Marine Pollution Bulletin xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

A model study of the effects of river discharges and winds on hypoxia in summer in the Pearl River Estuary

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ARTICLE INFO

Article history:
Received 19 May 2016
Received in revised form 10 October 2016
Accepted 14 October 2016
Available online xxxx

Keywords:
Hypoxia
River discharge
Monsoon
Numerical model
Pearl River Estuary

ABSTRACT

The deterioration of dissolved oxygen conditions in the Pearl River Estuary (PRE) in summer has recently attracted considerable-scientific and political-attention. This paper documents the development, calibration, and verification of a coupled three-dimensional hydrodynamic and water quality model for the PRE. A comparison of the model's performance against field observations indicated that the model is capable of reproducing key hydrodynamic and water quality characteristics of the estuary within an acceptable range of accuracy. Furthermore, a scenario analysis showed that the extent of the hypoxic zone responds differently to changes in the river discharge at different inlets. Moreover, the hypoxic zone also changes in response to variations in the southwest wind in summer; specifically, a larger hypoxic zone develops as southwest winds blow in a more southward direction. However, the hypoxic conditions are much more sensitive to changes in the wind speed than changes in the wind direction.

1. Introduction

Dynamic patterns of dissolved oxygen (DO) concentrations occur along coastlines because of complex interactions involving physical and biochemical processes (Diaz and Rosenberg, 1995; Borsuk et al., 2001). Variations in freshwater discharge, salt-water intrusion, circulation, bathymetry, temperature, wind, meteorology, and biological production and respiration combine to produce strong estuarine DO gradients (Stanley and Nixon, 1992). A water body that has a DO level below 3.0 mg l^{-1} is commonly considered "hypoxic" (Dai et al., 2006). Usually, coastal hypoxia usually damages the coastal ecosystem and affects fisheries via food web interactions. Furthermore, a low DO level can change the natural redox conditions of the marine environment and impact the cycles of various materials (Turner et al., 2008; Bianchi and Allison, 2009). Hence, coastal hypoxia has been a cause of increasing concern in recent years.

Currently, coastal hypoxia has been reported in nearly 500 locations worldwide (Diaz and Rosenberg, 2008; Conley et al., 2011). The Baltic basins hypoxic zone (approximately 70,000 km^2) reached peak levels in 1971 and is the largest hypoxic zone in the world (Conley et al., 2009), and the Gulf of Mexico's hypoxic zone reached 20,700 km^2 in midsummer 2001 and represents the second largest zone (Rabalais et al., 2002). Other hypoxic areas include the York River (Diaz et al., 1992), estuaries in Virginia (Kuo and Neilson, 1987), the New York Bight (Waldhauer et al., 1985), the Long Island Sound (Welsh and Eller, 1991), the Yangtze Estuary (Li et al., 2002), the Pamlico River Estuary (Stanley and Nixon, 1992), the Florida Keys (Lapointe and Matzie, 1996), and the Erka Estuary in the Adriatic Sea (Legovic et al., 1991).

The Pearl River is one of the largest rivers in China and has a strong influence on its estuary and adjacent shelf; thus, stratified and turbid plumes develop, especially during summer. Previous studies have reported episodic hypoxia with short persistence and small coverage in the Pearl River Estuary (PRE) and adjacent coastal waters (Yin et al., 2004a; Rabouille et al., 2008). In addition, the mechanism underlying the occurrence of hypoxia has been extensively discussed. For example, a water quality model has been developed by Guan et al. (2001a, 2001b) to examine the effects of stratification on the distribution of DO in the PRE. Yin et al. (2004a) demonstrated that along with the effects of phosphorus limitations and increased nutrient inputs by anthropologic activities, estuarine circulation and stratification are important factors involved in controlling the distribution of DO and hypoxic conditions in the PRE. Additionally, Luo et al. (2009) has discussed the temporal and spatial variation of DO in the bottom of the PRE and suggested that hypoxia in the PRE decreases during spring tide and increases during neap tide. Furthermore, Zhang and Li (2010) developed a coupled hydrodynamic-biological model to investigate the DO budget of the PRE in summer and above the pycnocline. In this model, the horizontal transport of DO is mainly balanced by reaeration, and photosynthesis

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http://dx.doi.org/10.1016/j.marpolbul.2016.10.042
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Please cite this article as: Wei, X., et al., A model study of the effects of river discharges and winds on hypoxia in summer in the Pearl River Estuary, Marine Pollution Bulletin (2016), http://dx.doi.org/10.1016/j.marpolbul.2016.10.042

appears to play a more important role in the shelf area than inside the PRE because of reduced turbidity. Below the pycnocline, however, biochemical processes balance the horizontal transport of DO.

Certain problems remain unresolved. For example the upper PRE has four major river discharge inlets (Humen, Jiaomen, Hongqili and Hengmen) (Fig. 1), although the inlet that has the largest effect on the distribution of DO is unclear. Furthermore, whether variations in the southeast winds affect the stratification and distribution of DO and whether the hypoxia zone is more sensitive to variations in wind speed or direction are not well understood. In this study, a three-dimensional coupled hydrodynamic and water quality model, the Environmental Fluid Dynamics Code (EFDC) model, is employed to address these issues.

