Continental Shelf Research 143 (2017) 54–66

Contents lists available at ScienceDirect

Continental Shelf Research

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

Hydrodynamic and transport responses to land reclamation in different areas of semi-enclosed subtropical bay

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ARTICLE INFO

Keywords:
Land reclamation
Subtropical bay
Tidal energy flux
Water age
Numerical model
Deep Bay

ABSTRACT

Many coastal areas worldwide have been reclaimed to meet the increasing land demand. Understanding the effects of land reclamation on the hydrodynamics and transport processes of a semi-enclosed bay is therefore of significance. From a case study of Deep Bay (DB) in China and referring to idealized bay models, the effects of two types of land reclamation, one that narrows the bay mouth and another that reduces the water area inside the bay, were examined in this study. Simulation results of idealized models show that the current velocity at the bay mouth and the incoming tidal energy flux are negatively correlated with the width of bay mouth, as the tidal prism remains almost constant when the bay mouth width reduces. The bay mouth width reduction would also increase the tidal energy dissipation inside of the bay due to friction increase. In DB, a 30% reduction in the mouth width increased the bay mouth current velocity by up to 5% and the total incoming energy flux by 18%. The narrowed bay mouth also substantially changed the bay's vertical structure of salinity, increasing the stratification strength by 1.7×10^{-4} s^{-2}. For reductions in the water surface area in the head of the bay, results from idealized bay simulations show that the current velocity throughout the bay, the incoming tidal energy flux, and salinity at the inner bay all decrease with water area reduction. Reclaiming 14% of area in DB, the current velocity reduced by 9% at the bay mouth, but increased in the middle and inner parts. The incoming tidal energy flux also increased as the coastline became more streamlined after reclamation, and the salinity at inner bay decreased. Both reclamation types have substantially altered the water and salt transport processes and increased the water exchange ability of the bay with the adjacent sea.

1. Introduction

More than 60% of the world's population currently lives in coastal regions (i.e., within 400 km of a coast), and this will increase as the population expands (Hinrichsen, 1999). Coastal areas have been reclaimed to meet the increasing demand for land in many parts of the world. The earliest land reclamation began in the Netherlands in the 1500s for agricultural development and continued until the 2000s, but created numerous serious environmental problems (Hoeksema, 2007). In China, the rate of reclamation closely follows economic development in coastal regions, and reclamation projects approved by the State Council between 2011 and 2020 are of 2469 km^2 (Wang et al., 2014).

The potential effects of reclamation on the coastal environment can be far-reaching, so accurate assessment is important for planning and management. The hydrodynamic effects of reclamation have been studied often, as they are fundamental to environmental impact assessment. Shi et al. (2011) examined the hydrodynamic changes caused by reclamation in a semi-enclosed bay, and found the tidal prism to be decreasing and thus positively correlated with water area. Studies were conducted in Tokyo Bay to investigate the changes in hydrodynamics and transport processes due to reclamation from 1960 to 2000. Current velocity and residence time decreased by 20% and 35%, respectively, for a 20% loss of water surface area inside the bay (Okada et al., 2011). Recent studies have examined the changes introduced by reclamation inside Jiaozhou Bay, a semi-enclosed bay in China, and reported the magnitude of incoming tidal energy flux (i.e. originally 1.06×10^4 kW at 1935) was almost reduced by half at the outer entrance with progressive reclamations from 1935 to 2008 (Gao et al., 2014). However, most studies have examined reclamation in the inner part of the bay, and few focus on the effects on the vertical structures of hydrodynamics and transport processes. Virtually no studies examine or compare the effects of reclamation at the bay mouth or other areas of a semi-enclosed bay, particularly the influences on the vertical structures.

Studies of the effects of reclamation on salinity conditions inside the

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http://dx.doi.org/10.1016/j.csr.2017.06.008
Received 1 July 2016; Received in revised form 9 May 2017; Accepted 12 June 2017
Available online 13 June 2017
0278-4343/

bay are also limited, but salinity has recently been demonstrated to be a key factor in both the survival and growth of mangrove (Su et al., 2014), and also for the zonation and the growth of benthic animals, which in turn are vital food supplements for water birds (Saraswat et al., 2011; Sousa et al., 2008; Ysebaert et al., 2003). Yang and Chui (2016) investigated the salinity trends at different regions of a semi-enclosed bay, Deep Bay, China and found an increasing trend at the bay mouth but a decreasing trend at the bay head, and further suggested that reclamation could be a major cause. However, they did not examine in detail the effects of reclamation on the hydrodynamic and transport processes of the bay.

In this study, Deep Bay in China is used as a case study to examine the effects of reclamation in different areas on the hydrodynamic and transport processes of a semi-enclosed bay. The recent reclamation projects in Deep Bay can be divided into phases one and two, which occurred at the mouth and in the middle part of the bay, respectively. Simulation experiments were performed to examine the hydrodynamic and transport effects of the bay mouth narrowing and the inside area loss. Unlike that of Yang and Chui (2016), this study examined the changes throughout the whole bay, as the outer bay could be simulated and analyzed using a much larger simulation domain extending beyond Deep Bay. It also quantified the effects through different hydrodynamic and transport indicators (e.g., current velocity, tidal energy flux, stratification strength, and water age) and analyzed both horizontal and vertical changes. A series of idealized models was then used to generalize the responses to different levels of bay mouth narrowing and area loss inside the bay.

