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Research papers

Impact of the bottom drag coefficient on saltwater intrusion in the extremely shallow estuary

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A R T I C L E I N F O

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A B S T R A C T

The interactions between the extremely shallow, funnel-shaped topography and dynamic processes in the North Branch (NB) of the Changjiang Estuary produce a particular type of saltwater intrusion, saltwater spillover (SSO), from the NB into the South Branch (SB). This dominant type of saltwater intrusion threatens the winter water supplies of reservoirs located in the estuary. Simulated SSO was weaker than actual SSO in previous studies, and this problem has not been solved until now. The improved ECOM-si model with the advection scheme HSIMT-TVD was applied in this study. Logarithmic and Chézy-Manning formulas of the bottom drag coefficient (BDC) were established in the model to investigate the associated effect on saltwater intrusion in the NB. Modeled data and data collected at eight measurement stations located in the NB from February 19 to March 1, 2017, were compared, and three skill assessment indicators, the correlation coefficient (CC), root-mean-square error (RMSE), and skill score (SS), of water velocity and salinity were used to quantitatively validate the model. The results indicated that the water velocities modeled using the Chézy-Manning formula of BDC were slightly more accurate than those based on the logarithmic BDC formula, but the salinities produced by the latter formula were more accurate than those of the former. The results showed that the BDC increases when water depth decreases during ebb tide, and the results based on the Chézy-Manning formula were smaller than those based on the logarithmic formula. Additionally, the landward net water flux in the upper reaches of the NB during spring tide increases based on the Chézy-Manning formula, and saltwater intrusion in the NB was enhanced, especially in the upper reaches of the NB. At a transect in the upper reaches of the NB, the net transect water flux (NTWF) is upstream in spring tide and downstream in neap tide, and the values produced by the Chézy-Manning formula are much larger than those based on the logarithmic formula. Notably, SSO during spring tide was 1.8 times larger based on the Chézy-Manning formula than that based on the logarithmic formula. The model underestimated SSO and salinity at the hydrological stations in the SB based on the logarithmic BDC formula but successfully simulated SSO and the temporal variations in salinity in the SB using the Chézy-Manning formula of BDC.

1. Introduction

In single-channel estuaries, saltwater intrusion generally develops in the along-channel direction. However, in bifurcated estuaries, lateral saltwater intrusion may be significant and can play an important role in determining the temporal variation and spatial distribution of salinity in the spring-neap tidal cycle (Wu et al., 2006; Gong and Shen, 2011; Wang et al., 2012). The Changjiang, also known as the Yangtze River, is one of the largest rivers in the world. The Changjiang Estuary has a 90-km-wide river mouth and is characterized by multiple bifurcations (Fig. 1). Firstly, the estuary is divided by Chongming Island into the South Branch (SB) and North Branch (NB). The SB and its lower reaches form the main channel of the Changjiang and contribute to the majority of river discharge, while the NB is heavily silted. Secondly, the lower SB is bifurcated into the South Channel (SC) and the North Channel (NC) by Changxing Island and Hengsha Island. Finally, the SC is bifurcated into the South Passage (SP) and the North Passage (NP) by Jiuduansha Island. According to water column stratification or vertical salinity structure, estuaries can be divided into three categories: type A (salt wedge or strongly stratified), type B (partially mixed), and type C (vertically well mixed) (Prichard, 1955; Cameron and Prichard, 1963). Shen et al. (2003) concluded that the NB and SB belong to the type C, and the NC, NP and SP present as type B during spring tide and present as type A during neap

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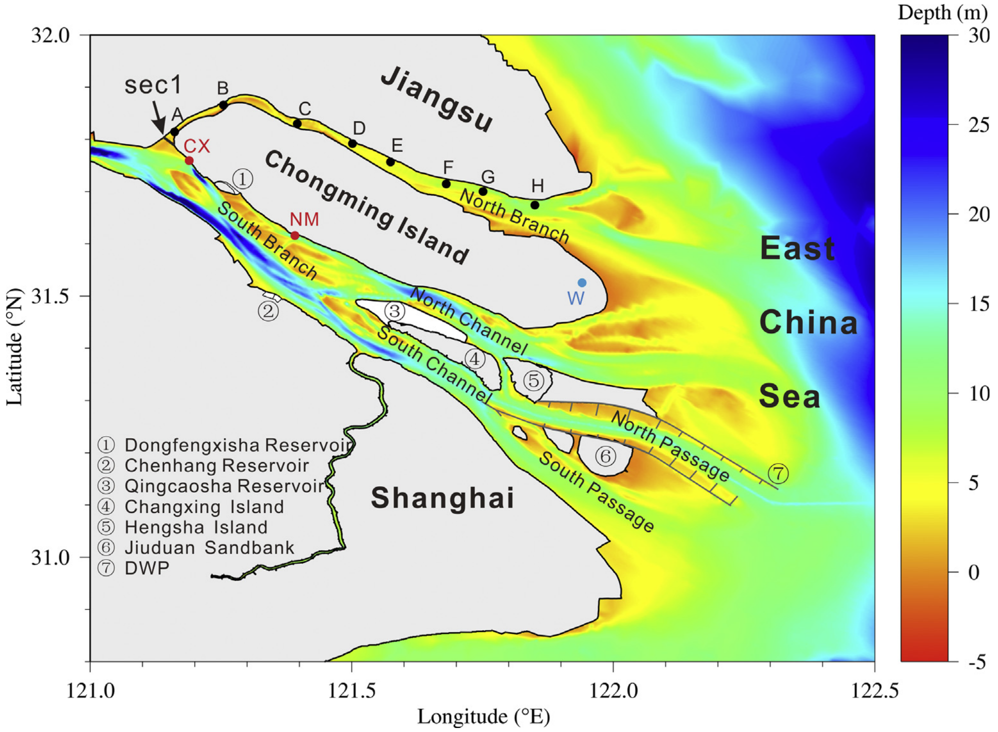

