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TECHNICAL COMMUNICATIONS

Determining Critical River Discharge as a Means to Provide Water Supply Security to the Changjiang River Estuary, China

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ABSTRACT

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Shanghai is one of the six cities worldwide experiencing severe water shortage in the 21st century. To solve the water supply shortage problem, a strategic water source transfer from the Huangpu River to the Changjiang Estuary has been completed; approximately 80% of the supply of fresh water in Shanghai is taken from the water sources in the estuary, but the estuary experiences saltwater intrusion during periods of low river discharge, *e.g.*, the dry season. The reservoirs cannot take water if the salinity is higher than 0.45 psu at the water intakes. The longest water residence time of the Chenhang Reservoir (CHR) is 7 days; thus, the CHR will experience water supply problems if the duration of saltwater intrusion is longer than 7 days. In this study, saltwater intrusion was simulated, and the critical river discharge was ascertained under different river discharge conditions using the improved Estuarine, Coastal, and Ocean Model, semi-implicit. The saltwater spillover from the North Branch arrived in the middle reaches of the South Branch during the subsequent moderate tide and neap tide, threatening the water intake of the CHR. During a period of spring–neap tides, the longest periods for which the CHR could not take water from the Changjiang Estuary were 5.0, 6.5, and 8.2 days under river discharge conditions of 11,500, 10,000, and 9000 m^3/s, respectively. The saltwater intrusion increased when the river discharge declined, and the availability of useable freshwater resources in the estuary became severe. By finely adjusting the river discharge in the model, the authors found that the critical river discharge was 9500 m^3/s. If the amount of river discharge reaches 9500 m^3/s, the Shanghai government can ask the Changjiang Water Resources Committee to discharge more water from the Three Gorges Reservoir to restrain the saltwater intrusion and ensure water security in the megalopolis of Shanghai.

ADDITIONAL INDEX WORDS: *Freshwater resource, saltwater intrusion, numerical model.*

INTRODUCTION

Shanghai is an international megalopolis located near the Changjiang Estuary. Before 2010, the water supply of Shanghai primary came from the Huangpu River; however, the water quality was not good, and the supply capacity was insufficient, resulting in Shanghai becoming one of the six worst cities worldwide in terms of its severe water shortage in the 21st century, as determined by the United Nations Educational Scientific and Culture Organization. Because of a high population density and a rapidly developing economy, Shanghai has a high demand for raw water of good quality. The Changjiang Estuary has abundant fresh water with relatively good water quality. To solve problems related to water supply shortages, it is necessary to build reservoirs and transport water from the Changjiang Estuary (Liu, Yang, and Jiang, 2013; Wang, Zhu, and Gu, 2011; Zheng, 2001). Three reservoirs have been built in the estuary, *i.e.* the Chenhang Reservoir (CHR), the Qingcaosha Reservoir, and the Dongfengxisha Reservoir (locations marked in Figure 1b). The CHR was built in 1996, and it has an effective capacity of 8.60×10^6 m^3 and a daily water supply of 2.06×10^6 m^3 for the 2 million people in the NW districts of Shanghai. The CHR is located on the south side of the South Branch and is supplying 20% of all water in Shanghai. The Qingcaosha Reservoir was completed in 2010, and it has an effective capacity of 4.35×10^8 m^3 and a daily water supply of 7.19×10^6 m^3 for the 13 million people in the relevant districts of Shanghai. The area of the reservoir is approximately 10 times the area of West Lake in Hangzhou, China, and the reservoir is the largest estuarine reservoir in the world. The Dongfengxisha Reservoir was built in 2011 for the 700,000 people on Chongming Island. The reservoir has an effective capacity of 8.9×10^6 m^3 and a daily water supply of 2.1×10^5 m^3. Approximately 80% of the fresh water supplied to Shanghai is taken from water sources in the Changjiang Estuary.

