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Numerical investigation of pollution transport and environmental improvement measures in a tidal bay based on a Lagrangian particle-tracking model

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Abstract

In view of the severity of oceanic pollution, based on the finite volume coastal ocean model (FVCOM), a Lagrangian particle-tracking model was used to numerically investigate the coastal pollution transport and water exchange capability in Tangdao Bay, in China. The severe pollution in the bay was numerically simulated by releasing and tracking particles inside it. The simulation results demonstrate that the water exchange capability in the bay is very low. Once the bay has suffered pollution, a long period will be required before the environment can purify itself. In order to eliminate or at least reduce the pollution level, environmental improvement measures have been proposed to enhance the seawater exchange capability and speed up the water purification inside the bay. The study findings presented in this paper are believed to be instructive and useful for future environmental policy makers and it is also anticipated that the numerical model in this paper can serve as an effective technological tool to study many emerging coastal environment problems.

Keywords: Particle-tracking; Water exchange capability; Lagrangian system; Coastal pollution; Tangdao bay; FVCOM

1. Introduction

All over the world, many coastal waters have suffered from gradually increasing pollution over the past few decades as a result of excessive effluent discharge and anthropogenic nutrient inputs (Carpenter et al., 1998; Kemp et al., 2005). Especially during the past three decades, the marine environment in the coastal region of China has faced huge amounts of stress from anthropogenic activities and population growth. Many pollutants from land-based sources, such as sewage, oil hydrocarbons, nutrients, pesticides, marine debris, and toxic waste, enter the sea. Of all of these pollutants, the annual discharge amount of the sewage and that of the major toxic materials into the sea water from factories and cities along the coasts of China are over 10 billion tons and 146 million tons, respectively. The increasing environmental pollution significantly threatens the survival and safety of coastal communities. Therefore, studies focusing on the coastal pollution have become extremely urgent and vital to protecting marine ecosystems and ensuring sustainable development of the environment around the coastal region of China.

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During the past few decades, many studies have been carried out to analyze oceanic purification capacity. The research results show that water exchange plays a critical role in coastal ecosystem purification (Kraufvelin et al., 2001; Xiao et al., 2015). The self-purification rate of the water will increase if the water exchange rate can be enhanced. In order to quantify the water exchange rate, a residence time theory based on the advection-diffusion process of a tracer has been proposed by Delhez et al. (1999) to evaluate the strength of water exchange. The residence time is an indicator of how long a pollutant will reside in a bay before being forced out of its mouth due either to tidal flow or river discharge. When the water exchange capability is enhanced, the residence time will decrease. Liu et al. (2004) used a dispersion model coupled with the Princeton ocean model to estimate the residence time of the water in Jiaozhou Bay (JZB). The average residence time of JZB water is about 52 d. There are also significant differences in the water exchange rate in different parts of the bay. Nevertheless, the residence time is a kind of statistical data that cannot demonstrate the real-time water exchange situation. With the development of research technology, in order to study the pollution process and water exchange capability of the coastal water with an acceptable accuracy, the particle-tracking method has been given more attention recently and used to simulate oil spills (Korotenko et al., 2004; Periáñez; Pascual-Granged, 2008; Wang et al., 2005), radionuclides (Nakano and Povinec, 2003; Periáñez; Elliott, 2002), and the flow state of pollution in both the bay and the coastal ocean (Li et al., 2014; Murray and Gillibrand, 2006; Tilburg et al., 2007). In the study of Gong et al. (2008), the particle-tracking model driven by hydrodynamic fields was used to investigate the temporal evolution of flushing properties in Xiaohai Lagoon, caused by the influences of human activities and natural evolution. A three-dimensional (3D) hydrodynamic model coupled with a Lagrangian particle-tracking approach developed by Liu et al. (2007) was employed to estimate residence time in the Danshuei River estuarine system of northern Taiwan, and the results demonstrated that density-induced estuarine circulation may play an important role in the estuary.

In this study, a Lagrangian particle-tracking model was used to numerically investigate the coastal pollution transport and water exchange capability in Tangdao Bay, in China. Tangdao Bay is semi-enclosed and elongated. The bay is famous for the beauty of its natural scenery and leisurely walkways, and it has been dubbed by tourists as the "bay in the sea". Along with the coastal development, its environment has been seriously affected by the coastal polluted water and garbage. Xiao et al. (2011) carried out some experiments using the chemical oxygen demand (COD) method, with the aim of investigating the current pollution level of the seawater in Tangdao Bay and the pollutant exchange correlation between Tandao Bay and JZB. Zhao et al. (2014) established a two-dimensional (2D) hydrodynamic simulation model using the software package MIKE21 to study the tidal flow in Tangdao Bay, and their simulation results demonstrated that the seawater exchange capability of Tangdao Bay is very weak. Therefore, studying the hydrodynamic environment in Tangdao Bay, predicting the capacity of seawater exchange, and proposing improvement measures to enhance the purification capability of the coastal water are matters of urgency. In this study, the capacity of seawater exchange was investigated numerically and the environmental improvement measures for Tangdao Bay were put forward.

2. Study area

Tangdao Bay, located at the outskirts of Qingdao City, is situated at the southern end of the Qingdao Economic and Technological Development Zone, in Shandong Province, in the eastern region of China. The study area is a part of Lingshan Bay, which has a width of 23.4 km and a total area of 107 km^2. Tangdao Bay is located in the Huangdao District, in Qingdao City, as shown in Fig. 1. The measurement positions are located at P1, P2, and P3. The bay has a narrow inverted *U* shape from the northeast to the southwest, and the mouth of the bay faces the southwest, connecting the Yellow Sea and Tangdao Bay. Its area is about 17 km^2, and the length of the coastal line is about 23.9 km. A narrow ditch exists at the bottom of Tangdao Bay, which is about 500 m wide and 2 km long. Tangdao Bay is surrounded by southeastern hills and low mountains. Hence, the wind and waves are weak. The energetic tide is the most dominant factor controlling the hydrodynamic environment of the bay.

3. Methodology

3.1. FVCOM model

The computational system consists of a fully 3D fluid dynamics model and a particle-tracking model, which couple with each other and match in time simultaneously. In the present hybrid system, the released particles flow along with the large-scale background flow predicted by the finite volume coastal ocean model (FVCOM). In FVCOM, the governing equations are discretized using a finite volume method on a triangular mesh in the horizontal plane and a σ-grid in the vertical direction. In both its external and internal modes (Chen et al., 2003), the convection terms are discretized using upwind schemes, and the time derivative terms are discretized by the Runge-Kutta method.

In order to obtain a smooth representation of irregular bottom topography, all equations are transformed into σ coordinates. The σ coordinate transformation expression is written as follows:

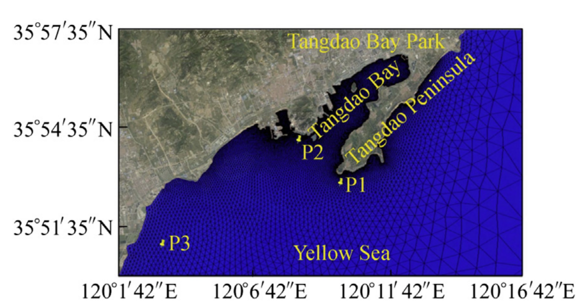

Fig. 1. Location of Tangdao Bay.

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