Ocean Engineering 139 (2017) 85–94

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Numerical simulation of the hydrodynamics and water exchange in Sansha Bay

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ARTICLE INFO

Keywords:
Sansha Bay
Hydrodynamic model
Seawater half-exchange time

ABSTRACT

A two-dimensional shallow water hydrodynamic finite element model (SHYFEM) was applied to Sansha Bay, Fujian, China. The model was used to investigate the hydrographic characteristics of the bay and in particular its water-exchange ability with the open sea. Comparisons between model output and observations indicate that the model is generally capable of reproducing the variability of water level and currents in the study region. Further analysis suggests that the magnitude of currents is larger in deep water areas such as channels, reaching approximately 1 m s^{-1}, whereas it is often less than 0.5 m s^{-1} in shallow water areas such as tidal flats. By contrast, the residual currents are much weaker, without a clear inward or outward direction. Seawater in deeper areas tends to exchange faster with the open sea compared to that in shallower regions. The half-exchange time of sea water is < 10 d along main channels, while it exceeds 30 d in bay heads. Model sensitivities suggest that (i) dredging of tidal flats increases the exchange rate of seawater near bay heads, (ii) increasing river runoff or opening up an extra passage can significantly increase the exchange rate locally yet slightly decrease it in other secondary bays.

1. Introduction

Sansha Bay, situated in the northeastern area of Fujian, China, is a semi-enclosed bay consisting of several secondary bays such as Baima Harbor, Yantian Harbor, Dongwuyang, Guanjingyang and Sanduao (see Fig. 1 for locations). Sansha Bay has a relatively large water area of approximately 675 km^2, but there is only one narrow gateway (i.e., Dongchong Channel) of approximately 3-km wide in the south bridging the bay and the outer waters (i.e., the Taiwan Strait). Due to such a geographical feature, Sansha Bay has historically been a natural sheltered bay (Wang et al., 2009). It is also a famous spawning ground of the large yellow croaker in China.

In recent years, water quality and ecosystem of Sansha Bay have been strongly affected by land-based pollution, coastal industries, aquaculture, and urbanization, resulting in severe habitat degradation (Wang et al., 2011; Wu et al., 2012; Sun et al., 2015). Previous studies have pointed out that dissolved inorganic nitrogen (DIN) and active phosphorus (AP) are the two primary factors inducing degraded water quality (Liu et al., 2003; Shen et al., 2014; Sun et al., 2015). Sources of DIN and AP have been attributed primarily to river inputs (including massive untreated industrial and domestic sewage) and cage aquaculture (Cai, 2007; Shen et al., 2014; Sun et al., 2015). The increasing trend of DIN and AP in Sansha Bay is in turn becoming an important factor hindering the sustainable development of cage aquaculture (Cai, 2007). Therefore, ecological restoration in Sansha Bay is practically important and has attracted increasing attention from various communities.

In addition to regular ecological restoration schemes (e.g., Boesch et al., 2001), it is generally more efficient to propose appropriate physical restoration schemes based on the known hydrodynamic background. Better understanding of the hydrographic characteristics of Sansha Bay and its water-exchange ability with the open sea facilitates proposing the physical-based schemes in a more effective way. Given the limited observations, physical oceanographic aspects of Sansha Bay have not been well understood. Most previous studies focused on the tidal features or the effect of reclamation on channels (e.g., Wang et al., 2002; Ye et al., 2007).

Two cruises were conducted in Sansha Bay in order to collect newly in-situ observations: one in summer (August–September 2012) and the other in winter (January–March 2013). Cruise measurements included

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http://dx.doi.org/10.1016/j.oceaneng.2017.04.031
Received 4 August 2016; Received in revised form 31 December 2016; Accepted 20 April 2017

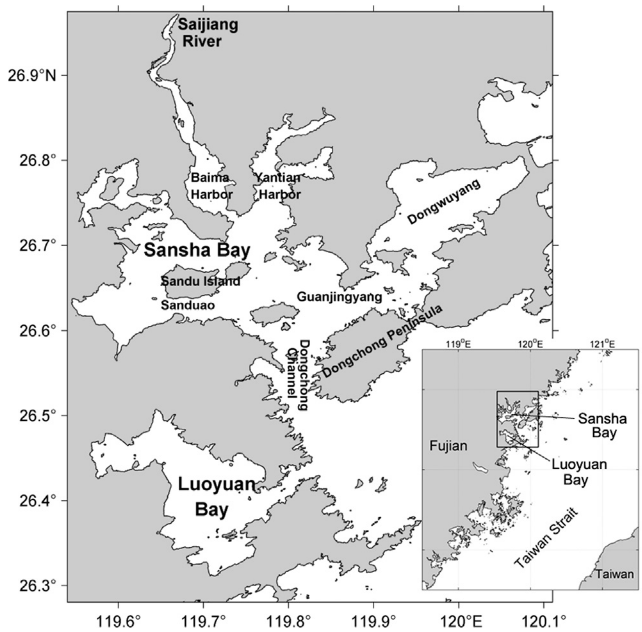

Fig. 1. Map of Sansha Bay with the main islands, harbors and channels labeled. The lower right inset shows the location of Sansha Bay.

temperature, salinity, currents, and time series of water level. Based on these observations, a preliminary understanding of the hydrographic/hydrodynamic features was obtained (Lin et al., 2016a). The interactions between tides and regional wind forcing were also investigated using measurements of water level and the contemporaneous wind fields (Lin et al., 2016b). Nevertheless, in-situ measurements are still rather limited and costly, which naturally calls for the need of developing a hydrodynamic model for Sansha Bay. The above-mentioned observations could also be used in model validation. The application of a robust hydrodynamic model can be useful in better understanding the regional oceanography and also in proposing more effective physical-based restoration schemes.