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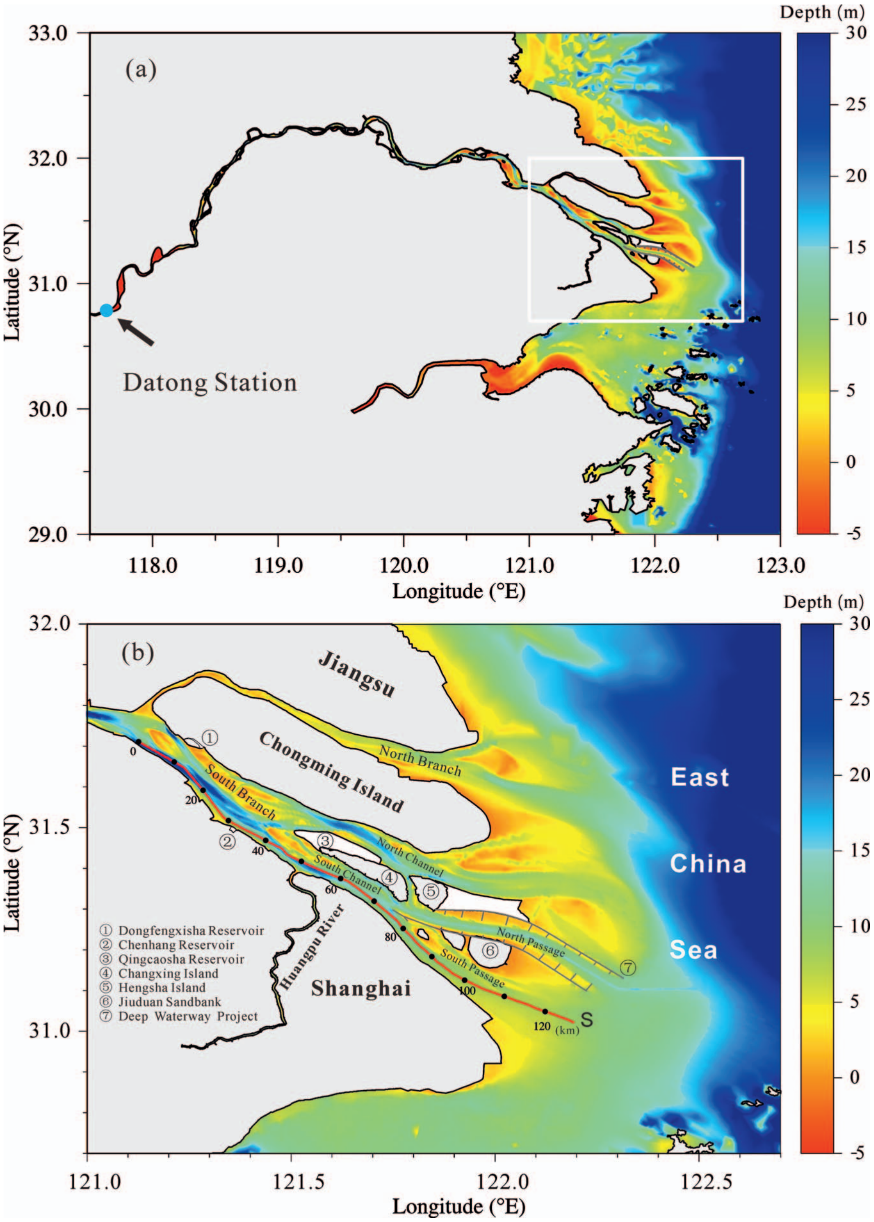

Figure 1. Situation map from Datong Station to the Changjiang Estuary (a) and enlarged views of the Changjiang Estuary (b). (b) The locations of the three estuarine reservoirs are marked. The red line indicates section S in the profile distribution of the salinity along the South Branch, South Channel, and South Passage, and the figures beside this line represent the respective distances from the starting point of the section.

Shanghai successfully completed the strategic transfer of water sources from the Huangpu River to the Changjiang Estuary; however, there is still a major problem, *i.e.* saltwater intrusion during periods of low river discharge, *e.g.*, the dry season. During saltwater intrusion, the reservoirs can no longer use water from the Changjiang Estuary if the salinity is higher than 0.45 psu (*i.e.* the salinity standard for drinking water, similarly hereinafter) at the water intakes. Extremely low discharges of the Changjiang River happened in summer 2006, induced by a serious drought in the river's basin, and they caused a severe saltwater intrusion from the North Branch into the South Branch that occurred months earlier than usual (Dai *et al.*, 2008; Zhu *et al.*, 2010). It was found that the saltwater intrusion in the Changjiang Estuary in February 2014 was severe, resulted in a period during which it was not suitable take water from the Qingcaosha Reservoir to reach to 23 days, which seriously threatened the safety of the water supply in Shanghai (Wang and Zhu, 2015). Saltwater intrusion is a common phenomenon in estuaries where fresh water and salt water converge. In the Changjiang Estuary, saltwater intrusion is mainly controlled by river discharge and tides (Li *et al.*, 2010; Qiu, Zhu, and Gu, 2012; Shen, Mao, and Zhu, 2003;

