Marine Pollution Bulletin 111 (2016) 160–177

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

A numerical study on flow and pollutant transport in Singapore coastal waters

Ming Xu, Vivien P. Chua *

National University of Singapore, Department of Civil and Environmental Engineering, 1 Engineering Drive 2, Singapore

ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form 8 July 2016
Accepted 10 July 2016
Available online 16 July 2016

Keywords:
Singapore coastal waters
Nested model
Unstructured-grid
Circulation
Pollutant transport
Dispersion coefficient
"4/3-law"

ABSTRACT

Intensive economic and shipping activities in Singapore Strait have caused Singapore coastal waters to be under high risk of water pollution. A nested three-dimensional unstructured-grid SUNTANS model is applied to Singapore coastal waters to simulate flow and pollutant transport. The small domain (~50 m resolution) Singapore coastal model is nested within a large domain (~200 m resolution) regional model. The nested model is able to predict water surface elevations and velocities with high R^2 values of 0.96 and 0.91, respectively. Model results delineate the characteristics of circulation pattern in Singapore coastal waters during the Northeast and Southwest monsoons. The pollutants are modeled as passive tracers, and are released at six key sailing locations Points 1–6 in Singapore coastal waters and are named as Passive Tracers 1–6, respectively. Our results show that the rate of dispersion is twice as large for the Northeast monsoon compared to the Southwest monsoon due to differences in large-scale monsoons and small-scale local winds. The volume averaged concentration (VAC) diminishes faster and the local flushing time is shorter during the Northeast monsoon than the Southwest monsoon. Dispersion coefficients K and the VAC decreasing rate are maximum for Tracers 2 and 3 with shortest local flushing time due to the strong surrounding currents and abrupt bathymetry changes near Senang and St. John Islands. Dispersion coefficients K and the VAC decreasing rate are minimum for Tracer 1 due to weak currents induced by the semi-enclosed coastline near Tuas. It is found that both the lateral dispersion coefficient K_y and the compound dispersion coefficient K obey a "4/3-law", which defines a linear correlation between dispersion coefficients and 4/3-power of selected length scale.

1. Introduction

Singapore Strait lies in the strategic crossroad of major shipping routes and houses one of the busiest shipping ports in the world. During the last two decades, Singapore has experienced rapid growth in the oil and chemical industry, and is one of the largest oil refining centers in the world, with a crude oil processing capacity of at least one million barrels per day (Chen et al., 2005). Singapore coastal waters is defined as the area approximately between 103°E to 104.6°E and 0.3°N to 2°N. The three main surrounding water bodies are Malacca Strait to the west, the Java Sea to the south and the South China Sea to the east. The circulation in this region is highly complex due to its complicated bathymetry, irregular coastlines, seasonal monsoons and the differences in tidal influences (Chen et al., 2005; Chen et al., 2010; Kurniawan et al., 2011; Hasan et al., 2012; van Maren and Gerritsen, 2012).

Singapore coastal waters are highly influenced by the Asian monsoon system. During October to March, northeasterly winds prevail over this region, while during April to September, wind turns southwest over most of the region (Hellerman and Rosenstein, 1983). Strong currents are observed during most of the year. The maximum current speed is about 2 m/s occurring at the heights of both monsoon seasons. Overall, there exists significant seasonal variability in the circulation patterns (Xu and Chua, 2016). During April to August, eastward flow dominates most of the region. While during October to February, the currents are reversed to a mainly westward flow. Westward residual flows with magnitudes around 20 cm/s are observed in Singapore Straits (van Maren and Gerritsen, 2012).

Six key sailing points in Singapore coastal waters are published by National Geospatial-Intelligence Agency, USA (NGA US, 2013), as shown in Fig. 1. Frequent shipping and economic activities at these locations increase the risk of water pollution. Some examples include the oil spill accident in 1996 that occurred around Point 3 (near St. John Island) (Chao et al., 2003), and the Evoikos-Orapin Global oil spill accident in 1997 that occurred around Point 2 (near Senang Island) (Yew et al., 2001).

Numerical modeling is a popular method to assess the transport and dispersion of pollutants in the coastal zone. Lardner et al. (1988) formulated a convection-diffusion model to simulate transport of passive pollutants in the Arabian Gulf. The pollutant was regarded as a large ensemble of small discrete quantities and is subject to diffusion and convection process. Huang and Spaualding (1995) employed a three-dimensional numerical model to examine the impacts of water pollution caused by combined sewage overflow (CSO) on the surface of Mt.

* Corresponding author.
E-mail addresses: xuming@u.nus.edu (M. Xu), vivienchua@nus.edu.sg (V.P. Chua).