2. Methodology

2.1. Study area

The Pearl River is the second largest river in China after the Yangtze River and ranks 13th in the world in terms of freshwater discharge. The drainage basin is located in a sub-tropical climate zone with annual rainfall of 1600–2300 mm. The annual water discharge of the Pearl River is approximately 3.26×10^{11} m^3, with 80% occurring in the wet season from April to September (Zhao, 1990). The maximum river discharge occurs in July and the runoff is distributed among eight inlets (inlet mouths are called gates in Chinese). Approximately half of the river discharge passes through Lingdingyang, which is referred to as "the Pearl River Estuary (PRE)" in this study, through the four easternmost inlets: Humen, Jiaomen, Hongqilimen and Hengmen (Fig. 1). Tides in the PRE are irregular and semi-diurnal and present amplitudes that range from approximately 0.85–0.95 m near the Wanshan Islands to approximately 1.7 m near Humen (Zhao, 1990). Despite this small tidal range, the average flood tide volumes reach as high as 73,500 m^3 s^{-1}, which is nearly 13 times the average freshwater discharge.

The PRE is a funnel-shaped estuary that is approximately 70 km long and 5–35 km wide, and it covers a huge surface area of approximately 2000 km^2. The average depth is approximately 4.8 m, although the depth can reach more than 20 m in the eastern part the of lower PRE. There are two deep channels (i.e., the West Channel and East Channel) in the upper PRE and many small islands outside the mouth of the estuary (Fig. 3b). In this region, a number of dynamical factors are observed, including freshwater discharge, tides, winds, the bottom topography, and coastal currents that control the hydrodynamic processes and circulation as well as the distribution of physical parameters, such as water temperature and salinity (Wong et al., 2004).

2.2. EFDC model

The EFDC (Hamrick, 1992) model, which is employed in this study, has been widely used to study coastal and estuarine hydrodynamics and is applied as a coastal management tool (e.g., Lin et al., 2008; Wan et al., 2012; Chan et al., 2013).

The EFDC is configured to solve three-dimensional, vertically hydrostatic, free surface, turbulent-averaged equations of motion for a variable density fluid. The model uses stretched or sigma vertical coordinates and Cartesian or curvilinear orthogonal horizontal coordinates to represent the physical characteristics of a water body. The model can simulate general discharge control structures, drying and

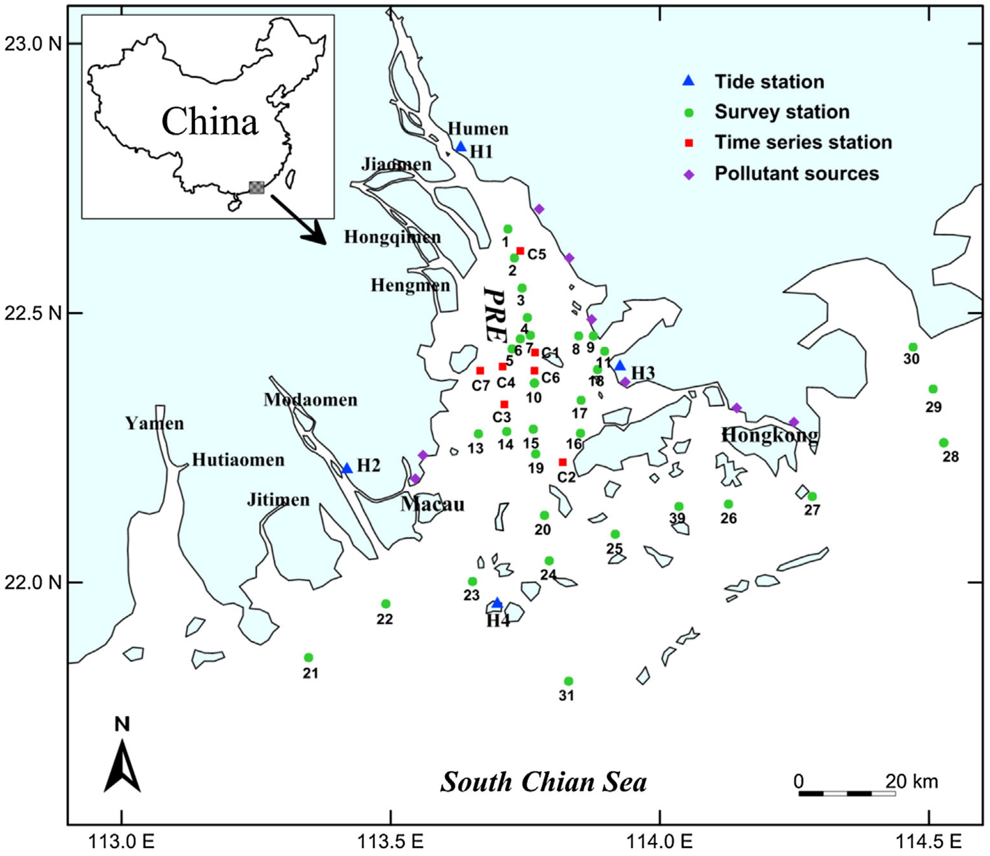

Fig. 1. The Pearl River Estuary and the location of monitoring stations.

Please cite this article as: Wei, X., et al., A model study of the effects of river discharges and winds on hypoxia in summer in the Pearl River Estuary, Marine Pollution Bulletin (2016), http://dx.doi.org/10.1016/j.marpolbul.2016.10.042