Wu *et al*., 2006; Zhu *et al*., 2010); however, it can also be influenced by wind (Li, Zhu, and Wu, 2012), topography (Li *et al*., 2014), river basin and estuarine projects (Qiu and Zhu, 2013; Zhu *et al*., 2006), and sea-level rise (Qiu and Zhu, 2015). The phenomenon of saltwater intrusion that occurs in this estuary is the saltwater spillover (SSO) from the North Branch into the South Branch that occurs under strong tidal conditions during the dry season (Lyu and Zhu, 2018; Shen, Mao, and Zhu, 2003; Wu and Zhu, 2007; Wu *et al*., 2006, 2010). The natural evolution and artificial reclamation of the intertidal zone from the 1950s to 2000s lead the upper reaches of the North Branch to become almost orthogonal to the South Branch, while the lower reaches became funnel shaped. The evolution of the river regime of the North Branch has helped to prevent runoff from entering the North Branch, especially during the dry season, resulting in a tidal range that is larger in the North Branch than in the South Branch. The strong tidal range in the North Branch induces significant subtidal circulation and a net landward flow when river discharge is low during spring tide. This residual transport forms a type of saltwater intrusion known as the SSO from the North Branch into the South Branch, which is the most characteristic type of saltwater intrusion in the estuary. Only a small amount of the salt water returns to the North Branch, because the shoals in the upper reaches of the North Branch are exposed to the air during ebb tides. The salt water that spills into the South Branch is transported downstream by runoff and arrives in the middle reaches of the South Branch during the subsequent neap tide and moderate tide, which influences the water sources in the South Branch. The saline water around the water intakes of the CHR and the Dongfengxisha Reservoir are wholly derived from the SSO (Li, Zhu, and Wu, 2011; Wu *et al*., 2006). However, the salt water around the water intake of the Qingcaosha Reservoir comes from both the SSO and the landward saltwater intrusion in the North Channel (Qiu and Zhu, 2015; Shen, Mao, and Zhu, 2003).

The longest residence time of the water supply in the reservoir is determined by the effective water capacity and the daily water supply. The Qingcaosha Reservoir has a large effective water capacity (Table 1), and its longest water supply residence time is 68 days (Zhu, Gu, and Wu, 2013). Although the effective water capacity of the Dongfengxisha Reservoir is low, its daily water supply for Chongming Island is also low; thus, its longest water supply residence time is 26 days (Zhu and Wu, 2013). The CHR has a smaller effective water capacity and a relatively larger daily water supply, so its longest water supply residence time is only 7 days. It is obvious that the CHR is confronted with a problem if the duration of the saltwater intrusion (*i.e.* salinity greater than 0.45 psu at its water intake) lasts longer than 7 days; in this scenario, the reservoir will be unable to supply water to the NW districts of Shanghai. If this situation happens, the Shanghai government will have to ask the Changjiang Water Resources Committee to discharge more water from the Three Gorges Reservoir to restrain the saltwater intrusion from the estuary. First, the Changjiang Water Resources Committee needs to know at which level of river discharge it will be required to discharge water from the Three Gorges Reservoir, *i.e.* it needs to identify the critical river discharge in relation to the water supply of the CHR. The critical river discharge can be ascertained by adjusting the river discharge to a certain value in a hydrodynamic numerical model; *e.g.*, the salinity can be greater than 0.45 psu at the water intake of the CHR for only 7 days.

Table 1. *The capacity, daily supply, and water residence time in the three reservoirs.*

Reservoirs	Capacity ($\times 10^4$ m^3)	Daily Supply ($\times 10^4$ t/d)	Water Residence Time	Population ($\times 10^4$)
Dongfengxisha	976	15	26	82
Chenhang	956	130	7	300
Qingcaosha	52,400	550	68	1300

In this paper, the authors will study this issue and determine the critical river discharge for the CHR, which has great practical significance for water supply security in Shanghai. In the next experiments, the semimonthly mean wind of 10 years using data from the National Centers for Environmental Prediction is adopted. The authors will set the river discharge to be 11,500 m^3/s to simulate the saltwater intrusion in the dry season and to see how long the salinity was higher than 0.45 psu at the water intake of the CHR. If the longest residence time of the water supply of the CHR under this river discharge condition is less than 7 days, the authors will perform more experiments with river discharge values of 10,000 and 9000 m^3/s to determine the conditions under which the period of saltwater intrusion at the water intake of the CHR approaches 7 days. The authors will perform more experiments with river discharge values of 12,000 and 13,000 m^3/s to determine the conditions under which the period of saltwater intrusion at the water intake of the CHR approaches 7 days. Then, the river discharge will be fine-tuned in the model until the period of saltwater intrusion was equal to 7 days. This river discharge value will be the critical river discharge value the authors want to identify.

The remainder of this paper is organized as follows. In "Methods," the numerical model and experiments are described. In "Results," the spatial distribution of salinity and the temporal variation of salinity at the water intake of the CHR are analyzed and discussed under different river discharge conditions. Finally, the conclusions are presented.

