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Impact of the eastern water diversion from the south to the north project on the saltwater intrusion in the Changjiang Estuary in China

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Abstract
The south to the north project (WDP) on the saltwater intrusion in the Changjiang Estuary is studied by the improved three-dimensional (3D) numerical model. The net unit width flux in the Changjiang Estuary as well as the sectional salt flux is calculated in the North Branch (NB), the South Branch (SB), the North Channel (NC), the South Channel (SC), the North Passage (NP) and the South Passage (SP), respectively. The net seaward water flux in the SB is reduced, and the net water flux spilling over from the NB to the SB is enhanced after the eastern WDP. Under the mean river discharge condition in the dry season, the net salt flux spilling over from the NB to the SB is increased by 2.09 t/s and 0.52 t/s during the spring and neap tides, respectively, due to the eastern WDP. The saltwater intrusion in the Changjiang Estuary is enhanced by the eastern WDP. Compared with that during the spring tide, the net water diversion ratio during the neap tide in the NC is smaller, and thus the enhancement of the saltwater intrusion by the eastern WDP is smaller in the NC, and larger in the NP and the SP. The tidally averaged surface salinity at the water intakes of the Dongfengxisha Reservoir, the Chenhang Reservoir and the Qingcaosha Reservoir rises both during the spring and neap tides.

Key words: eastern water diversion from the south to the north project, saltwater intrusion, Changjiang Estuary, numerical calculation, the water resource

1 Introduction

The Changjiang Estuary has three bifurcations and four outlets to the sea (Fig.1). Saltwater intrusion is controlled mainly by river discharge and tidal range (Shen et al., 2003; Han, 1983; Zhu et al., 2010; Wu et al., 2006; Liu et al., 2010; Chen et al., 2010; Li et al., 2010), and also influenced by the wind stress and the shelf circulation (Zhu et al., 2008; Wu et al., 2010; Xiang et al., 2009). The river discharge of the Changjiang River has a distinct seasonal variation. The decrease of river discharge in the dry season intensifies the saltwater intrusion in the estuary. The tide controls the saltwater intrusion in different time-scales. In the intratidal timescale, the semidiurnal flood-ebb tide drives saltwater flowing into the estuary during flood and out of the estuary during ebb. The fortnightly spring-neap tide generates the saltwater intrusion much stronger during the spring tide than during the neap tide. The saltwater intrusion is enhanced by the seasonal variation of tide when the tidal range reaches the maximum during March (Song et al., 2010). The Changjiang Estuary is located in the East Asian monsoon area, and there is a strong northerly wind prevailing during winter. The northerly wind produces a landward Ekman water transport, which intensifies saltwater intrusion in the North Branch (NB) and the North Channel (NC) (Wu et al., 2010; Li et al., 2010). The Taiwan Warm Current and the North Jiangsu (Subei) Coastal Current off the Changjiang Estuary carry high salinity water to the estuary, which is the source of the saltwater

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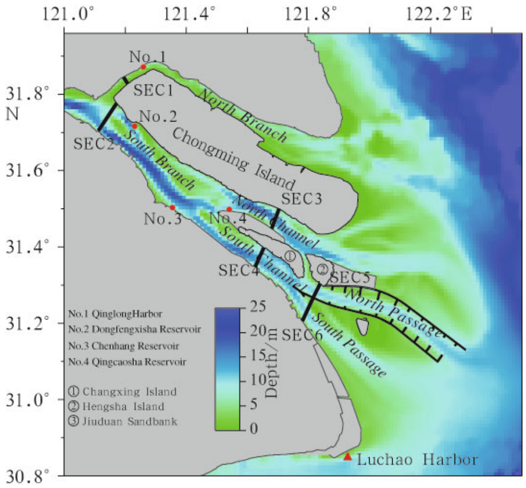

Fig.1. Sketch map of the Changjiang Estuary and its topography. Red dots are the output sites of the model; SEC1, SEC2, SEC3, SEC4, SEC5 and SEC6 are the transects in the upper reaches of the NB, in the upper reaches of the SB, in the NC, in the SC, in the NP and in the SP, respectively.

intrusion there (Xiang et al., 2009). The most remarkable feature of the saltwater intrusion into the Changjiang Estuary is the saltwater spilling over (SSO) from the NB into the SB in the dry season (Xiao et al., 2000; Mao et al., 2001; Gu et al., 2003; Wu and Zhu, 2007). During the spring tide, the water level rises greatly in the upper reaches of the NB owing to its funnel shape, leading to the massive saltwater spilling over the shoals there into the SB. Only small amount of the saltwater returns to the NB because the shoals are exposed to the air during the ebb tide. The massive saltwater that is spilled over into the SB from the NB is transported downstream under the influence of runoff, and arrives at the middle reaches of the SB during the subsequent moderate and neap tides, impacting the Chenhang Reservoir and the Qingcaosha Reservoir and the safety of the water supply in Shanghai.

The water diversion from the south to the north project (WDP) is a strategic project to ease the shortage of water resources in northern China. China has been enduring flood in the south and drought in the north. The water resources will be reallocated reasonably by the WDP through the inter-basin water transfer to mitigate the shortage of water resources in northern China. The WDP has three water transfer plans, namely, the Western Route Project, Middle Route Project and Eastern Route Project (Fig.2). The Eastern Route Project draws water from Yangzhou, which is in the lower reaches of the Changjiang River, and conveys the drew water to northern China through the Grand Canal and the parallel rivers (Shen et al., 2003). The Eastern Route Project will be completed in three phases from 2010 to 2030. The water transfer fluxes are 500, 600 and 800 m^3/s in the first, second and third phase, respectively. There can be a conflict between the needs of those who wish to draw water from the upper reaches of the river, and those who are affected by the resulting increased salt intrusion in the lower reaches of the estuary (Brockway et al., 2006), and the conflict is much more serious as such a project is so close to the Changjiang Estuary.

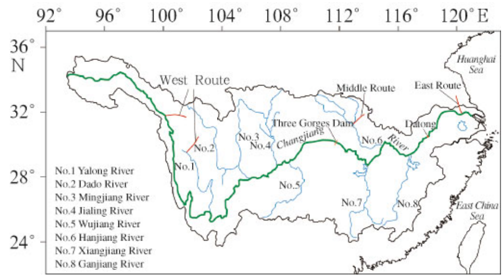

Fig.2. Sketch map of the Changjiang River Basin and the WDP.