2. Methods

2.1. Study area

Deep Bay (DB) is a semi-enclosed subtropical bay situated between Shenzhen (SZ) in China and the Hong Kong Special Administrative Region (HKSAR), and is adjacent to the Pearl River Estuary to the west (Fig. 1). DB is a typical tidal-dominated bay with an average depth of 3.0 m. It is semi-diurnal tide in DB with an average tidal range of 1.7 m. Five rivers drain into DB, but only the Shenzhen River in the innermost part of the bay has continuous flow, while the other four are mostly dry except during storm events. The dominant wind direction in the dry season (Oct–Mar) is from the north-east and in the wet season (Apr–Sep) from the south-west.

A large area has been reclaimed in Shenzhen to meet the recent land demand from rapid development. From 1986 to 2007, 82.1 km^2 of land in Shenzhen was reclaimed, 21.2 km^2 of which is inside DB, resulting in an 18% loss of the original water surface area. The main land reclamation projects between 1986 and 1996, referred to as phase one, took place at Chiwan, while phase two, between 1996 and 2007, took place in the middle part of the bay (Fig. 1a). Phase one reclaimed 2.4 km^2 at the bay mouth and narrowed the mouth width by 2.1 km, which is 30% of its original value. Phase two reclaimed 15.6 km^2 inside DB, with an area almost 5.5 times larger than that of phase one.

The bathymetry has also changed significantly during the past decades. According to the bathymetry surveys of 1986, 1996, and 2007 (Fig. 1(b), (c), and (d)), the water depth along the northern coastline on the Shenzhen side at the bay mouth increased from 1996, but in the inner bay it started to decrease from 1986. The deepened area along the northern coastline was due to the development of ports and harbors which turned shallow areas into water channels.

The flow discharge of the Shenzhen River has also presented considerable changes. According to the river runoff estimation of Chan (2009), the total flow discharge of the Shenzhen River increased by 20% from 1996 to 2007, which may also contribute to hydrodynamic changes in DB. Due to the high level of urbanization, over 80% of the Shenzhen River flow was sewage discharge from water treatment plants, which gather municipal effluent together with stormwater from the urban areas (Shenzhen Water Pollution Regulation Office, 2007). Thus, the 20% increase in flow discharge of the Shenzhen River was mainly due to sewage discharge increase, and as the population and urbanization increase, the discharge may also further increase in the future.

2.2. Deep Bay model description and configuration

The hydrodynamic conditions of DB were simulated by the Environmental Fluid Dynamic Code (EFDC) (Hamrick, 1992; Hamrick and Wu, 1997). EFDC has been widely used to simulate hydrodynamic conditions for a number of water bodies worldwide (Cavalcante et al., 2012; Gong and Shen, 2011; Shen and Lin, 2006). This code is robust in simulating the wetting and drying of intertidal areas (Chan and Lee, 2010; Ji et al., 2001), which can ensure accurate simulations of intertidal mudflats inside DB.

The simulation domain included the whole Pearl River Estuary with DB and adjacent sea areas (Fig. 1a), so the complex hydrodynamic condition at the mouth area of DB could be accurately simulated (Dong et al., 2004). Curvilinear orthogonal and sigma coordination were respectively set in horizontal and vertical directions. To balance computational accuracy and efficiency, fine resolution grids of approximately 100–300 m in size were used inside DB, and coarse resolution grids up to 5000 m were used in the Pearl River Estuary and adjacent sea. In the horizontal direction there were about 24,000 grids, and 10 equal sigma layers in the vertical direction. The wetting and drying depths were set to be 0.10 m and 0.15 m respectively in the wetting and drying scheme, and the 0.05 m difference between these two thresholds minimized the switching between wetting and drying, which improved the computational efficiency. The time step was set to be 5 s to ensure that the maximum Courant Number was within 0.9.

River flow discharge was set as the boundary conditions in the main Pearl River outlets (e.g., Humen, Jiaomen, Hongqili and Hengmen, whose locations are shown in Fig. 1a) and the Shenzhen River. The freshwater discharge of the Pearl River was estimated using the Rational Equation with seasonally varying rational runoff coefficients derived from Niu and Chen (2010) for the Pearl River Basin, and precipitation data from the National Oceanic and Atmospheric Administration of the United States. The estimated monthly discharge data of the Pearl River agreed well with the observations of Niu and Chen (2010), which confirmed the accuracy of this estimation method. The discharge of the Shenzhen River was set as per the estimated value in Chan and Lee (2010). Thirteen tidal components, including diurnal, semidiurnal, shallow water, and long period components, were used to set the tidal forcing at the open boundary in the adjacent sea. The salinity at the river flow boundaries and the open sea boundary were set to be 0.15 psu and 35 psu, respectively. NCEP Reanalysis wind data at six-hour intervals were applied (Kalnay et al., 1996). Coastline and bathymetry data were extracted from marine charts produced by the Maritime Safety Administration of the People's Republic of China.

Cold start was used in the models for the initial condition, with a flat free surface and constant salinity of 30 psu for the entire domain. A warm-up period of one year was used to ensure a dynamic quasi-steady condition was attained.

2.3. Simulation scenarios for Deep Bay

Two scenarios, referred to as V1996 and Baseline, were conducted to validate the model's performance in simulating the hydrodynamic conditions in DB. Two more (CB1996 and CB1986) were performed to investigate the effects of changes in coastline and bathymetry, and one scenario (Dry) was performed to evaluate the effects of changes in freshwater discharge in the Shenzhen River. The settings for each simulation scenario are shown in Table 1. Observations of tidal elevation, salinity, current velocity, and direction were validated in V1996 and Baseline. The actual hydrodynamic conditions in 2007 was