METHODS

A semi-implicit, three-dimensional, numerical model used in this study is the Estuarine, Coastal, and Ocean Model, semi-implicit (ECOM-si; Blumberg, 1994), which originated from the explicit Princeton Ocean Model (Blumberg and Mellor, 1987) and underwent some improvements by Chen and colleagues in 2001.

Under the assumption of incompressibility, the model used the Boussinesq and hydrostatic approximations and introduced the horizontal nonorthogonal curvilinear and vertical-stretched sigma coordinate system. The governing equations of ocean circulation and water mass, which consist of momentum, continuity, temperature, salinity, and density equations, can refer to Zhu, Wu, and Li (2015).

The model used sigma coordinates in the vertical direction and a nonorthogonal curvilinear grid in the horizontal direction. A wet–dry scheme was included to describe the intertidal flat with a critical depth of 0.1 m (Zheng, Chen, and

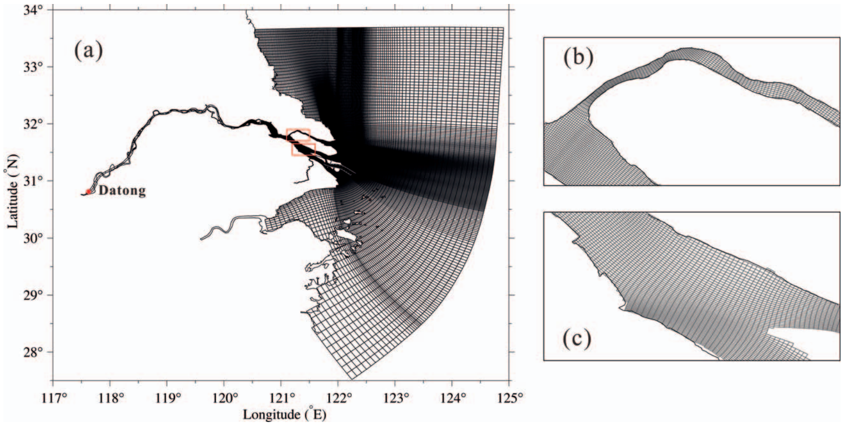

Figure 2. Model domain and grids (a). Enlarged views of the model grid at the bifurcation between the North Branch and the South Branch (b) and in the lower reaches of the South Branch (c).

Liu, 2003; Zheng, Chen, and Zhang 2004). A high-order spatial interpolation at the middle-temporal level coupled with a total variation diminished limiter for a mass advection scheme was developed by Wu and Zhu (2010). The scheme solves transport equations and prevents numerical oscillations with third-order accuracy. The model has been successfully used in previous research on the saltwater intrusion in the Changjiang Estuary (Li, Zhu, and Wu, 2012; Lyu and Zhu, 2018; Qiu and Zhu, 2013, 2015; Wu and Zhu, 2010).

The model domain covered the entire Changjiang Estuary, Hangzhou Bay, and adjacent seas from 117.5° to 125° E and 27.5° to 33.7° N (Figure 2a). In this study, the total cell number was refined to 337 × 225 in the horizontal direction and 10 uniform sigma layers in the vertical direction to better resolve the topography around the river mouth. The minimal grid resolution reached almost 100 m in the bifurcation of the South Branch and North Branch to better simulate the SSO (Figure 2b); moreover, this resolution was approximately 200 m in the lower reaches of the South Branch (Figure 2c). The model grids are almost orthogonal and smooth all over, and they fit the shape of the coastline in the bifurcated channels and near the deep waterway project. The resolutions varied from 300 to 500 m around the river mouth and then gradually decreased to 10 km at the open boundary. The integrated time step was set to 40 s.

The open sea boundary was derived from the NaoTide data set (National Astronomical Observatory of Japan, 2017) and driven by 16 astronomical 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. The daily river discharge recorded at Datong Station was used as the river boundary condition in the model (Anhui Provincial Hydrographic Bureau, 2019). Wind data, with a resolution of 0.5 × 0.5°, were adopted based on the semimonthly mean of 10 years using data from the National Centers for Environmental Prediction. The initial salinity distribution was derived from the Ocean Atlas in the Huanghai Sea and the East China Sea (Hydrology) (Editorial Board for Marine Atlas, 1992) outside the Changjiang mouth and from observed data recorded inside the river mouth. Wave dynamics are not considered, because wave height within the river mouth is small in normal weather conditions (Hu *et al*., 2009).

