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A numerical study on land-based pollutant transport in Singapore coastal waters with a coupled hydrologic-hydrodynamic model

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ABSTRACT

Frequent flooding events and intensive agricultural, economic and industrial activities in Singapore-Malaysia Catchment have made Singapore coastal waters come under high risk of land-based pollution. A coupled hydrologic-hydrodynamic model is employed to perform three-dimensional land-based pollutant transport simulations in Singapore coastal waters. The hydrologic model component (2012 version of Soil and Water Assessment Tool) is found to be able to predict streamflow accurately, with correlation coefficients larger than 0.9 and a high Nash-Sutcliffe efficiency of more than 0.8. The hydrologic model (SWAT) is coupled with the hydrodynamic model (SUNTANS) by transferring streamflow and pollutant concentrations at nine rivers along common boundaries. The coupled hydrologic-hydrodynamic model is validated with observed sea surface elevations and velocities. A low Root-Mean-Square-Error (RMSE) of 0.10 m and a high correlation coefficient of 0.98 are observed for sea surface elevations. The coupled model predicts depth-averaged U and V velocities accurately, with low RMSEs of 0.06 m/s and 0.07 m/s respectively and high correlation coefficients exceed 0.95. During the Northeast monsoon, pollutants from Source 1 (Johor River), Source 2 (Tiram River), Source 3 (Layang River) and Source 4 (Layau River) are dispersed into the Singapore Strait after around 2 days of release, with Johor Estuary and Tekong Island highly affected. During the Southwest monsoon, it takes around 9 days for pollutants from Sources 1–4 to affect the whole Johor Estuary and Tekong Island, which almost four times of dispersion time during the Northeast monsoon. The overall mean dispersion coefficient $\bar{K}$ of 47.99 m^2/s during the Northeast monsoon is roughly four times that of 11.33 m^2/s during the Southwest monsoon, due to larger amount of land-based pollutants are introduced by streamflow in December and differences in the large-scale monsoon effects. It is found that the dispersion coefficient K obeys a "4/3-law", with the length scale L defined as the distance of the center of concentration travelled.

1. Introduction

The Singapore-Malaysia catchment is defined as the area approximately between 103°E to 104.6°E and 0.3°N to 2°N (Fig. 1). The incidences of heavy rainfall during the monsoon seasons have caused flooding in Singapore-Malaysia catchment. Flooding causes severe damage such as destroyed infrastructure, transportation, and economic loss. In Singapore, frequent flash flood events are experienced during the Northeast monsoon (PUB Singapore, 2014). In the southern part of Peninsular Malaysia, flood disasters from 1900 to 2011 have caused the deaths of 311 people, affected 1,232,058 people and led to total damages of around USD 943,378,468.6 (International Disaster Database, 2011). In addition, land-based pollutants resulted from frequent agricultural, economic and industrial activities in this region would be carried into Singapore coastal waters by streamflow, especially during flood events. The transport of land-based pollutants in Singapore coastal waters would significantly affect coastal management, public health and recreation activities along shorelines, which would be raised as a potential public concern.

Singapore coastal waters is defined as the area approximately between 103°E to 105°E and 0.5°N to 2°N (Fig. 1(a)). 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, 2010;

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Nomenclature

s_o^R	the reference salinity	h	the free-surface height
C_d	the drag coefficient	κ	the von Karman's constant
$\bar{K}$	the overall mean dispersion coefficient	Ω	the angular velocity of the Earth
K_x	the longitudinal dispersion coefficient	L	the distance the tracer field center travelled
K_y	the lateral dispersion coefficient	X	the desired quantity to compare
L_y	the lateral scale of the tracer plume	d	the bottom height
U_1	the magnitude of the horizontal velocity vector in the first grid cell above the bed	f	the Coriolis term
		r_b	the baroclinic head
$\bar{X}$	the quantity averaged over the calibration period	s	the salinity
z_0	the roughness coefficient	t	the time
z_1	the location of U_1 at a distance of one-half the bottom-most vertical grid spacing above the bed	$u(x,y,z,t)$	the Cartesian velocity component in the x direction
		$v(x,y,z,t)$	the Cartesian velocity component in the y direction
α_y	the scale-dependent factor	$w(x,y,z,t)$	the Cartesian velocity component in the z direction
ν_H	the horizontal eddy viscosity	$\boldsymbol{u}$	the velocity vector
ν_V	the vertical eddy viscosity	Φ	the variance of the pollutant concentration field
ρ_0	the constant reference density	Φ_x	the longitudinal variance of the pollutant concentration field
$\rho_0 + \rho$	the total density		
ϵ_H	the horizontal turbulent eddy-diffusivity	Φ_y	the lateral variance of the pollutant concentration field
ϵ_V	the vertical turbulent eddy-diffusivity		
h	the free-surface height	ϕ	the latitude

Kurniawan et al., 2011; Hasan et al., 2012; van Maren and Gerritsen, 2012).