http://dx.doi.org/10.1016/j.marpolbul.2016.07.014
0025-326X/

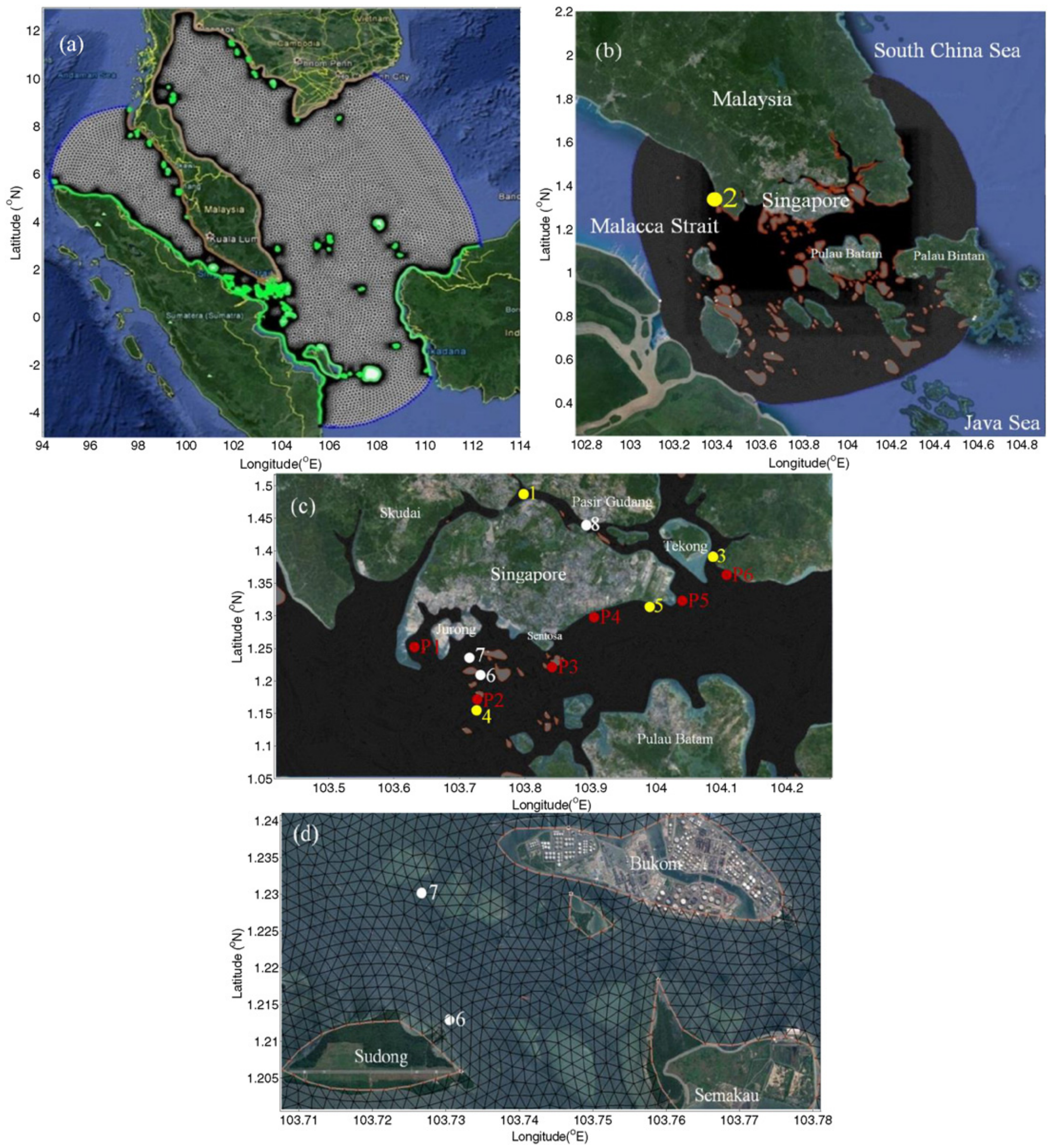

Fig. 1. Unstructured-grid of (a) the larger domain model, (b) the nested small domain model with zoom-in view of (c) Singapore Island and (d) Bukom Island. Locations of stations for model validation are shown. Legend: water surface elevations (Stations 1, 2, 3, 4, 5), currents (Stations 6, 7, 8), Passive Tracers (P1–P6).

Hope Bay, Rhode Island, Massachusetts. Model results indicated that the CSO plume was transported in the bay along the eastern shore and high concentrations remained near the surface. Chau and Jiang (2002) developed and implemented a three-dimensional, curvilinear grid numerical model to simulate Chemical Oxygen Demand distribution and transport in the Pearl River Estuary. Due to wastewater discharged from the Pearl River Delta Region, strong inter-boundary effects of pollutants between the Guangdong Province and the Hong Kong Special Administrative Region were observed. Zhang and Song (2010) developed a three-dimensional numerical model for wind-driven circulation and pollutant transport. A simple and efficient concentration-correction method was introduced to keep conservancy for scalar transport, as large surface elevation variation exists in lakes. The numerical model was applied to Taihu Lake and their results showed that the model can simulate wind-induced pollutant transport accurately.

Very few research has been performed to investigate transport of pollutants in Singapore coastal waters. Yew et al. (2001) developed an oil spill-food chain interaction model to investigate the impacts of oil spills on marine organisms. The coupled model included a multiphase oil spill model (MOSM) and a food chain model, and was applied to the Evoikos-Orapin Global oil spill in the Singapore Strait. Chao et al. (2003) applied a three-dimensional oil spill model to simulate an oil slick movement in Singapore coastal waters. They showed that the model was able to predict the oil spill mass balance, horizontal movement of surface oil slick and oil particle concentration distribution in the water body. Model predictions compared well with satellite images and field observations of oil slicks on the water surface in Singapore Strait. There is increasing public concern over pollutant transport in Singapore coastal waters, as it would significantly affect coastal management, human health and recreation activities along shorelines. To mitigate public concern about potential risk of pollution in Singapore coastal waters due to frequent economic and industrial activities, a thorough and systematic study on pollutant transport is necessary, especially to identify pollutant transport spatially and temporally. While previous studies of pollutant transport in Singapore coastal waters fail to identify sensitive pollutant transport locations in this region and illustrate pollutant transport temporally.

To fill this gap, a nested unstructured-grid SUNTANS model (Fringer et al., 2006) is employed to investigate the effects of different locations (six key sailing points) and time (two monsoon seasons) on pollutant transport in Singapore coastal waters. This study would deepen our understanding of transport and mixing of pollutants in Singapore coastal