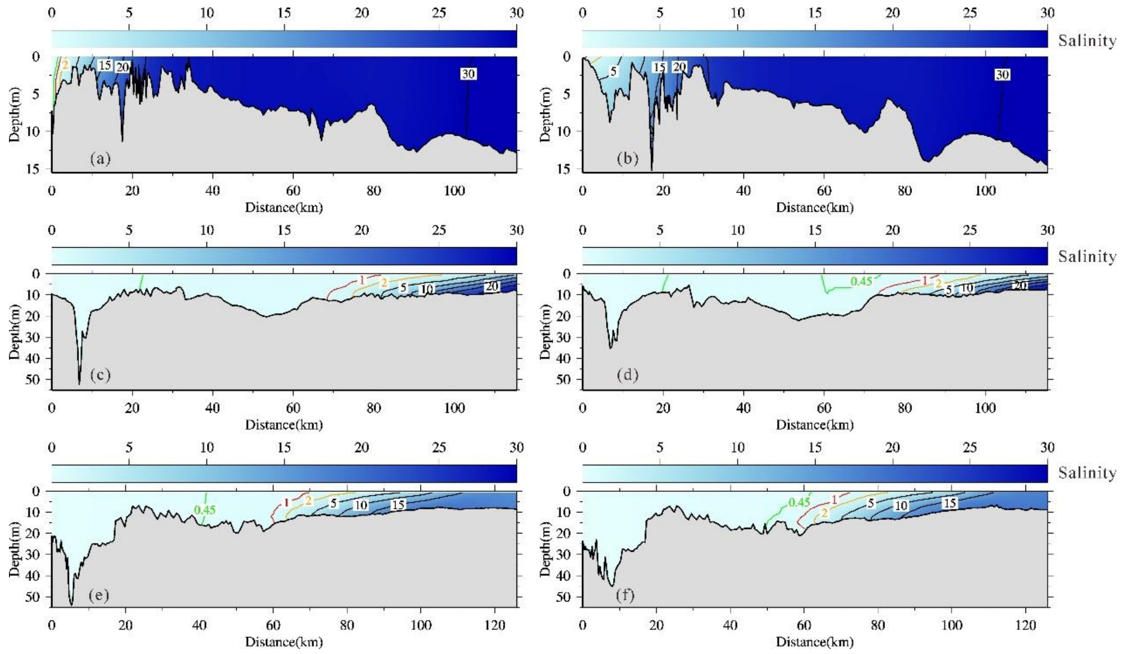

Fig. 11. Distribution of salinity along profiles P1(a, b), P2 (c, d) and P3 (e, f) during neap tides in 2007 (left panel) and 2017 (right panel)

3.4 Scenario of Complete Silt-up of the North Branch

Over hundred years ago, the North Branch was the main channel discharging the river water into the sea and sediments were gradually deposited, especially since the 1960s, due to large tidal flat reclamation (Shen et al., 2003). Comparing the topography change in 2017 and 2007, the deposition at the upper entrance of the North Branch was very severe (Fig. 5). It is generally acknowledged that the North Branch will completely silt-up in the future. So we suppose the scenario that the North Branch would vanish and simulate its impact on saltwater intrusion and freshwater resources.

The SSO disappeared in the scenario of the North Branch silt-up, resulting in a salinity decrease in the South Branch. On the other hand, the river discharge was reduced in the North Channel, North and South Passages because there was no water spillover from the North Branch into the South Branch, which accounted for 2.9% of the total river discharge during the spring tide in 2017 (Table 3), resulting in enhanced saltwater intrusion (Fig. 12). The salinity decrease was at the upper reaches of the South Branch during spring tide and moved down to the middle and lower reaches of the South Branch. Salinities at the water intakes of the three reservoirs all decreased. The maximum salinity increase east of Chongming Island reached 2. Therefore, vanishing of the North Branch weakened the saltwater intrusion in the South Branch and enhanced it in the North Channel, North and South Passages.