The saltwater intrusions in many estuaries have been studied. Lerczak and Geyer (2006) investigated the subtidal salt balance and the mechanisms driving the downgradient salt flux in the Hudson River. Turrell et al. (1996) studied the salt intrusion and the density-driven secondary circulations during the spring tide in the Conwy Estuary, UK. McManus (2005) demonstrated the nature of the layering and its variation through the tidal cycle in the Tay Estuary, Scotland. Milnes and Renard (2004) investigated and quantified the impact of solute recycling from irrigation relative to seawater intrusion in the Kiti aquifer, South Cyprus. Sierra et al. (2004) employed a two-layer hydrodynamic numerical model to evaluate the role of flow regulation in the Ebro salt wedge dynamics, with particular emphasis on the potential discharge reduction due to the planned water diversion. Brockway et al. (2006) presented an analytical solution for the salt intrusion in the Incomati Estuary to predict the minimum river flow required to prevent salt intruding to an extent where it causes a detrimental effect on water transmission. Gillibreand and Balls (1998) used a one-dimensional salt intrusion model to simulate salinity distributions for the periods of high and low river flow in the Ythan Estuary, Scotland, and to illustrate how the nitrate concentrations respond to variations in river flow. Shen et al. (2003) used frequency and correlation analysis to predict the days of different chloride contents and the possible maximum chloride content at the Wusong Gauge Station after the eastern WDP, based on the measured river discharge and chloride data. Shen et al. (2002) predicted the increase of saltwater intrusion length in the SB and in the SC, and the variation of the area occupied by the Changjiang River diluted water through the correlation between the river discharge and the salinity at the gauge stations.

Most of the above mentioned references indicate that the saltwater intrusion is determined mainly by the river discharge and tide. In fact, the effect of the eastern WDP is by reducing the river discharge, but how the eastern WDP impact the saltwater intrusion has never been studied deeply and quantitatively, that is why we study it in this paper.

2 Method

2.1 *Numerical model*

The improved 3D numerical model ECOM-si (Zhu, 2003; Zhu and Zhu, 2003; Wu et al., 2010) is applied to studying the impact of the eastern WDP on saltwater intrusion into the Changjiang Estuary. This model has been widely used to study the hydrodynamic process and the saltwater intrusion into the Changjiang Estuary for many years, and many achievements were obtained (Shen et al., 2003; Wu et al., 2006; Chen et al., 2010; Li et al., 2010; Zhu et al., 2008; Wu et al., 2010; Xiang et al., 2009).

The topography of the research area is updated by the data observed in 2007. The 16 main tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, U_2, V_2, T_2, L_2, $2N_2$, J_1, M_1, OO_1) are taken to drive the open sea boundary elevation. The western boundary at Datong is forced by the river discharge. The initial conditions of elevation and current are set to zero, and the initial condition of salinity is taken from several observed data inside of the mouth and from Ocean Atlas Commission (1992) off the mouth. The tidal flats in the Changjiang Estuary are treated with a wetting-drying method in which the minimum depth is set to 0.2 m. The model domain and the mesh are not presented in this study. Interested readers can find them in other studies (Wu et al., 2010; Li et al., 2010).

2.2 *Model validation*

The improved ECOM-si model has been well validated by the water level, current and salinity, which was observed by in situ survey in the Changjiang Estuary (Chen et al., 2010; Li et al., 2010; Wu et al., 2010; Xiang et al., 2009; Zhu et al., 2008). Here we validate the model with the salinity data measured at the Chenhang Reservoir and Qingcaosha Reservoir with relatively long time series from February 16 to March 4 in 2007. The model is run from 1 January 2007, using the river discharge measured at the Datong Gauge Station to specify the model's river boundary. Wind data are derived from QSCAT/NCEP, with a spatial resolution of 0.5°×0.5° and a temporal resolution of 6 h. It can be seen on the whole that the modeled salinity is quite consistent with the measured data (Figs 3 and 4), indicating that the numerical model can simulate the change of salinity in the Changjiang Estuary well.

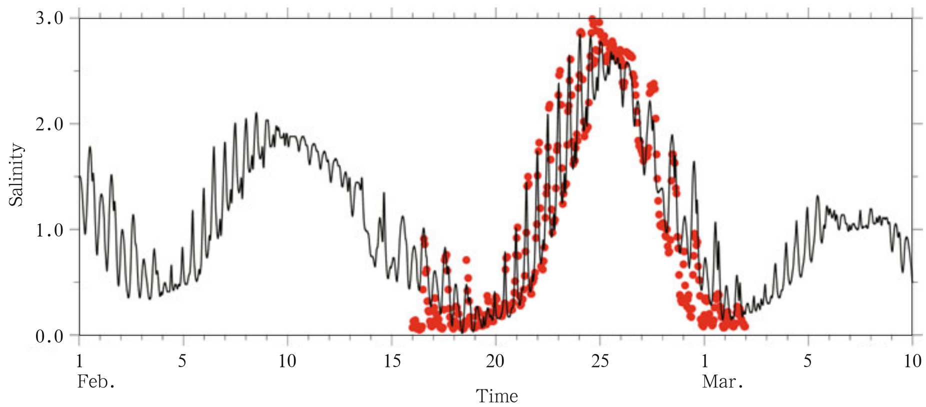

Fig.3. Model validation with the surface salinity at the Qingcaosha Reservoir from February 16 to March 4 in 2007. Red dots denote the observed data; black line denotes the model calculated data.

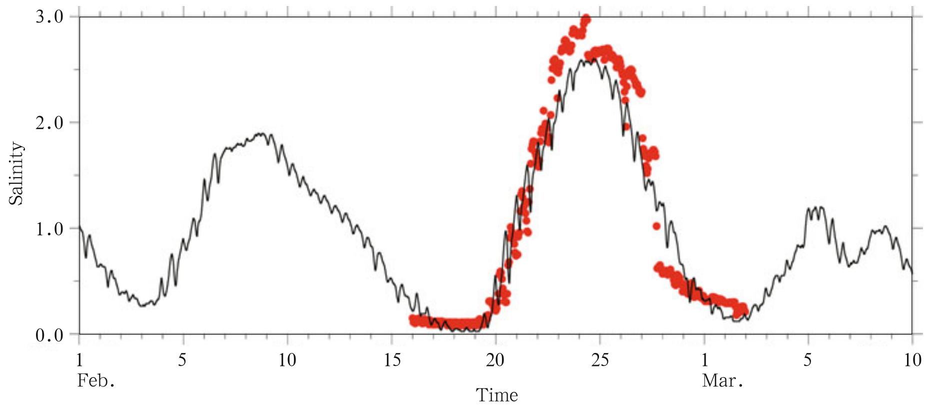

Fig.4. Model validation with the surface salinity at the Chenhang Reservoir from February 16 to March 4 in 2007. Red dots denote the observed data; black line denotes the model calculated data.