In Singapore coastal waters, very little research about pollutant transport is conducted, not mentioning land-based pollutant transport. In Yew et al. (2001), an oil spill-food chain interaction model is presented to investigate the impacts of oil spills on several key marine organisms. The coupled model is composed of a multiphase oil spill model (MOSM) and a food chain model. Dissolved, emulsified and particulate oil concentrations in the water column, oil slick thickness on the water surface and dissolved and particulate oil concentration in bed sediments are predicted by MOSM. The food chain model addresses the uptake of toxicant by marine organisms. The coupled model is applied to the famous Evoikos-Orapin Global oil spill in the Singapore Strait. Chao et al. (2003) implemented a three-dimensional oil spill model to simulate an oil slick movement in Singapore coastal waters. The oil slick is divided into a number of small elements in the model to simulate the oil advection, spreading, evaporation, turbulent diffusion, vertical dispersion, dissolution, shoreline deposition and adsorption by sediment. Model results prove its capability in predicting the mass balance of oil spill, the horizontal movement of surface oil slick and the oil particle concentration distribution in water body. Model predictions match well with satellite images and field observations of oil slicks on the surface in the Singapore Straits, and measurements of the vertical concentration of oil particles in flume.

In order to enhance prediction accuracy and applicability, coupling method is widely adopted. Coupled models can avoid parametric modelling in uncoupled approach, which would introduce substantial uncertainty and errors. In Inoue et al. (2008), a two-dimensional depth-integrated hydrodynamic model of the basin is coupled with a hydrological model of local runoff from the surrounding drainage basin. The integrated model is forced by local wind, observed tides from the Gulf of Mexico, rainfall and evaporation over the model domain. The model can be used to simulate salinity changes in response to a variety of climatic conditions including drought and flood, and the introduction of freshwater diversions. Dresback et al. (2013) developed the ASGS-STORM (ADCIRC Surge Guidance System – Scalable, Terrestrial, Ocean, River, Meteorological) system which incorporates tides, waves, winds, rivers and surge to produce a total water level. It was tested during Hurricane Irene in real-time by forcing the coupled system with forecasted wind and pressure fields computed using a parametric tropical cyclone model. Therein, a skill assessment of wind speed and direction, significant wave heights, and total water levels was used to evaluate ASGS-STORM's performance. ASGS-STORM showed notable skill in capturing these parameters when utilizing Advisory 28 while it showed slight over-prediction for two advisories (Advisory 23 and 25) due to the over-estimation of the storm intensity. Therefore, an accurate input from the weather forecast is a necessary, but not sufficient, condition to ensure the accuracy of the guidance provided by the system.

Therefore, to mitigate public concern about potential risk of land-based pollution due to frequent agricultural, economic and industrial activities, a thorough and systematic study on possible land-based pollutant transport in Singapore coastal waters is necessary. To make preliminary efforts to fill this gap, a coupled hydrologic-hydrodynamic model is employed to perform three-dimensional land-based pollutant transport simulations in Singapore coastal waters. Accurate streamflow and pollutant concentration input is the key step. The hydrologic model component will be responsible for simulating accurate stream flow and pollutant concentration, since little observed data are available in this region. The hydrodynamic model component should be able to simulate sea surface elevations and current velocities with a reasonable degree of accuracy after introducing stream flows and pollutant concentrations from the hydrologic model. With this study, people would be a deepened understanding of potential land-based pollutant transport and its impacts on coastal area. This research would also provide guidance to manage coastal activities to reduce the risk of possible land-based pollution.

This paper is organized as follows. Section 2 describes the model setup. Section 3 shows the model calibration and validation results. Section 4 presents pollutant transport simulations and dispersion coefficients. Section 5 draws conclusions.

2. Coupled hydrologic-hydrodynamic model

In this section, two components of the coupled hydrologic-hydrodynamic model are introduced. The governing equations and model set up of the hydrologic model (SWAT) and hydrodynamic model (SUNTANS) are presented, respectively.