Fig. 1. Topography of the Changjiang Estuary. Black dots indicate the locations of measurement stations in February 2017; red dots indicate the locations of hydrologic stations Nanmen (NM) and Chongxi (CX); sec1 is a transect located in the inlet of the NB; W is the location of the weather station at the Chongming eastern shoal; and DWP is the Deep Waterway Project.

tide. Saltwater intrusion in the Changjiang Estuary is mainly controlled by the river discharge and tide (Shen et al., 2003; Wu et al., 2006; Li et al., 2010; Zhu et al., 2010; Qiu et al., 2012) but is also influenced by wind (Li et al., 2012), topography (Li, et al., 2014), river basin and estuarine projects (Zhu, et al., 2006; Qiu and Zhu, 2013) and sea level rise (Qiu and Zhu, 2015). River discharge is recorded at the Datong gauge station, which is located 620 km from the Changjiang mouth. Discharge exhibits pronounced seasonal variations, with the lowest monthly mean value of 11,200 m^3s^{-1} in January and the highest monthly mean value of 49,700 m^3s^{-1} in July (Changjiang Water Resources Commission, based on data from 1950 to 2016). The tides in the estuary exhibits semidiurnal, diurnal, and fortnightly spring-neap signals (Zhu, et al., 2015).

The natural evolution and artificial reclamation of the intertidal zone from the 1950s to 2000s has severely narrowed the upper reaches of the NB (Zhu and Bao, 2016). Consequently, the upper reaches of the NB have become almost orthogonal to the SB, while the lower reaches have become funnel shaped. The evolution of the river regime of the NB has helped to prevent runoff from entering the NB, especially during the dry season, was also making the tidal range larger in the NB than in the SB. Strong tidal forcing in the NB induces significant subtidal circulation, resulting in a net landward flow when river discharge is low during spring tide (Wu et al., 2006; Xue et al., 2009). This residual transport forms a type of saltwater intrusion known as saltwater spillover (SSO) from the NB into the SB, which is the most characteristic type of saltwater intrusion in the estuary. During spring tide, the water level rises considerably in the upper reaches of the NB due to its funnel shape, leading to a massive amount of SSO from the shoals into the SB. Only a small amount of the saltwater returns to the NB because the shoals in the upper reaches of the NB are exposed to the air during ebb tide. The saltwater that is spilled into the SB is transported downstream by runoff and arrives in the middle reaches of the SB during the subsequent neap tide. This process impacts Dongfengxisha Reservoir, Chenhang Reservoir and Qingcaosha Reservoir (QCSR) and threatens Shanghai's water supply. The massive QCSR was built in 2010 along the northwestern portion of Changxing Island, and it supplies more than 70% of the freshwater for Shanghai. Water from the Changjiang is allowed to flow into QCSR when the salinity is lower than 0.45 (the salinity standard of drinking water), but this operation is suspended when saltwater intrusion influences the water intake.

Although the author's research group has conducted intensive studies of saltwater intrusion in the Changjiang Estuary, we found that the modeled SSO was weaker than the real situation, especially during spring tide. The mean topographic depth is 3.07, 3.44 and 5.07 m (here and throughout the manuscript, the datum is the mean sea level of the Yellow Sea) in the upper, middle and lower reaches of the NB, and tidal flats with depths of less than 2 m account for 39%, 23%, and 32% of these reaches, respectively. Therefore, the NB is extremely shallow. The bottom drag coefficient (BDC) determined by the law of the wall in previous studies may be unsuitable for the extremely shallow NB.

The BDC C_d is determined by the law of the wall, and the logarithmic profile can be obtained via integration (Batchelor, 1953).

$$\tau_b = \rho C_d |u_b| u_b \tag{1}$$

$$C_d = \left[\frac{1}{\kappa}\ln\left(\frac{z_b}{z_0}\right)\right]^{-2} \tag{2}$$

where τ_b is the bottom friction stress; C_d is the BDC; u_b is the bottom current velocity at z_b; z_b is the height from the bottom; κ is the von Karman constant (equal to 0.4); and z_0 is the bottom roughness, which is set to 0.001 m in this study. In many studies, the structure of tidally induced flow in channels and embayments has been characterized as logarithmic (Dyer, 1980; Soulsby and Dyer, 1981; Lueck, 1988).