2.3 *Numerical experiments*

Two numerical experiments before and after the eastern WDP are made with the monthly mean river discharge of 11 200 m^3/s in January, recorded at the Datong Gauge Station and 10 400 m^3/s, reduced by 800 m^3/s due to the third phase WDP, respectively. Accordingly, the tide in January is adopted to drive the model. The tidal range is about 4.4 m during the spring tide and about 2.0 m during the neap tide at the Luchao Harbor Station (see Fig.1) in January, which is stronger than that in December (the weakest) and weaker than that in March (the strongest) (Song et al., 2010). The northerly wind prevails over the Changjiang Estuary and causes the saltwater intrusion more severely in winter. Hence, we conduct the experiments with the constant northerly wind of 5 m/s. Because it needs a long time to adjust the initial salinity field, the calculated results after 30 d are adopted, and the current and salinity results are analyzed and compared quantitatively during the subsequent spring-neap tidal cycle (about 15 d).

3 Results and analysis

3.1 *Net unit width water flux*

To delineate water transport directly, the net unit width water flux (NUWF, with a unit of m^2/s) is used to represent local distribution of water transport. It is defined as follows (Wu et al., 2006):

$$\langle Q_{\rm u}\rangle = \frac{1}{T}\int_0^T \overline{V_i} D_i {\rm d}t, \tag{1}$$

where $\overline{V}_i$ is the depth-averaged velocity normal to the unit width at the grid labeled i, defined as $\overline{V}_i = \sum_{j=1}^{n} V_{ij}$, in which n is the number of layers in vertical direction; and D_i is the water depth; T is the integral period, one or several tidal periods. It takes into account the variation of water depth, the magnitude and direction of water transport in the NUWF. This method can present the water transport in the estuary better (Wu and Zhu, 2007).

The NUWFs before and after the eastern WDP are obtained by time-averaging through a spring and neap tides, respectively, after the model runs 30 d. The distribution of NUWF near the bifurcation of the South and North Branch is enlarged to show it clearly.

3.1.1 *During the spring tide*

The depth-averaged NUWF is controlled mainly by the river discharge. The net water flux is seaward in the SB, and is much larger in the river channel than that at the shoals (Fig.5a). Owing to the funnel shape of the NB, the net water flux is directed landward, and spills over from the NB into the SB (Fig.5b). The difference of NUWF between after and before the eastern WDP is landward, indicating that the net water transport is reduced after the eastern WDP due to the decrease of the river discharge (Fig.6a). The decline of river discharge causes an increase of net water flux spilling over from the NB into the SB and a decrease of the net seaward water flux (Fig.6b).

3.1.2 *During the neap tide*

During the neap tide, the depth-averaged NUWF variation between after and before the eastern WDP is similar to that during the spring tide (not shown). The tide is weaker during the neap tide and the water that is spilled over into the SB during the flood tide can flows back into the NB during the ebb tide. Hence the water flux spilled over from the NB is much smaller than that during the spring tide. Similar to that during the spring tide, the decline of the river

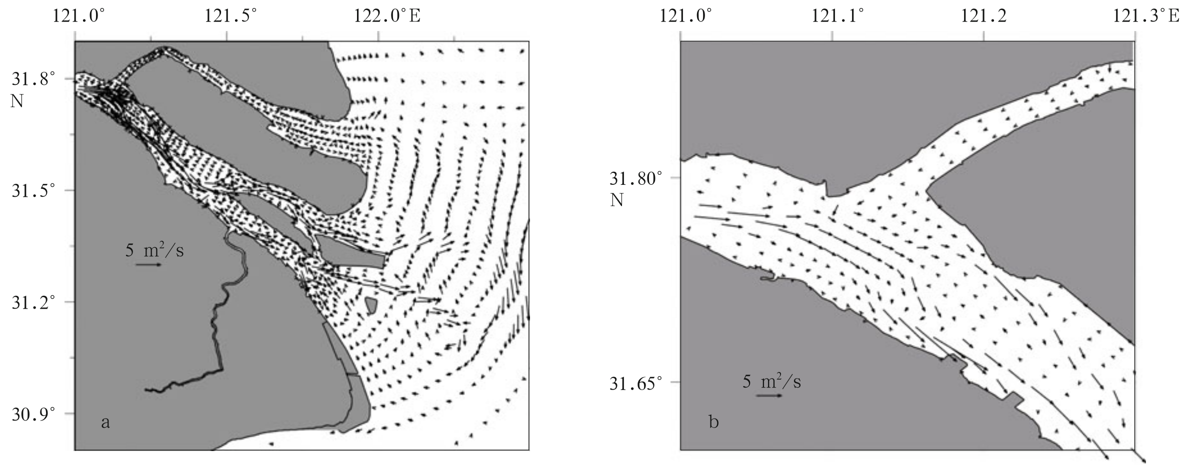

Fig.5. Distribution of the NUWF in the Changjiang Estuary (a) and in the enlarged area near the bifurcation of the NB and SB (b) during the spring tide, before the eastern WDP.