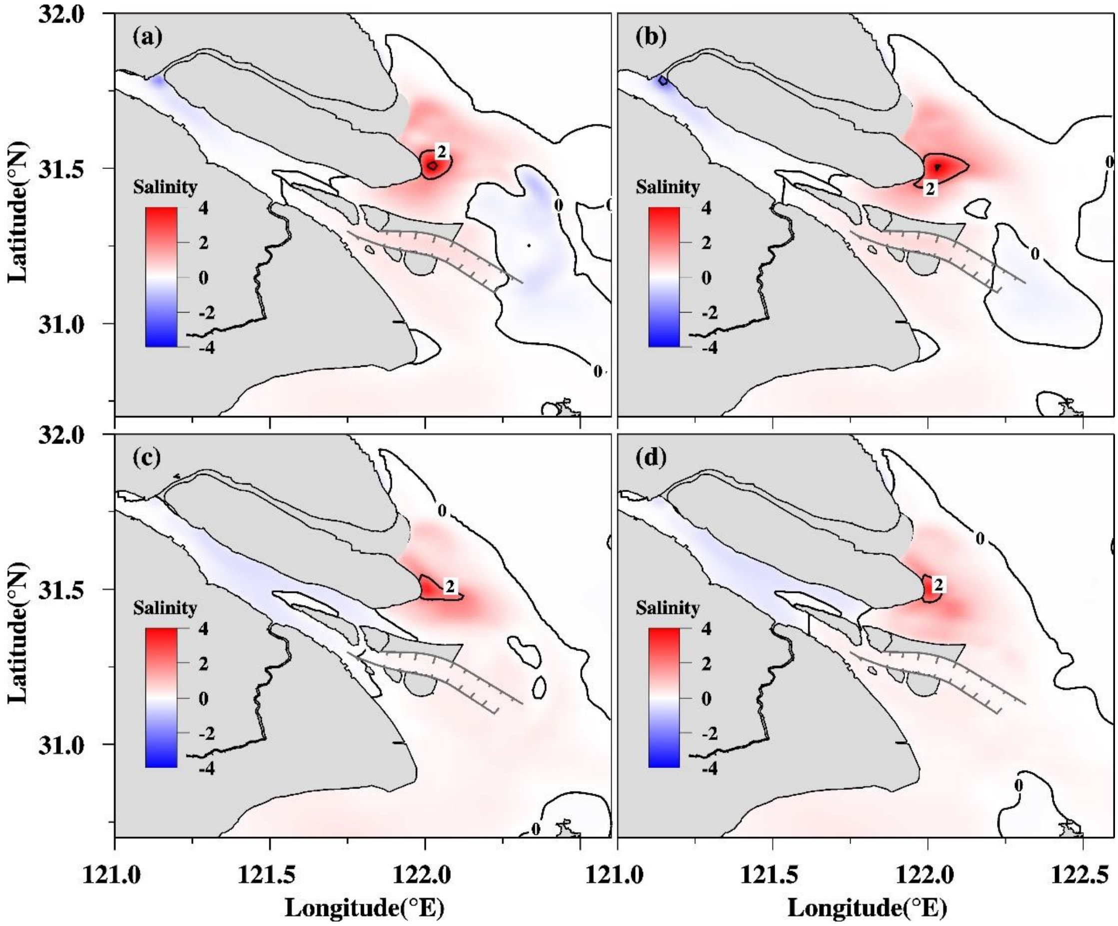

Fig. 12. Changes in salinity between the scenario of complete silt-up in the North Branch and 2017 topography in the surface (left panel) and bottom (right panel) layers during spring tides (a, b) and neap tide (c, d).

3.5 Impacts on Water Resources

The saltwater intrusion frequently threatens the freshwater intake from the Changjiang Estuary during winter due to low river discharge. Confirming the results of past studies, the salinities at the DFXSR and CHR were completely influenced by the SSO, but the QCSR was mainly impacted by the SSO and the saltwater intrusion along the North Channel (Chen and Zhu, 2014; Li and Zhu, 2018; Lyu and Zhu, 2018b).

The temporal surface salinity variations and tidally averaged salinity in different tidal patterns (spring, middle tide after the spring tide (MTST), neap and middle tide after the neap tide (MTNT)) at the water intakes of the DFXSR, CHR and QCSR in 2007, in 2017 and in the scenario of vanishing of the North Branch are shown in Fig. 13 and Table 8, respectively. The temporal variations in the salinities showed that there were semidiurnal flood and ebb periods and semimonthly spring and neap period variations induced by tide. In 2007 and 2017, at the water intake of the DFXSR, the salinity was higher during the spring and MTST, and the salinity was lower during the neap and MTNT. The duration in which the salinity was lower than 0.45 was approximately half of the time in 2007 and 2017 in a complete neap-spring cycle, and the reservoir had enough time to take water from the Changjiang Estuary. In 2007, the tidally averaged salinity at the water intake of the DFXSR during spring tide, MTST, neap tide and MTNT were 0.80, 0.97, 0.16 and 0.08, respectively. At the water intake of the CHR, the duration in which the salinity was lower than 0.45, was greater than two-thirds of the time. Additionally, it took approximately 2.0 days for the saline water induced from the SSO flowed downstream to move from the water intake of the DFXSR to the water intake of the CHR, which we determined by comparing the salinity peak phase difference at the water intakes of the CHR and DFXSR (Fig. 13). In 2007, the tidally averaged salinity at the water intake of CHR during spring tide, MTST, neap tide and MTNT were 0.09, 0.74, 0.31 and 0.02, respectively, meaning that water resources were optimistic in the CHR except during MTST. In 2007, at the water intake of the QCSR, the duration in which the salinity was lower than 0.45 was approximately half of the time. The tidally averaged salinity at the water intake of the CHR during spring tide, MTST, neap tide and MTNT were 0.10, 0.50, 0.53 and 0.22, respectively, meaning that water resources were optimistic in the QCSR except during MTST and neap tide. The above simulated temporal variation processes in salinity at the water intakes of three reservoirs were reasonably close to the published studies (Zhu et al., 2013; Zhu and Wu, 2013; Chen et al., 2019).