A two-dimensional hydrodynamic model was applied for Sansha Bay in this study, based on the shallow water hydrodynamic finite element model (SHYFEM) developed by Umgiesser et al. (2004). The model will be used to examine the hydrographic characteristics (e.g., variations of water level and currents) in Sansha Bay and its water-exchange ability with the outer waters (e.g., half-exchange time).

2. The numerical model

The SHYFEM was designed to simulate physical processes in lagoons, coastal seas, estuaries and lakes (Umgiesser et al., 2004; Umgiesser, 2009). The model uses the finite element technique and an effective semi-implicit scheme, making it particularly suitable to be applied in bays with complicated geography and bathymetry such as Sansha Bay. The finite element technique allows for more convenient increasing of the spatial resolution as needed in regions of particular interest, and the model is also capable of handling wetting and drying processes in a mass conserving way (Umgiesser et al., 2004). The model is also coupled with an advection and diffusion numerical module to simulate the transport of passive or active tracers induced by currents (Cucco and Umgiesser, 2006).

2.1. The model equations

The SHYFEM is particularly suited to be run in very shallow basins (Umgiesser et al., 2004) under strong influence of tides, so the water is normally assumed to be vertically well-mixed and hence ignores stratification. The set of hydrodynamic equations is then reduced to the depth-averaged shallow water equations (e.g., Csanady, 1982). The momentum and continuity equations are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv=-g\frac{\partial \eta}{\partial x}-\frac{ru\sqrt{u^2+v^2}}{H}$$
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+fu=-g\frac{\partial \eta}{\partial y}-\frac{rv\sqrt{u^2+v^2}}{H}$$
$$\frac{\partial \eta}{\partial t}+\frac{\partial (uH)}{\partial x}+\frac{\partial (vH)}{\partial y}=0 \qquad (1)$$

where $u$and $v$are zonal and meridional components of velocity, respectively; η is sea surface elevation, H is the total water depth ($H=h+\eta$ with $h$being the mean depth), $f$is the Coriolis parameter, $r$is the bottom drag coefficient and g is the acceleration due to gravity.

The model is coupled with an advection and diffusion module which is used to describe the simulated current induced transport of a passive tracer P, which represents the concentration of a pollutant. The equation reads:

$$\frac{\partial P}{\partial t}+\frac{\partial UP}{\partial x}+\frac{\partial VP}{\partial y}=\frac{\partial}{\partial x}\left(HK_x\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(HK_y\frac{\partial P}{\partial y}\right)+S \qquad (2)$$

where Pdenotes the concentration of a pollutant, $U$and V are the depth-integrated velocities (namely total or barotropic transports) in x- and y-directions, respectively, calculated by the hydrodynamic model, $K_x$and $K_y$are the coefficients of diffusivity, and S denotes the pollutant source per unit area and per unit time. The pollutants are assumed to be conservative materials in the model.

During ebb tide, the open boundary condition is given by $\frac{\partial P}{\partial t}+\vec{V}\bullet\vec{n}\frac{\partial P}{\partial n}=0$, where $\vec{n}$ is the unit normal vector and $\vec{V}$ is the velocity vector. During flood tide, the open boundary condition is given by $P=C_0$, where C_0 is the background concentration.

2.2. The model setup

The finite element mesh specifically developed for Sansha Bay is shown in Fig. 2, representing the Sansha Bay, Luoyuan Bay (to the south of Sansha Bay) and their outer regions with triangular elements of different size and shape. The finite element technique allows the model to capture the complicated coastline more accurately, and also to increase the spatial resolution in areas of particular interest. A total of 21407 nodes and 37581 triangular cells were used to represent the model domain with higher spatial resolution, up to 10 m, in secondary bays.

In addition to the solid boundaries naturally formed by the bay-head coastlines of each secondary bay, the model also has an open southeastern boundary which is set to be a straight line connecting stations Tailu and Waicheng (Fig. 2a). The model bathymetry (Fig. 2a) was obtained by digitizing the nautical chart of Sansha Bay and Luoyuan Bay published in 2009. It is shown that the water depths in the vicinity of each bay head are typically less than 5 m. Parts of such areas are defined as tidal flats which are wet during high tide while are dry during low tide. The water depths at channels are relatively deep, reaching about 20–30 m, and it is the deepest at the bay mouth, exceeding 50 m.

The model starts to integrate from rest, i.e., at time $t=0$, $u=v=\eta=0$. The in-situ water-level time series at stations Tailu and Waicheng are used as open boundary conditions to drive the model. Since Sansha Bay is a relatively small near-enclosed bay, tidal forcing at the open boundary is much more important than other forcing such as the local winds. The good agreement between observations and model simulations, as will be shown below, proves that considering tides at the open boundary as the only model forcing is a