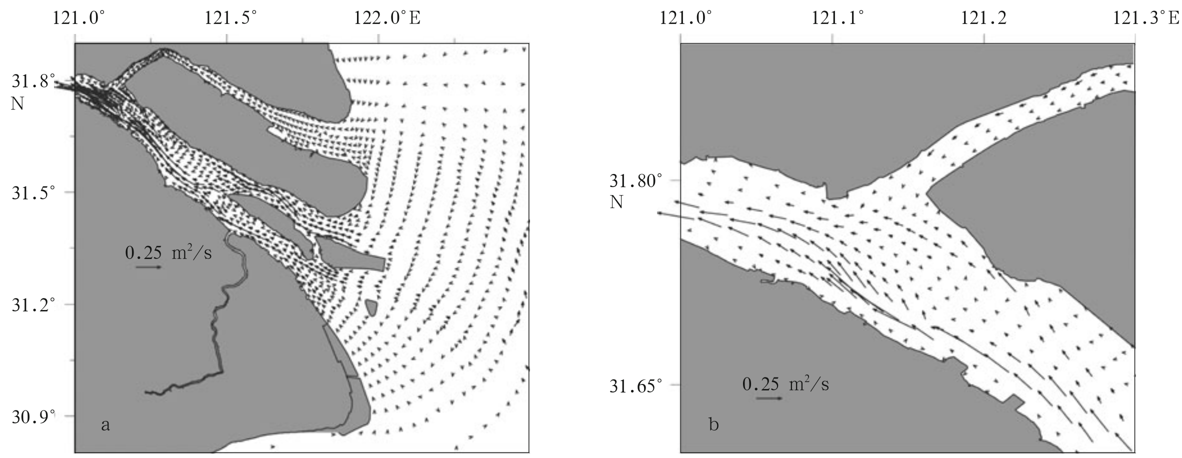

Fig.6. Distribution of the NUWF difference between after and before the eastern WDP in the Changjiang Estuary (a) and in the enlarged area near the bifurcation of the NB and SB (b) during the spring tide.

discharge results in an increase of net water flux spilling from the NB into the SB and a decrease of the net seaward water flux.

3.2 *Tidally averaged salinity*

3.2.1 *During the spring tide*

Before the eastern WDP, the modeled distribution of tidally averaged salinity during the spring tide shows that the NB is occupied by high salinity water (Fig.7a). The salinity in the NB reduces gradually upstream, with a value of 25–28 at the river mouth and about 0.5 near the bifurcation of the NB and the SB, and there is a salinity front in the upper reaches. Owing to the Coriolis force, the saltwater intrusion there is stronger on the north side of the channel than that on the south side. In the SB, there exists SSO, which results in the salinity in the upper reaches exceeds 1.0, and presents a feature that the salinity in the middle reaches is lower than that in the upper and lower reaches along the longitudinal direction. The saltwater intrusions in the NC, the NP and the SP originate mainly from the open sea, and the saltwater intrusion is stronger in the SP than in the NP, and stronger in the NP than in the NC. Under the interaction of the tide and the runoff, a salinity front is formed around the sand bars at the river mouth. The bottom salinity is higher than the surface salinity at the sand bars there (not shown). Near the bifurcation of the NB and SB, the salinity is about 10 at the surface and 15 at the bottom in the upper reaches of the NB, and is about 1.5 at the surface and 2.0 at the bottom in the upper reaches of the SB. The salinity at the bottom is higher than that at the surface there. In other areas, the salinity is vertically uniform due to the mixing by the bottom friction and surface wind stress, as well as the shallow water. The modeled results mentioned above are consistent with the previous studies (Shen et al., 2003; Chen et al., 2010; Li et al., 2010; Zhu et al., 2008; Wu et al., 2010).

After the eastern WDP, the saltwater intrusion is enhanced due to the decrease of river discharge (Fig.7b, Fig.8). On the whole, the salinity increases significantly near the areas where the salinity fronts exist. In the NB, the salinity there rises by 0.1–0.5 at the river mouth, 0.2 in the middle reaches and above 0.5 in the upper reaches. In the NC, the salinity rises by 0.2–0.5 around the sand bars and 0.1–0.2 in the upper reaches. The salinity rises by about 0.5 in the NP, 0.4–0.6 in the SP, and 0.1–0.5 in the SC. In the upper reaches of the SB, the salinity increases by 0.1–0.2 due to the enhancement of the SSO. As a whole, the saltwater intrusion into the Changjiang Estuary is enhanced after the eastern WDP, with the enhancement varying in different channel reaches.

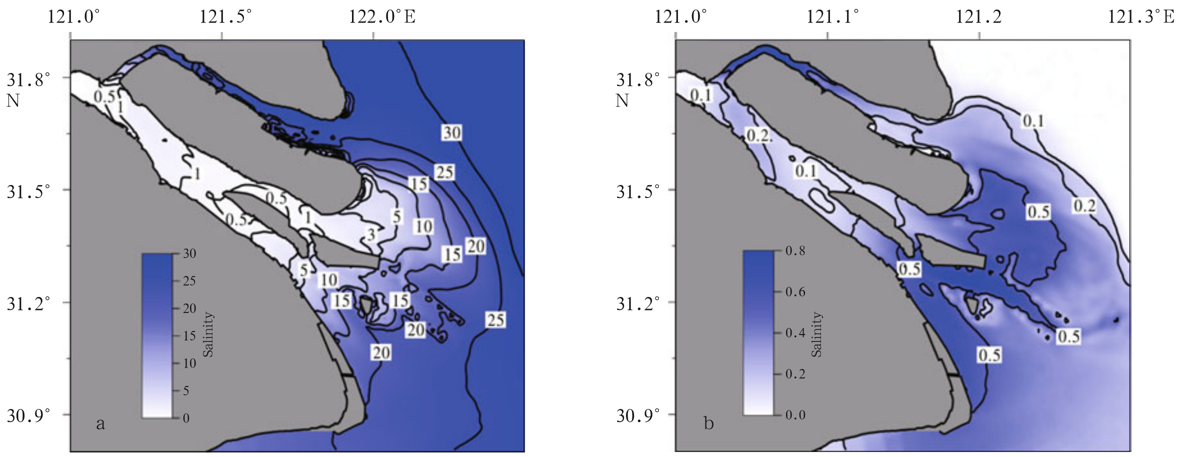

Fig.7. Tidally averaged surface salinity before the eastern WDP (a) and its difference between after and before the eastern WDP (b) during the spring tide.