As mentioned above, the SSO were somewhat weakened after the last ten years, which resulted in the salinity being slightly decreased overall at the water intakes of the DFXSR, CHR and QCSR (Fig. 13). Owing to the saltwater sources were mainly from the SSO, the salinity was decreased by 0.17 and 0.06 at the water intake of the DFXSR during spring tide and MTST, and there were no changes during neap tide or MTNT. The salinity was decreased by 0.07 and 0.16 at the water intake of the CHR during spring tide and MTST, and there was a slight increase of 0.02 during MTNT. The salinity decreased by 0.00, 0.09, 0.04 and 0.02 at the water intakes of the QCSR during spring tide, MTST, neap tide, and MTNT, respectively, which meant that the change in topography in the past ten years was favorable for the water resources of the three reservoirs in the Changjiang Estuary.

In the scenario of vanishing of the North Branch, the salinity approached 0 at the water intakes of the DFXSR and CHR and significantly decreased at the water intake of the QCSR due to vanishing of the SSO. The scenario of complete silt-up in the North Branch was greatly favorable for the utilization of freshwater resources in the Changjiang Estuary.

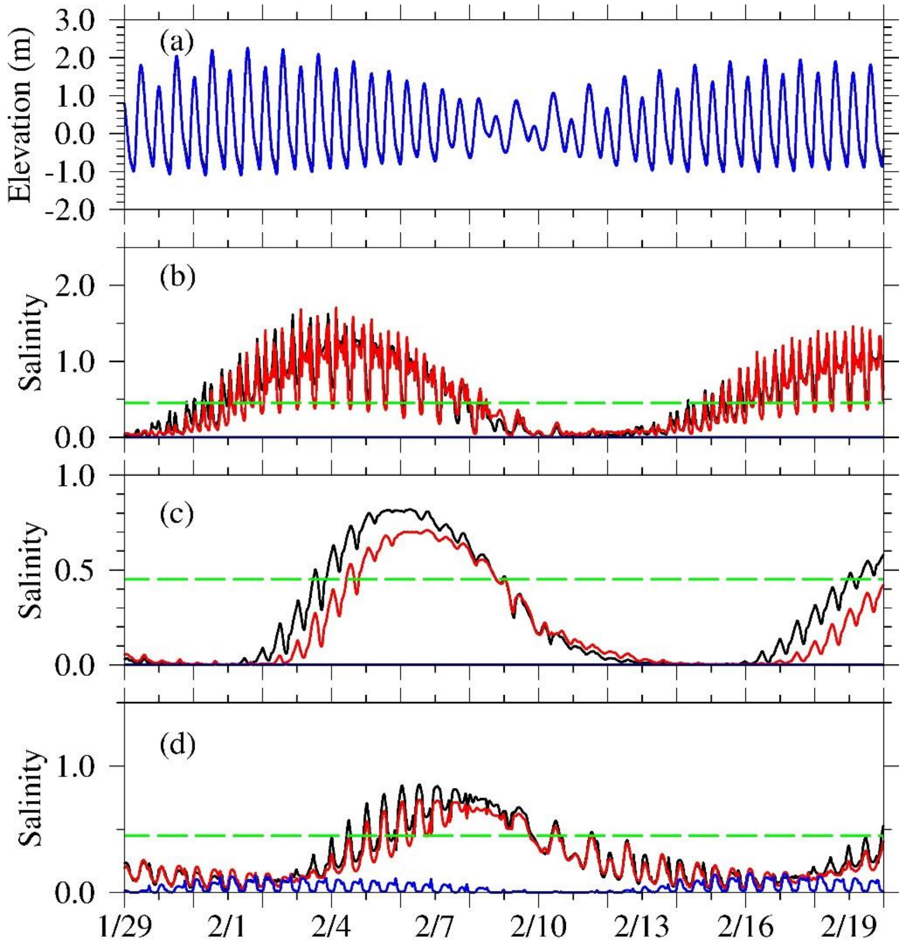

Fig. 13. Time series of computed water levels at the water intake of the QCSR (a), surface salinity at the water intakes of the DFXSR (b), CHR (c) and QCSR (d) from January 29 to February 19. (Black lines: 2007 topography; red lines: 2017 topography; blue line: complete silt-up in the North Branch; green dashed line: the standard salinity of drinking water).

