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A three-dimensional hydrodynamic and salinity transport model of estuarine circulation with an application to a macrotidal estuary

Yan Xing, Congfang Ai*, Sheng Jin

State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

A three-dimensional semi-implicit finite volume numerical model has been developed and applied to study tidal circulation and salinity stratification in the region of Oujiang River Estuary, China. The model employs horizontally unstructured grids and boundary-fitted coordinate system in the vertical direction. Governing equations consisting of continuity, momentum, and transport equations are all solved in the integral form of the equations, which provides a better representation of the conservative laws for mass, momentum, and transport in the coastal region with complex geometry and bottom bathymetry. The model performance was firstly quantified with skill assessment statistics on the choice of different parameters and validated with observed tidal elevation, current velocity, direction and salinity data over a spring–neap tidal cycle collected in 2006. Numerical results show that the model with wetting–drying capability successfully simulated the tidal currents and salinity fields with a reasonable accuracy and indicate that the Oujiang River Estuary is a macrotidal estuary with strong tidal mixing. In addition, the model results also show that the Oujiang River Estuary is a well-mixed estuary during spring tide. Then, the numerical simulations were performed to compare the hydrodynamic process and salinity distribution before and after a river training, which was conducted by blocking the south branch of the Oujiang River mouth. The results reveal that with the only north access to the sea, the influence of the blocking project on the flood discharge capacity is limited and the incremental velocity is beneficial to the navigation channel maintenance, although it will cause some scour to the embankment. Furthermore, the redistribution of tidal prism passing in or out the north branch makes a little severe salinity intrusion during high tide or low tide. However, the salinity intrusion is still within acceptable range, although it can cause some adverse effect on water intaking of production and life. The variations of salinity levels in Yueqing Bay situated at the north of the river mouth are not obvious, so the blocking project will not bring damage to local aquiculture. However, significant changes of salinity happen inside or outside of the south branch, so enough attention need to be paid to the changes of environment caused by the salinity variation after the blocking project. Overall, by weighing advantages and disadvantages of the blocking project, it is feasible and the model can be considered as a tool for managing and studying estuarine circulation.

1. Introduction

The tidal circulation and salinity transport processes in estuaries generally are very complex and highly dynamic due to the presence of sinuous coastlines, islands, channels, shoals and some man-made structures. Complexities can also arise because of the mixture of salt and fresh water as well as the synchronous impacts of runoff, tides, waves, winds and offshore currents. The freshwater inflows produce a net seaward transport, while the tides with the denser seawater lead to periodic seaward and landward transport, which result in the classical two-layer circulation of net upriver flow in the bottom layer and net downriver flow in the upper layer. However, in the case of macrotidal estuaries with tidal ranges of more than 2 m, destratification can occur when tide-induced turbulence is large enough to fully mix the water column. Although the mixing of the water column prevents the formation of two layers with opposite flows, vertical variations in density still exist [1,2]. The baroclinic pressure gradient, which pushes the denser seawater upriver along the bottom layer of the estuary, still does its work. Intertidal zones of estuaries with large tidal flats, which are submerged by water at high tide but naked at low tide, can create favorable natural conditions for aquaculture, and also play an important role on tidal circulation and salinity distribution. The long-term stability and sustainability of the hydrological salinity environment are necessary for the continued prosperity of aquaculture. Understanding the tidal circulation and salinity transport mechanism in estuaries is of great importance for coastal engineering, disaster prevention, water security and intertidal zone aquiculture. Numerical simulation is a good and effective approach

* Corresponding author.
E-mail address: acfdlut@163.com (C. Ai).

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for this task. Some numerical models have been developed, such as FVCOM [3], EFDC [4], POM [5] and ROMS [6], and have been successfully applied to simulate the circulation and transport processes of coastal oceans and estuaries [7–10].

The Oujiang River (OR) is a mountainous river and is meandering eastwards to the East China Sea (ECS). It is the second longest river in Zhejiang Province, China with the length of 388 km and has a drainage basin of 17,985 km^2. The river discharge has a strong seasonal variation. About 76% of runoff occurs in the flood season from March to August, and the other 24% occurs in the rest of the year. Based on the observed data of upriver hydrological station, the mean annual flow and sediment transport are up to 470 m^3/s and 2.5×10^6 tons, respectively, and maximum and minimum flows are 22,800 m^3/s in 1952 and 10.6 m^3/s in 1967, respectively. The Oujiang River is split into the north branch and the south branch before it enters into the sea by an island named Lingkun (Fig. 1). The north branch, as a main access to the sea, carries about 79% and 74% of the total flow during flood tide and during ebb tide, respectively. The south branch enters into the Wenzhou shoal through a submerged dike, which was built in 1970s for siltation. The Wenzhou shoal is very shallow in most of the region. Large intertidal zones exist at the mouth of the river, which are submerged by water at high tide and naked at low tide. Plenty of shoals such as Wenzhou shoal, Oufei shoal and Yueqing shoal are all above the local sea level [11].