The numerical model described earlier has been validated many times in the Changjiang Estuary, and the results suggest that the model can successfully simulate the hydrodynamic processes and saltwater intrusion in the estuary (Li, Zhu, and Wu, 2012; Lyu and Zhu, 2018; Qiu and Zhu, 2013). Because of the space limitations of the present paper, detailed descriptions of the model validation process can be found in the literature mentioned earlier.

River discharge is one of the most important dynamic factors that determines estuarine saltwater intrusion. The measured river discharge at Datong Station (Figure 1a), which accounts for 94.7% of the total discharge in the river basin, is the upper tidal limit in the dry season and is generally used as an upper boundary of the estuary in the numerical model. The river discharge has seasonal variation, which increases from January to July and then decreases from July to December. Although the monthly mean river discharge has a minimum value of 11,500 m^3/s in January and reaches a maximum value of 49,800 m^3/s in July (Changjiang Water Resources Commission, based on data from 1950 to 2016), there is still some time that the river discharge is low. For instance, from October 1978 to May 1979, the daily minimum river discharge was 7400 m^3/s. As a result, Chongming Island was surrounded by salt water for 3 months (Shen, Mao, and Zhu, 2003). Therefore, the authors set the river discharge value to 11,500 m^3/s to simulate the saltwater intrusion in the dry season and to see how long the salinity was higher than 0.45 psu at the water intake of the CHR. Because the period of saltwater intrusion is less than the longest residence time of the water supply of the CHR under this river discharge condition, the authors performed more experiments with river discharge values of 10,000 and 9000 m^3/s to determine the conditions under which the period of saltwater intrusion at the water intake of the CHR approaches 7 days. Then, the river discharge was fine-tuned in the model until the period of saltwater intrusion was equal to 7 days. This river discharge value represents the critical river discharge value the authors wanted to identify.

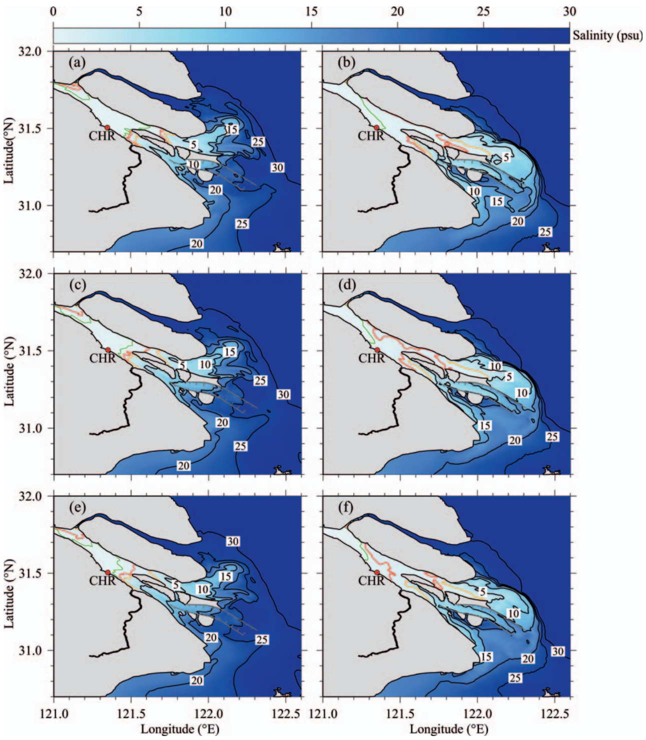

Figure 3. Surface distributions of salinity at flood slack during the spring tide (left panel) and neap tide (right panel) under river discharges of 11,500 m^3/s (a and b), 10,000 m^3/s (c and d), and 9000 m^3/s (e and f). The green line is the isohaline of 0.45 psu, the orange line is the isohaline of 1.0 psu, and the yellow line is the isohaline of 2.0 psu.

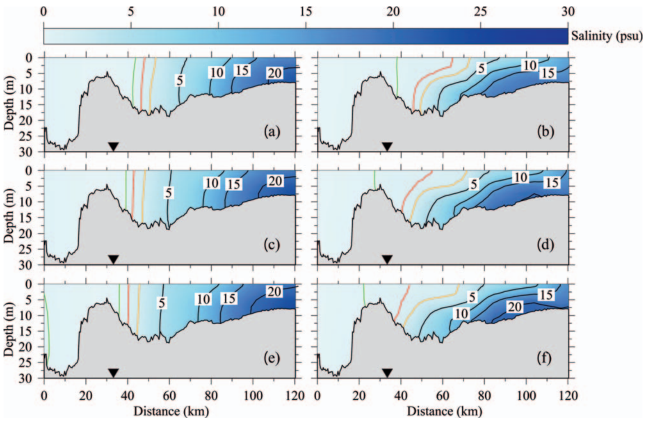

Figure 4. Profile distributions of salinity along section S at flood slack during the spring tide (left panel) and neap tide (right panel) under river discharge values of 11,500 m^3/s (a and b), 10,000 m^3/s (c and d), and 9000 m^3/s (e and f).