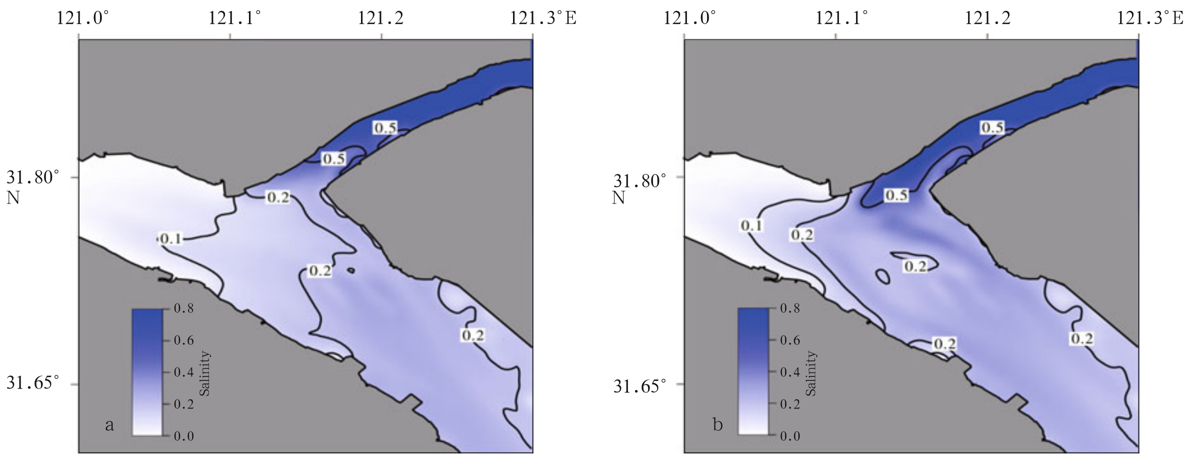

Fig.8. Tidally averaged surface (a) and bottom (b) salinity difference between after and before the eastern WDP in the enlarged area near the bifurcation of the NB and SB during the spring tide.

3.2.2 *During the neap tide*

Before the eastern WDP, the saltwater intrusion during the neap tide is weaker than that during the spring tide due to the weaker tide (Fig.9a). Accordingly, the SSO becomes much weaker. In the SB, the saltwater that spilled over into the SB during the spring tide moves downstream to the middle SB with the runoff, and the salinity along the SB is uniformly increased seaward. The isohalines move seaward at the river mouth. The salinity near the Chenhang Reservoir and the Qingcaosha Reservoir reaches 0.5 and 1.0, respectively, and the freshwater vanishes. The salinity in the upper reaches of the NB is about 5.0, with the bottom salinity slightly higher than the surface one. Owing to the weaker tidal mixing, the stratification is greater in the SP and the NP during the neap tide (not shown).

After the eastern WDP, the saltwater intrusion is enhanced due to the decrease of river discharge (Fig.9b, Fig.10). The area where the salinity experiences a notable increase is still around the salinity fronts. In the NB, the salinity increases by 0.1–0.5 at the river mouth, 0.2 in the middle reaches and 0.1–0.5 in the upper reaches. In the NC, the salinity increases by 0.4–0.5 around the sand bars and 0.2–0.3 in the upper reaches. The salinity rises by 0.5–0.7 in the NP, 0.5–0.6 in the SP and 0.2–0.5 in the SC. In the upper reaches of the SB, the increase of salinity is less than 0.1, which is smaller than that during the spring tide due to the weaker SSO. The enhancement of saltwater intrusion is smaller in the NC and larger in the SP and the NP, compared with that during the spring tide (Fig.7b). In Li et al.'s (2010) study, the net water diversion ratio in the NC is 54.91% during a spring tide and 43.86% during a neap tide. Because of the decrease of the net water diversion ratio in the NC during the neap tide, the effect of river discharge reduction by the eastern WDP in the NC is not as strong as that during the spring tide, resulting in the enhancement of saltwater intrusion which is smaller than that during the spring tide. With the increase of the net water diversion ratio in the SC during the neap tide, the enhancement of saltwater intrusion into the NP and the SP is more distinct during the neap tide than during the spring tide.

3.3 *Temporal salinity variation*

The modeled salinities at the Qinglong Harbor and the water intakes of the Dongfengxisha Reservoir, the Chenhang Reservoir and the Qingcaosha Reservoir

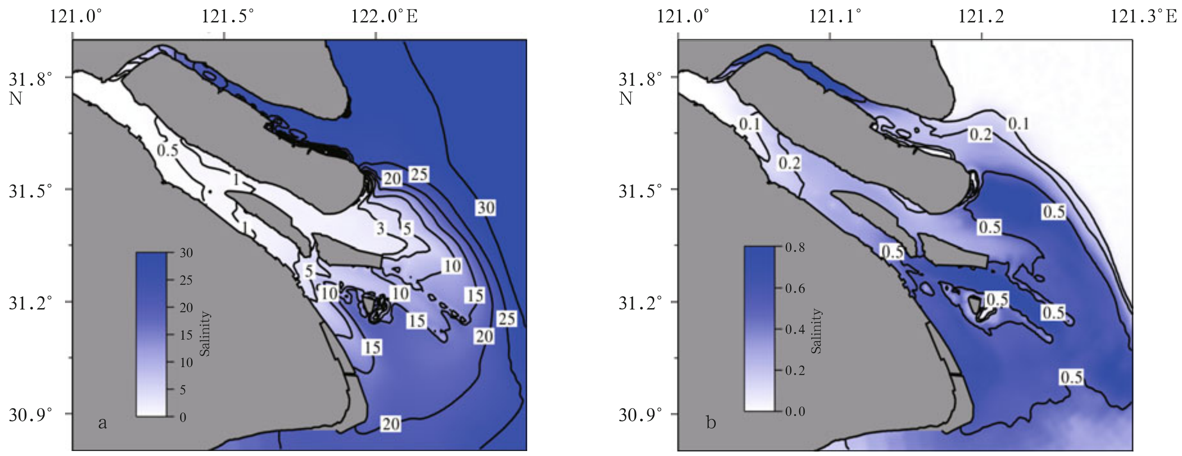

Fig.9. Tidally averaged surface salinity before the eastern WDP (a) and its difference between after and before the eastern WDP (b) during the neap tide.