The Oujiang River Estuary (ORE) as a part of the East China Sea is a macrotidal estuary. The estuary, with the scales of 35 km long and 30 km wide at the mouth, is characterized by its bifurcation shape and has two outlets (north branch and south branch) into the ECS. The complex geometry consists of tens of staggered shoals, deep tidal creeks as well as more than 40 big and small islands, which are scattered outside mouth of the ORE. Tide in the ORE is a semidiurnal tide, with an average tidal range of 4.5 m and a maximum value over 7 m at Longwan gauge station. Freshwater meets with salt water at the mouth region with the mean salinity from 3.7 psu to 26 psu and salinity profiles are well-mixed over the water depth because of the strong tidal mixing characteristic of the ORE.

In order to meet booming land demands due to urban expansion and deepwater port construction, there has a plan to block the south branch of the Oujiang River mouth for reclamation. Therefore, the model is developed and applied to reproduce this blocking project to assess the influence of ambient flow pattern and redistribution of tidal prism as well as salinity levels around the ORE.

A few numerical models have been carried out in this area. A two-dimension horizontal model has been developed to study the feasibility of reclamation area from the point of its impacts on the hydrodynamic sediment environment [11]. The study of tidal current and sediment movement gave a better understanding of the environments around the ORE, but it cannot represent the vertical structure of variables and did not consider salinity distribution in this area. The EFDC model was modified and used to investigate the variations of current, salt intrusion and vertical stratification under different conditions of river inflow and wind in the Oujiang River reach [12]. The responses of salinity distributions in Oujiang River reach under different conditions were well predicted, but the simulation only studied the river reach based on structured grids without complex geometry and man-made structure North Jetty outside the mouth. In this study, a three-dimensional finite-volume hydrodynamic and salinity transport model based on unstructured grids was developed and applied to study tidal circulation and salinity stratification in Oujiang River Estuary, which contains not only the river reach inside the mouth but also the region outside the mouth. After a series of calibration and verification, the developed model was performed to comprehend the influence of a blocking project on ambient flow pattern and redistribution of tidal prism as well as salinity distribution around the ORE.

The paper is organized as follows. The model description is described in Section 2. Model calibration and verification are shown in Section 3. In Section 4, the application of the model to assess the impacts of south branch blocking project is discussed. Finally, conclusions are drawn in Section 5.

2. Model description

2.1. Governing equations

The governing equations describing free surface flows can be derived from the Reynolds-averaged Navier–Stokes equations under the hydrostatic assumption and the Boussinesq approximation. The continuity equation for an incompressible fluid has the following form:

$$\nabla\cdot \vec{U} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

and the momentum equations and salinity transport equation expressed in a non-conservative forms are

$$\begin{aligned} &\frac{D\vec{U}}{Dt} + f\ \vec{n} \times \vec{U} + g\nabla\eta + g\nabla\left(\int_{-h}^{\eta} \frac{\rho-\rho_0}{\rho_0}\right) \\ &= \nabla\cdot\left(\nu^h \nabla \vec{U}\right) + \frac{\partial}{\partial z}\left(\nu^v \frac{\partial \vec{U}}{\partial z}\right) \end{aligned} \tag{2}$$

$$\frac{DS}{Dt} = \nabla\cdot(k^h \nabla S) + \frac{\partial}{\partial z}\left(k^v \frac{\partial S}{\partial z}\right) \tag{3}$$

where $\vec{U}(x, y, z, t)$ is the horizontal velocity with components (u,v); $w(x,y,z,t)$ is the vertical velocity; $f = 2\Omega_{earth} \sin\varphi_{lat}$ is the Coriolis parameter, here Ω_{earth} is the angular velocity of earth rotation, φ_{lat} is the latitude; $\vec{n}$ is the upwind unit vector; g is the gravitational acceleration; $\eta(x,y,t)$ is the tidal elevation; ρ denotes the water density; ρ_0 is a constant reference density; S is the salinity concentration; ν^h and ν^v are the coefficients of horizontal and vertical kinematic eddy viscosities, respectively; k^h and k^v are the horizontal and vertical diffusivity coefficients, respectively and ∇ is the horizontal gradient operator $(\partial/\partial x, \partial/\partial y)$.

In Eq. (2), the barotropic term is constant with depth, while the baroclinic term varies with depth and is a function of density distribution. The linear equation of state, in which the density is a polynomial function of temperature T and salinity S [13], is used to compute density based on the salinity simulation. The interaction of the barotropic and baroclinic terms can create tidal asymmetry between the ebb and the flood of tidal cycle. In the region of estuarine and coastal where the density gradient of the sea is most pronounced and the condition of baroclinicity is the most extreme [14], the baroclinic term cannot be ignored.

By integrating the continuity equation (Eq. (1)) over the water column and combining it with the free surface and bottom kinematic boundary conditions, the following free surface equation is obtained:

$$\frac{\partial \eta}{\partial t} + \nabla\cdot\left(\int_{-h}^{\eta} \vec{U}\, dz\right) = 0 \tag{4}$$

where h is the depth of bottom boundary measured from the undisturbed free surface.

2.2. Turbulence closure model

In the model, the horizontal eddy viscosity ν^h is fixed at 10 m^2/s and the horizontal diffusivity coefficient k^h is treated as a constant with a value of 1 m^2/s [15]. The vertical eddy viscosity and diffusivity coefficient are solved by Mellor and Yamada level 2.5 turbulence closure model [16] with stability functions modified by Galperin et al. [17], which is a two-equation model with computing the evolution of turbulent kinetic energy $q^2/2$ and turbulence length scale $q^2 l$.