RESULTS

The critical river discharge for the water source of the Changjiang Estuary was ascertained. Different experiments results will be analyzed later.

River Discharge of 11,500 m^3/s

At flood slack (the reference site is the water intake of the CHR) during spring tide, there was a strong salinity front near the river mouth, which was caused by the confluence and the mixing of sea water with fresh river water (Figure 3a). The North Branch was occupied by highly saline water because of its funnel shape, which amplified the tide in its upper reaches and lowered the amount of inflow river discharge caused by the wider tidal flat in those upper reaches (Shen, Mao, and Zhu, 2003; Wu *et al.*, 2006). The diluted water plume extended to the NE on the north side of the North Channel, which resulted in lower salinity near the entrance of the North Branch. This phenomenon is caused by tidal pumping (Li *et al.*, 2014). The salinity of the North Channel and South Channel was higher than 0.45 psu, and the salinity was approximately 0.45 psu near their bifurcation. The water with a salinity higher than 0.45 psu intruded the upper reaches of the South Branch, which was the result of the SSO. The salinity in the South Branch was less than 0.45 psu, except in the area influenced by the SSO. There was an area of fresh water near the CHR during the spring tide under the river discharge of the climatic state. Along section S, the salinity was lower than 0.45 psu, and fresh water existed from 0 to 43 km, because the saline water induced by the SSO was only on the north side of the upper reaches of the South Branch (Figure 4a). Water with salinity between 5 and 22 psu was located in the South Passage and was partially mixed in the vertical direction because of the strong mixing caused by the spring tide. There was sufficient fresh water around the water intake of the CHR.

At flood slack during neap tide, isohalines of 5, 2, and 1 psu in the North Channel and South Channel all moved seaward (Figure 3b), compared with those during spring tide, especially at the isohaline of 5 psu in the North Channel. The SSO disappeared, and the salinity decreased in the upper reaches of the South Branch. This result indicated that the saltwater intrusion weakened during neap tide. There was a certain amount of fresh water in the upper South Branch and on the south side of the middle South Branch. Although the downstream isohaline of 0.45 psu was close to the water intake of the CHR, there was still fresh water at the water intake. However, the salinity on the north side of the middle and lower South Branch was higher than 0.45 psu, and this elevated salinity level originated from the SSO (Li, Zhu, and Wu, 2012; Wu and Zhu, 2007). With the weakening of the tide and the influence of the north wind, the diluted water plume on the north side of the North Channel, which extended to the NE during the spring tide, disappeared during the neap tide. Along section S, you can see that the CHR was located at 33 km and the isohaline of 0.45 psu was located at 38.5 km, *i.e.* only 5.5 km downstream from the water intake of the CHR (Figure 4b). There were obvious salt wedges and high salinity stratification in the South Passage because of the weak vertical mixing that occurs during neap tides (Li *et al.*, 2015).

The water elevation at the water intake of the CHR had a semidiurnal and fortnightly variation, with a maximum tidal range of 2.4 m during the spring tide (Figure 5a). The salinity had small semidiurnal variation but had distinct fortnightly variation (Figure 5b). The saline water at the water intake of the CHR was derived from the SSO, which occurred during the spring tide and took between 2 and 4 days to move from the bifurcation of the North and South Branch to the CHR with the runoff (Mao, Shen, and Chen, 2004; Zhu *et al.*, 2010). Therefore, the salinity during the latter spring tide, the moderate tide after the spring tide, and the early neap tide was higher than 0.45 psu. The longest number of days that the CHR could not use water from the Changjiang Estuary during the period of spring–neap tides was 5.0 days. The salinity was lower than 0.45 psu, and the CHR could use water from the estuary during the middle and latter neap tide, the moderate tide after the neap tide, and the early and middle spring tide, which accounted for approximately two-thirds of the total time during the spring–neap tide period. Therefore, there was sufficient time for the reservoir to use fresh water from the river when the river discharge was a climatological value in the dry season.

River Discharge of 10,000 m^3/s

At flood slack during spring tide, isohalines of 0.45, 1, 2, and 5 psu in the North Channel and South Channel moved distinctly landward, and there was saline water with a salinity greater than 1.0 psu in the upper reaches of the South Branch, *i.e.* the SSO became stronger, resulting in a larger area of highly saline water compared with that under river discharge of 11,500 m^3/s (Figure 3c). The freshwater area in the South Branch decreased, but fresh water still existed near the water intake of the CHR. Along section S (Figure 4c), the isohaline of 0.45 psu was located 39.5 km from the starting point of the profile and moved 3.5 km upstream; in addition, the isohaline of 5 psu in the South Channel moved landward approximately 3.0 km relative to that under river discharge of 11,500 m^3/s. The preceding results indicated that the saltwater intrusion was enhanced as the river discharge decreased.