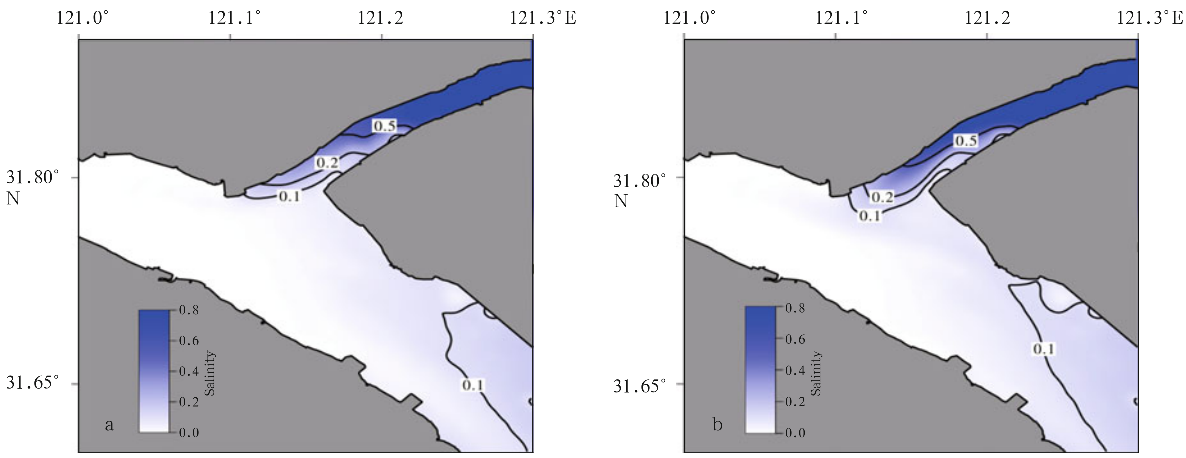

Fig.10. Tidally averaged surface (a) and bottom (b) salinity difference between after and before the eastern WDP in the enlarged area near the bifurcation of the NB and SB during the neap tide.

are output to compare their variations between after and before the eastern WDP. The salinity varies semidiurnally with the flood-ebb tide and fortnightly with the spring-neap tide (Fig.11). After the eastern WDP, the salinity peak during fortnightly period rises by about 0.5 at the three water intakes. The statistical mean salinity before and after the eastern WDP during the spring and neap tides at the four model output sites is presented in Table 1. The drinking water standard of salinity is 0.45, while the tidally averaged surface salinity at the water intakes of the Dongfengxisha Reservoir, the Chenhang Reservoir and the Qingcaosha Reservoir during the spring tide (the neap tide) rises by 0.26 (0.09), 0.18 (0.17) and 0.10 (0.28), respectively, due to the eastern WDP. Hence, the inter-basin water diversion has distinct negative effect on the freshwater intake in the water source areas in the Changjiang Estuary.

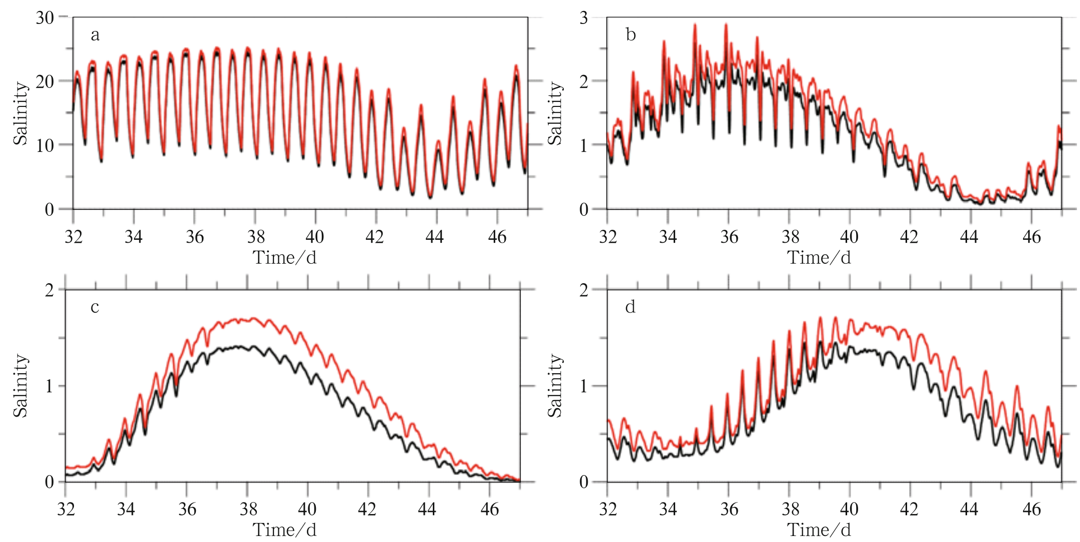

Fig.11. Temporal variation of surface salinity at the model output sites. The black and red lines denote the surface salinity before and after the eastern WDP, respectively. a. Qinglong Harbor, b. Dongfengxisha Reservoir, c. Chenhang Reservoir, and d. Qingcaosha Reservoir.

Table 1. Tidally averaged surface salinity at the model output sites during spring and neap tides

		Qinglong Harbor	Dongfengxisha	Chenhang	Qingcaosha
Spring tide	before the eastern WDP	18.17	1.88	0.97	0.45
	after the eastern WDP	19.08	2.14	1.15	0.55
	difference	0.91	0.26	0.18	0.10
Neap tide	before the eastern WDP	7.48	0.26	0.36	0.82
	after the eastern WDP	8.59	0.35	0.53	1.10
	difference	1.11	0.09	0.17	0.28

3.4 *Cross-sectional net salt flux*

The instantaneous cross-sectional salt flux at t is defined as follows:

$$S_{\text{sec}}(t) = \sum_{i=1}^{m} \overline{V_i S_i} D_i W, \tag{2}$$

where m is the number of grids along each section; W_i is the width of each grid; and $\overline{V_i S_i}$ is the depth-averaged value of the product of normal current speed and salinity in each grid. The net salt flux (with the unit t/s) at the cross-sections during a period of time T can be derived as follows:

$$\langle S_{\text{sec}} \rangle = \frac{1}{T} \int_0^1 S_{\text{sec}}(t) \mathrm{d}t. \tag{3}$$

In this study, the net salt flux (NSF) at each cross-section was computed during the spring tide and the neap tide. The statistic time T is set as the sum of six sequential flood-ebb tidal cycle periods (about 3 d). The NSF at the sections before and after the eastern WDP during the spring and neap tides is presented in Table 2. Negative values denote the saline water transporting landward.

