Estuarine, Coastal and Shelf Science 151 (2014) 285–294

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Land reclamation and its impact on tidal dynamics in Jiaozhou Bay, Qingdao, China

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ARTICLE INFO

Article history:
Accepted 25 July 2014
Available online 5 August 2014

Keywords:
China
Jiaozhou Bay
reclamation
tidal flats
tidal constants
tidal energy
tidal asymmetry

ABSTRACT

Over the past few decades, there has been large-scale land reclamation in Jiaozhou Bay, which inevitably has affected the hydrodynamics and sediment transport in the bay, and thus has consequences for its management. In this study we set up a three-dimensional barotropic hydrodynamic model based on the Finite Volume Coastal Ocean Model to investigate changes in tidal dynamic factors in Jiaozhou Bay from 1935 to 2008. According to the model, the M_2 tide has experienced only minor changes over this period. Land reclamation on a large scale took place between 1935 and 1966, leading to significant hydrodynamic changes during this period. Again according to the model, the M_4 tidal amplitude rose dramatically, by up to 80% at the northeastern part of Jiaozhou Bay, and this has caused a significant increase in the M_2–M_4 tidal-duration asymmetry. Concurrently, the M_2 tidal-energy fluxes across the entrances to both the inner and outer bay were both reduced by more than 50%. From 1966 to 2008, land reclamation was conducted on a smaller scale. Over this period, the M_2 tidal-energy flux continued to decrease but at a relatively smaller rate. Both the M_4 tidal amplitude and M_2–M_4 tidal-duration asymmetry also experienced a gradual decrease during this period, probably due to the reduced M_2 tidal energy, in contrast to the increase between 1935 and 1966. The changes in the M_2–M_4 tidal-duration asymmetry from 1935 to 2008 caused by the land reclamation were reproduced in the model by progressively removing tidal flats from the head of the bay to its mouth. However, the M_2–M_4 tidal-duration asymmetry showed a different variation when the tidal flats were removed progressively in the opposite direction, from the mouth to the head of the bay. Our study shows that the significant increase in the M_2–M_4 tidal-duration asymmetry between 1935 and 1966 was a consequence of the change in bottom friction when the tidal flats were land-filled; advection played only a secondary role.

1. Introduction

The coastal zone, the interface between the land and the sea, is an area of frequent exchange and transformation of materials and energy from climate, hydrology, biology, soil, sediment and other processes related to both land and sea. In order to speed up economic development and alleviate a land shortage, nearly 50% of coastal wetlands in China have vanished since the 1950s, mainly due to land reclamation (Gu et al., 2007).

Jiaozhou Bay (JZB) is located on the southern part of the Shandong Peninsula in northeastern China. JZB has an average depth of about 7 m, an area of about 340 km^2 and is open to the Yellow Sea (Fig. 1a). Its main channel is more than 60 m deep. An east-west line through Huangdao divides JZB into two parts: (1) an inner bay, and (2) an outer bay.

JZB is typical of a coastal area suffering from severe land reclamation. The alteration in the coastline caused by land reclamation from 1935 to 2008 can be seen in Fig. 1b. The greatest amount of reclamation took place at the head of the bay between 1935 and 1966, with Hongdao Island connected to the mainland. Between 1966 and 1986, Huangdao Island was transformed into a tombolo, with reclamation also in the northern and eastern parts of JZB; overall there was a decrease in the area of tidal flats of about 30% from 1935 to 1986. After 1986, reclamation continued in the northeastern part of JZB and also commenced in the outer bay (Fig. 1b). In the period 2000–2008, the bulk of land reclamation was in the outer bay.