Table 8

Averaged salinity over four tidal patterns at the water intakes of the DFXSR, CHR and QCSR in 2007 and 2017, the scenario of complete silt-up in the North Branch and in 2017

		Spring	MTST	Neap	MTNT
DFXSR	2007	0.80	0.97	0.16	0.08
	2017	0.63	0.91	0.16	0.08

	Scenario	0.00	0.00	0.00	0.00
	$\triangle_{2017\text{-}2007}$	-0.17	-0.06	0.00	0.00
	$\triangle_{scenario\text{-}2017}$	-0.63	-0.91	-0.16	-0.08
CHR	2007	0.09	0.74	0.31	0.02
	2017	0.02	0.58	0.31	0.04
	Scenario	0.00	0.00	0.00	0.00
	$\triangle_{2017\text{-}2007}$	-0.07	-0.16	0.00	0.02
	$\triangle_{scenario\text{-}2017}$	-0.02	-0.58	-0.31	-0.04
QCSR	2007	0.10	0.50	0.53	0.22
	2017	0.10	0.41	0.49	0.20
	Scenario	0.06	0.05	0.01	0.02
	$\triangle_{2017\text{-}2007}$	0.00	-0.09	-0.04	-0.02
	$\triangle_{scenario\text{-}2017}$	-0.04	-0.36	-0.48	-0.18

4. Conclusions

A well-validated 3D numerical model was used to simulate the impacts of topography change on saltwater intrusion over the past decade in the Changjiang Estuary. The residual water and salt transport, WDR and water resources with the topographies measured in 2007 and 2017 in the Changjiang Estuary were analyzed. During the period from 2007 to 2017, the reclamation projects and the changing climate resulted in a considerable change in topography in the estuary. The model was validated with the data measured in the South Passage in March 2018 and the results showed that the model produced satisfactorily the hydrodynamics and saltwater intrusion in the Changjiang Estuary.

The RUWF, RUSF, WDR and salinity distribution in 2007 and 2017 and the impacts of topography change in the last ten years were simulated and analyzed. Due to the topography change in the past ten years, the salinity decreased overall regardless of spring tide or neap tide in the North Branch, which was caused by the much shallower and narrower channel, resulting in a weaker SSO. In the North Channel, the salinity increased during spring tide, and the saltwater wedge weakened during neap tide due to a decrease in depth near the river mouth. The salinity increased slightly near the mouth of the North and South Passages during spring tide and decreased slightly in the upper reaches of the North and South Passages during neap tide. The changes in the saltwater intrusions in each channel were dynamically interpreted with the changes in RUWF, RUSF and WDR.

For the three reservoirs, there was about half time in a spring-neap period to take freshwater from the Changjiang Estuary into the reservoirs in the dry season of 2007 and 2017 under mean river discharge. Because the saltwater intrusion in the North Branch and the SSO were weakened over the last ten years, the salinity at the water intakes of the DFXSR, CHR and QCSR decreased slightly, which was favorable for the fresh resources of the three reservoirs in the Changjiang Estuary.

In the scenario of complete silt-up in the North Branch, the SSO disappeared, and saltwater weakened in the South Branch, which was significantly favorable for the utilization of freshwater resources and enhances the North Channel, North and South Passages.

On the whole, influenced by the topography change in recent decade, saltwater intrusion weakened in the North Branch, enhanced in the North Channel, North and South Passages during spring tide and weakened during neap tide. Moreover, the results showed that the deposition or even complete silt-up in the North Branch was favorable for utilization of freshwater resources.

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Appendix 1: A list of acronyms and their corresponding full names in the paper

Acronym	Full Name
SSO	Saltwater spillover
DFXSR	Dongfengxisha Reservoir
CHR	Chenhang Reservoir
QCSR	Qingcaosha Reservoir
NCEP	National Centers for Environmental Prediction
RUWF	Residual unit width water flux
RUSF	Residual unit width salt flux
NTSF	Net transection salt flux
NTWF	Net transection water flux
WDR	Water diversion ratio
CC	Correlation coefficient
RMSE	Root mean square error
SS	Skill score
MTNT	Middle tide after the neap tide
MTST	Middle tide after the spring tide

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