3.4.1 *During the spring tide*

Before the eastern WDP, the NSFs at all the sections are presented in Table 2. The NSF at SEC1 is –18.50 t/s, meaning that there exists the SSO over there. It is 18.03 t/s at SEC2, which approximately equals to that at SEC1, indicating that the salt in the upper reaches of the SB comes from the SSO. The NSF at SEC3 is larger than that at SEC4, meaning that more salt is transported seaward in the NC than in the SC. The NSFs are –30.99 t/s and 14.75 t/s at SEC6 and SEC5, respectively, showing that there are abundant salt transporting landward in the SP and seaward in the NP, due to the funnel shape of the SP. As this paper is focused on the impact of the eastern WDP on the saltwater intrusion, the relationship between the SSO and the saltwater intrusion in each channel cannot be analyzed in detail, due to the paper length limit. The details can be referenced in the papers (Wu et al., 2006; Li et al., 2010; Wu et al., 2010. Similarly hereinafter).

After the eastern WDP, due to decrease of the river discharge, the saltwater intrusion in the estuary is enhanced. The landward NSFs at SEC1 and SEC6 are increased by 2.09 t/s and 2.47 t/s, and the seaward NSFs at SEC2, SEC3, SEC4 and SEC5 are increased by 2.00, 0.58, 0.93 and 0.71 t/s, respectively.

3.4.2 *During the neap tide*

Before the eastern WDP, the saltwater intrusion is weakened compared with that during the spring tide due to the weaker tide. The NSF is –1.20 t/s at SEC1, which is reduced by 17.28 t/s. It can be seen in Fig. 9 that the SSO moves downstream into the NC and SC, resulting in the seaward NSFs at SEC3 and SEC4 are 7.08 t/s and 5.21 t/s, respectively, increasing by 4.27 t/s and 4.12 t/s compared with that during the spring tide. The landward NSF at SEC6 is –14.12 t/s, which is decreased by 16.87 t/s, but the seaward NSF at SEC5 is 23.96 t/s, increasing by 9.21 t/s.

After the eastern WDP, due to the same reason of smaller river discharge, the saltwater intrusion is enhanced, and differences of NSFs at the SECs can be seen in Table 2. During both spring and neap tides, the seaward NSF at SEC3 is larger than that at SEC4, meaning that more salt from the SSO is transported through the NC than through the SC.

Table 2. Net salt flux (t/s) at the sections

		SEC1	SEC2	SEC3	SEC4	SEC5	SEC6
Spring tide	before the eastern WDP	–18.50	18.03	2.80	1.10	14.75	–30.99
	after the eastern WDP	–20.59	20.03	3.38	2.03	15.46	–33.46
	difference	–2.09	2.00	0.58	0.93	0.71	–2.47
Neap tide	before the eastern WDP	–1.20	1.10	7.08	5.21	23.96	–14.12
	after the eastern WDP	–1.72	1.64	8.31	6.79	25.37	–13.76
	difference	–0.52	0.54	1.23	1.58	1.41	0.36

Notes: Negative values denote the saline water transports landward.

4 Discussion

The water supply of Shanghai comes from the upper Huangpu River, which flows across Shanghai, and the three reservoirs located in the Changjiang Estuary (Fig.1). Owing to the pollution from upper reaches and along the Huangpu River, the water quality there becomes worse and unstable. Thus the reservoirs in the Changjiang Estuary play a more important role in the water supply of Shanghai. Since the WDP has been mentioned, it is still a deputed project and one of the objections is that it may cause a deficiency of runoff in the dry season and then affects the saltwater intrusion. Hence, it is of significance to study the impact of the WDP on the saltwater intrusion, especially the impact on the freshwater intake in the water resources.

It is well known that a lower river discharge corresponds to a stronger salt water intrusion. In 1979, the Changjiang River Basin was in extreme drought, with a mean river discharge of 7 220 m^3/s in January recorded at the Datong Gauge Station. Thus two numerical experiments before and after the eastern WDP are set up here with the discharge of 7 220 m^3/s, and 6 420 m^3/s which reduced by 800 m^3/s due to the third phase eastern WDP, respectively, to discuss the impact on saltwater intrusion of the project on the freshwater intake in the water resource under the extreme drought condition. All of the other forces taken into account in the model are the same as the experiments in Section 2.3.

The modeled salinities at the four sites (Qinglong Harbor, Dongfengxisha, Chenhang and Qingcaosha) are presented in Fig.12. Comparing with the results

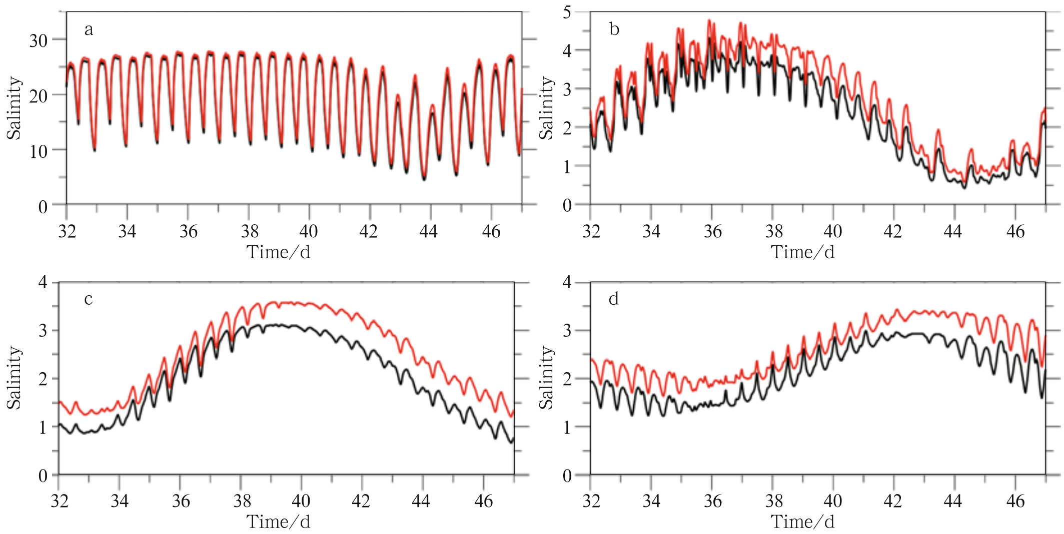

Fig.12. Temporal variation of surface salinity at the model output sites under the extreme drought condition. The black and red lines denote the surface salinity before and after the eastern WDP, respectively. a. Qinglong Harbor, b. Dongfengxisha Reservoir, c. Chenhang Reservoir and d. Qingcaosha Reservoir.