At flood slack during neap tide, the fresh water in the upper reaches of the South Branch decreased, and the salinity around the water intake of the CHR exceeded 0.45 psu (Figure 3d). There was no fresh water for the CHR when the river discharge was 10,000 m^3/s. Along the south middle coast of Chongming Island, the salinity was higher than 1.0 psu because of the enhanced SSO. Along section S (Figure 4d), the isohaline of 0.45 psu appeared 28.5 km from the starting point of the profile and was 4.5 km upstream from the water intake of the CHR. Compared with that under river discharge of 11,500 m^3/s, the isohaline of 0.45 psu moved 11.0 km upstream, and the isohaline of 1.0 psu in the South Channel moved landward by approximately 9.5 km.

The temporal variation of salinity at the water intake of the CHR showed that the longest number of days that the CHR could not use water from the Changjiang Estuary during a period of spring–neap tides was 6.5 days (Figure 5c), and this value increased by 1.5 days when the river discharge changed from 11,500 to 10,000 m^3/s. This result means that the availability of freshwater resources in the Changjiang Estuary becomes severe when the river discharge declines.

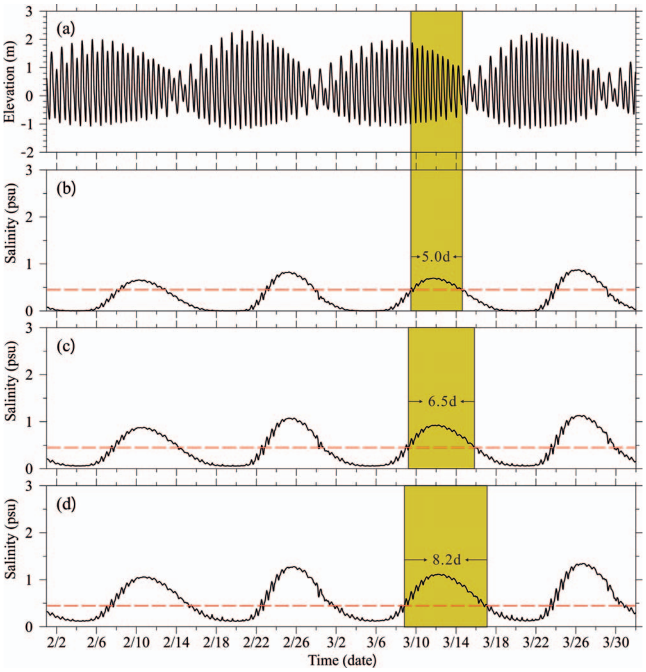

Figure 5. Temporal variation of elevation and salinity under river discharge of 11,500 m^3/s (a and b), 10,000 m^3/s (c), and 9000 m^3/s (d) at the water intake of the CHR. The yellow belt indicates the longest time the intake water is unsuitable. The red dashed line represents a salinity of 0.45 psu, which is the salinity standard for drinking water.

River Discharge of 9000 m^3/s

At flood slack during spring tide, the isohalines near the river mouth clearly moved upstream, and the freshwater area in the upper reaches of the South Branch was less than half the area seen when the river discharge was 11,500 m^3/s (Figure 3e), indicating that the saltwater intrusion was enhanced by the lower river discharge. There was still fresh water near the water intake of the CHR, but the downstream isohaline of 0.45 psu was close to the water intake. Along section S (Figure 4e), the isohaline of 0.45 psu was located at 2.0 km, meaning that the SSO touched the southern coast of the upper reaches of the South Branch. The downstream isohaline of 0.45 psu was 36.5 km from the starting point of the profile and moved 6.5 km upstream compared with that under river discharge of 11,500 m^3/s. The fresh water in the estuary worsened under conditions of lower river discharge.

At flood slack during neap tide, the fresh water in the upper reaches of the South Branch was further reduced, and the salinity around the water intake of the CHR was approximately 0.75 psu (Figure 3f). The area of water with a salinity higher than 1.0 psu was located on the northern side of the middle South Branch and in the lower reaches of the South Branch. Along section S (Figure 4f), the isohaline of 0.45 psu appeared 21.5 km from the starting point of the profile and was 11.5 km upstream from the water intake of the CHR. Compared with that under river discharge of 11,500 m^3/s, the isohaline of 0.45 psu moved 17.0 km upstream, and the isohaline of 1.0 psu in the South Channel moved landward by approximately 20.0 km.