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http://dx.doi.org/10.1016/j.ecss.2014.07.017
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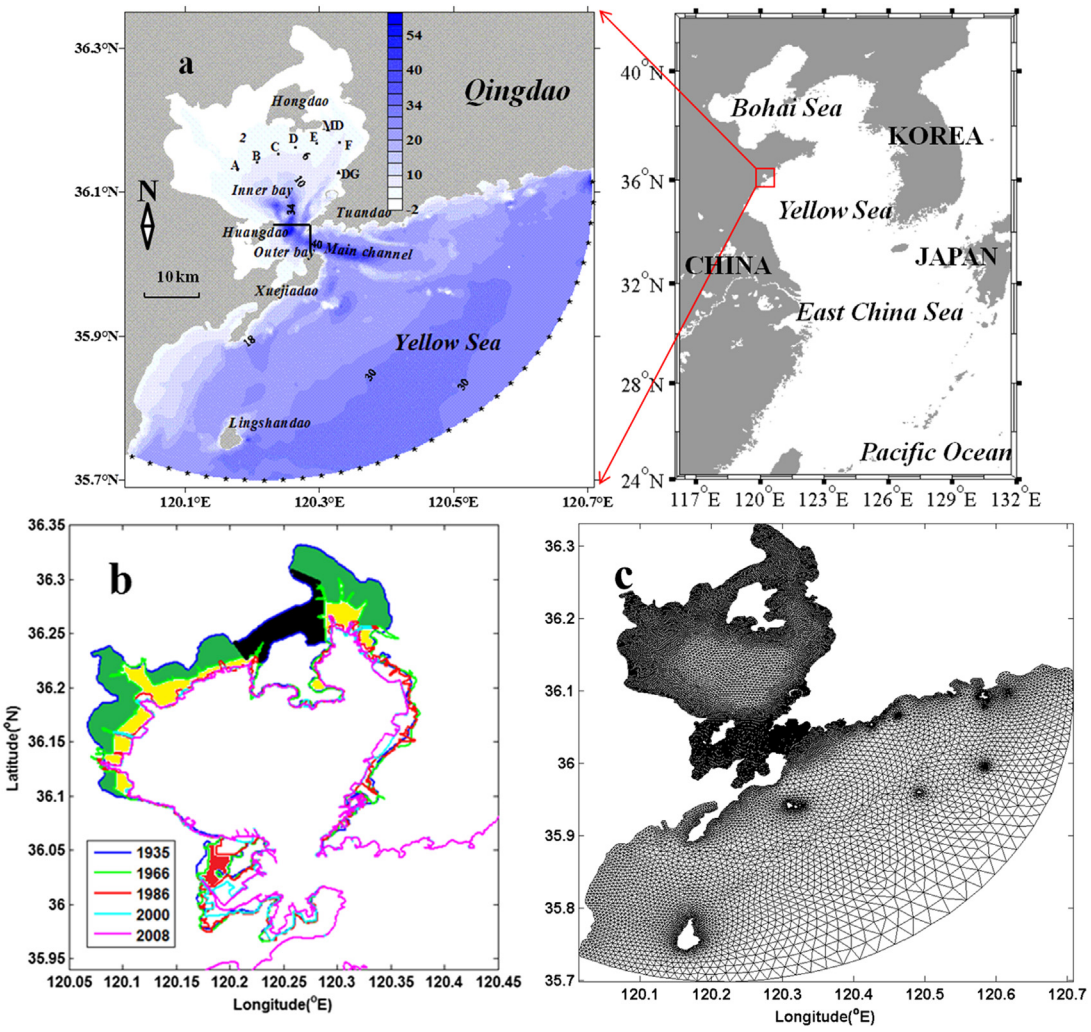

Fig. 1. **(a)** Bathymetry map of Jiaozhou Bay, Qingdao in 1935, showing the model domain. The star line shows the domain boundary in the Yellow Sea. A, B, C, D, E and F show the locations of the tidal-current stations. Maodao (MD) and Dagang (DG) are the tidal-elevation stations. An east-west line through Tuandao divides Jiaozhou Bay into an inner bay and an outer bay. A north-south line through Tuandao divides Jiaozhou Bay from the Yellow Sea. **(b)** Coastline changes in Jiaozhou Bay from 1935 to 2008. **(c)** Mesh and grid distribution for 1935.

The reduction in the sea area because of land reclamation has changed the hydrodynamics in JZB, for example reducing tidal volume, the water flushing rates, and the water's ability to carry sediment, all of which could cause significant problems for the coastal environment. Many studies have investigated the impact of reclamation. For example, Wang and Sun (2000), Liu et al. (2004) and Yu et al. (2007) investigated the impact of reclamation on hydrodynamics, including tidal prism and pollutant transport over short periods of time. Shi et al. (2011) set up the Environment Fluid Dynamic Code to study the tidal prism and Euler residual-current patterns in JZB from 1966 to 2008. Shi et al. (2011) concluded that the overall tidal prism had declined by 28% in 2008 compared to 1935, and that the consequent decrease in water exchange had led to an increase in average residence time from 36.1 days to 41.2 days. There was also a substantial change in the Euler residual-current patterns and the nearby shore bathymetry due to the land reclamation. Most of these studies have focused on relatively short periods of time, except for Shi et al. (2011). Moreover, few studies have looked at tidal-duration asymmetry, which affects sediment transport significantly in tidal estuaries, inlets and basins (Friedrichs and Aubrey, 1988). Tidal-duration asymmetry is defined as the inequality between the ebb and flood duration. When the flood duration is shorter than the ebb (flood dominant), a higher velocity during flood would be produced due to mass conservation (Aubrey and Speer, 1985). Higher flood velocities, associated with the larger bed stress, can lead to more sediment resuspension (Once the bed stress has exceeded the threshold) and further result in more sediment transport during flood than ebb, thereby the net landward sediment transport (Van Dongeren and De Vriend, 1994). In the same way, ebb dominant velocities can cause net seaward sediment transport (Lanzoni and Seminara, 2002). Changes in tidal-duration asymmetry are further complicated by a reduction in tidal-flat area under circumstances with various tidal ranges and water depth, as found by Friedrichs and Aubrey (1988) using a one-dimension model of a shallow well-mixed estuary. Li et al. (2012) removed all the tidal flats in the hydrodynamics model constructed for Darwin Harbour, Australia and found that the average-tidal asymmetry measured by elevation and skewness increased by 20% (flood dominance enhanced). Increasing of the elevation of mud and sand bank (tidal flats) in the Dee Estuary, Eastern Irish Sea, UK tends to raise the level of ebb dominance (Moore et al., 2009). However, in JZB, the variation tendency of the tidal-duration asymmetry due to the reduction in tidal-flat area is still not well understood.