under the runoff of 11 200 m^3/s, the saltwater intrusion is more severe (Fig.12). The salinity in the three freshwater intakes (Dongfengxisha, Chenhang and Qingcaosha) is almost above 0.5 during the whole spring-neap tidal cycle. It means that there is nearly no drinking water for those three reservoirs under the extreme drought condition. The mean salinity before and after the eastern WDP during the spring and neap tides at the four output sites is presented in Table 3. The tidally averaged surface salinity at the water intakes of the Dongfengxisha Reservoir, the Chenhang Reservoir and the Qingcaosha Reservoir during the spring tide (the neap tide) rises by 0.42 (0.32), 0.27 (0.62) and 0.46 (0.51), respectively, due to the eastern WDP. Under the extreme drought condition, the impact of the eastern WDP is apparently greater than that under the mean runoff condition.

There are two sources of the saltwater intrusion into the SB (e.g., Shen et al., 2003), one is the SSO, and the other is the offshore saltwater intrusion. In order to see how much salt at the SECs is from the SSO, two additional numerical experiments before and after the eastern WDP with the NB blocked at SEC1 are conducted to exclude the SSO. All other setups are the same as experiments in Section 2.3. The NSFs at SECs with the NB blocked are presented in Table 4.

Table 3. Tidally averaged surface salinity at the model output sites during spring and neap tides under the extreme drought condition

		Qinglong Harbor	Dongfengxisha	Chenhang	Qingcaosha
Spring tide	before the eastern WDP	22.27	3.46	1.86	1.48
	after the eastern WDP	22.96	3.88	2.13	1.94
	difference	0.69	0.42	0.27	0.46
Neap tide	before the eastern WDP	13.34	0.97	2.00	2.78
	after the eastern WDP	14.60	1.29	2.62	3.29
	difference	1.26	0.32	0.62	0.51

Table 4. Net salt fluxes (t/s) at the sections with the NB obstructed

		SEC1	SEC2	SEC3	SEC4	SEC5	SEC6
Spring tide	before the eastern WDP	0.00	0.00	0.14	–0.38	14.71	–34.69
	after the eastern WDP	0.00	0.00	0.15	–0.51	15.05	–37.57
	difference	0.00	0.00	0.01	–0.13	0.34	–2.88
Neap tide	before the eastern WDP	0.00	0.00	0.17	–0.03	21.92	–19.45
	after the eastern WDP	0.00	0.00	0.20	–0.02	22.79	–20.15
	difference	0.00	0.00	0.03	0.01	0.87	–0.70

Notes: Negative values denote the saline water transports landward.

In the case of NB blocked, there is no NSF at SEC1 certainly. The NSF at SEC2 is zero both during spring and neap tides before and after the WDP, meaning that the salt there is from the SSO completely. The NSFs at SEC3 and SEC4 are ranged from 0.14 t/s to 0.20 t/s and from –0.02 t/s to –0.51 t/s in difference cases, respectively, meaning that the salt is transported seaward in the NC and landward in the SC in the case of the NB blocked. Comparing the smaller values in Table 2 with the larger values in Table 4, we can conclude that the salt from the SSO is transported seaward more in the NC than in the SC. The NSF at the SEC6 changes greatly, which is larger than the NSF change at SEC4. The decrease of water flux caused by the blockage of the NB can enhance the saltwater intrusion into the SP. Some water flux in the SB from the NB is induced by the SSO, and the saltwater intrusion into the SP is very sensitive to the water flux variation because of the funnel shape there. The saltwater intrusion into the SP is enhanced significantly mainly due to the decrease of water flux caused by the blockage of the NB. The enhanced landward NSF in the SP makes the seaward NSF in the NP increasing, which satisfies the mass conservation. The changes of the NSF in the SP and the NP are caused partly by the SSO, mainly by the water flux change. So, it is hard to say how much salt from the SSO transports into the SP and the NP.

The saltwater intrusion into the Changjiang Estuary is complicated due to its complex topography and bifurcations. There are still lots of interesting topics remained to be studied in the Changjiang Estuary, for example, the quantitative relationship between the river discharge and the salinity. The quantitative relationship among the runoff, tidal range and the amount of SSO was well studied in the previous study (Wu et al., 2006). However, it needs a series of experiments with different runoffs to work out the relationship between the river discharge and the salinity. We will study it future.

5 Conclusions

Using the well validated 3D numerical model, the impact of the eastern WDP on the saltwater intrusion into the Changjiang Estuary is studied. The dynamic mechanism and the extent of the impact of the eastern WDP on the saltwater intrusion were revealed quantitatively.

Under the mean river discharge condition in the dry season, the depth-averaged NUWF is seaward in the SB and landward in the NB and the water in the NB spills over from the NB into the SB. The eastern WDP reduces the seaward water transport in the SB, and enhances the net water flux spilling over from the NB into the SB.

The eastern WDP causes a decrease of the river discharge, resulting in an enhancement of the saltwater intrusion, especially around the sand bars at the river mouth where the salinity experiences a notable increase. This project enhances the SSO and increases the net seaward salt flux in the SB. During the spring tide, the salinity in the upper SB is mainly affected by the SSO, while that around the sand bars at the river mouth where the salinity fronts exist is mainly impacted by the seawater intrusion. During the neap tide, the saltwater intrusion is weaker due to the weaker tide. Accordingly, the SSO is much weaker and has a less effect on the salinity in the upper SB. The enhancement of saltwater intrusion after the eastern WDP during the neap tide is weaker in the NC and greater in the SP and the NP compared with that during the spring tide.

After the eastern WDP, the tidally averaged surface salinity at the water intakes of the Dongfengxisha Reservoir, the Chenhang Reservoir and the Qingcaosha Reservoir during the spring tide (the neap tide) rises by 0.26 (0.09), 0.18(0.17) and 0.10(0.28) under the mean runoff condition, 0.42 (0.32), 0.27 (0.62) and 0.46 (0.51) under the extreme drought condition, respectively. Hence the inter-basin water diversion of the project has markedly negative effects on the freshwater intake in the water resource in the Changjiang Estuary.

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