The temporal variation of salinity at the water intake of the CHR showed that the longest number of days that the CHR could not use water from the Changjiang Estuary during the period of spring–neap tides was 8.2 days (Figure 5d), and this

Table 2. *The time of saltwater intrusion at the water intake of CHR under different scenarios.*

Scenarios	River Discharge (m^3/s)	Days
1	11,500	5
2	10,000	6.5
3	9000	8.2
4	9500	7

value increased by 3.2 days when the river discharge changed from 11,500 to 9000 m^3/s. The longest number of days that the CHR could not use water from the estuary exceeded 7 days, which is the longest period the water supply of the CHR can be restricted before the water security of the NW districts of Shanghai is threatened.

DISCUSSION

The preceding numerical experiments showed that saltwater intrusions in the Changjiang Estuary became stronger when the river discharge decreased. The longest number of days that the CHR could not use water from the Changjiang Estuary during the period of spring–neap tides was 5.2 and 8.2 days when the river discharge was 10,000 and 9000 m^3/s (Table 2), respectively. The longest residence time of the water supply of the CHR is 7 days; thus, the critical river discharge should be in the range from 10,000 to 9000 m^3/s. Therefore, the river discharge was finely adjusted to be from 9000 and 10,000 using 100 m^3/s intervals. The authors found that the longest number of days that the CHR could not use water from the Changjiang Estuary could reach 7.0 days when the river discharge is 9500 m^3/s. (Figure 6).

Therefore, the critical river discharge was 9500 m^3/s based on the longest residence time of the water supply of the CHR (Table 2). If a river discharge of 9500 m^3/s occurred, the Shanghai government could ask the Changjiang Water Resources Committee to discharge more water from the Three Gorges Reservoir to restrain the saltwater intrusion and ensure the water security of the megalopolis of Shanghai. Based on previous studies (Dai *et al.*, 2016; Mei *et al.*, 2015; Qiu and Zhu, 2013), Three Gorges Dam operation greatly affects seasonal variations in water discharge, increasing river discharge in January and February by 1750 m^3/s. Thus, it will be beneficial for the Changjiang Estuary to avoid discharge lower than the critical river discharge.

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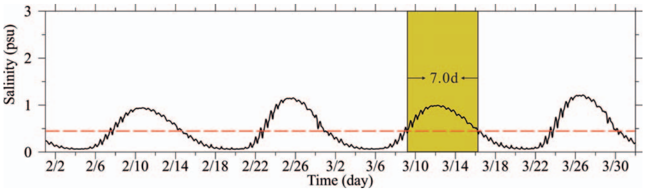

Figure 6. Temporal variation of salinity at the water intake of the CHR under river discharge of 9500 m^3/s. The yellow belt indicates the longest time the intake water was unsuitable.

CONCLUSIONS

In this study, saltwater intrusion was simulated and critical river discharge was determined under different river discharges using the improved ECOM-si. The characteristics of the saltwater intrusion were reproduced. There was a strong salinity front near the river mouth, and the North Branch was occupied by highly saline water. Near the river mouth, saline water is partially mixed because of strong tidal mixing during spring tides; in addition, the salinity showed high stratification because of weak vertical mixing during neap tides. The SSO occurred during the spring tide and was transported downstream by runoff; the SSO arrived in the middle reaches of the South Branch during the subsequent neap tide and moderate tide, and it threatened the water intake of the CHR in the South Branch. During the period of spring–neap tides, the longest number of days that the CHR could not use water from the Changjiang Estuary was 5.0 days, and the CHR could use fresh water from the river approximately two-thirds of the time during the spring–neap tide period when the river discharge had a climatological value of 11,500 m^3/s in the dry season.

The saltwater intrusion increased when the river discharge declined, and the availability of freshwater resources in the estuary became severe. The longest number of days that the CHR could not use water was 6.5 and 8.2 days under river discharge values of 10,000 and 9000 m^3/s, respectively, after which the water security of Shanghai was threatened.

The longest residence time of the water supply in the CHR is 7 days; thus, the critical river discharge should be between 10,000 and 9000 m^3/s. By finely adjusting the river discharge in intervals of 100 m^3/s between 9000 to 10,000 m^3/s in the model, the authors found that the critical river discharge was 9500 m^3/s, which corresponded to a value of 7.0 days in which the CHR could go without using water from the estuary. If a river discharge of 9500 m^3/s occurred, the Shanghai government could ask the Changjiang Water Resources Committee to discharge more water from the Three Gorges Reservoir to restrain the saltwater intrusion and ensure the water security of the megalopolis of Shanghai.

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