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Understanding Hydrodynamic Flow Characteristics in a Model Mangrove Ecosystem in Singapore

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Abstract

Recent importance has been placed on the ecological and socio-economic aspects of mangroves for adjacent coastal populations, in terms of flood defense, food resources, employment and generation of income. Anthropogenic stressors, such as direct clearance, hydrological alterations, climatic change effects or chemical pollution contribute to mangrove ecosystems degradation. While the relative impact is not well understood, the hydrodynamics specific to mangroves (intertidal, land-marine interface) are undoubtedly influencing those effects. In the present study, a computer-based model was built to understand the hydrodynamic flow characteristic in a mangrove ecosystem, the Sungei Buloh Wetland Reserve in Singapore, with the wider intent to better understand the transport of chemical substances in mangroves. Field surveys in the mangrove and the preliminary development of a two-dimensional hydrodynamic (2DH) model have been carried out. Higher bottom roughness was considered in the vegetated part of the model domain to account for the effect of mangrove roots. Spatial and temporal distributions, as well as minor mean differences between simulated and observed results, suggest that the developed model capture satisfactorily the tidal dynamics within the river, the wetland area covered with mangroves and in the strait. These results indicate that the hydrodynamics are properly understood within the Sungei Buloh mangrove ecosystem and can be used for modeling the fate of chemicals.

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Keywords: Field measurements, hydrodynamic modeling, mangrove ecosystem, bottom roughness, Delft3D, Sungei Buloh wetland

1. Introduction

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Mangrove ecosystems are unique transitional coastal ecosystems generally confined to the tropical and subtropical regions. Because of their position at the interface between land and sea, they are thought to play a key role in (i) the biogeochemical cycles in tropical estuarine ecosystems, (ii) the sustainability of marine coastal ecological systems, (iii) the support of aquaculture or (iv) the stabilization of the tropical coastal shoreline. However, mangrove forests are disappearing fast, either because of direct clearance (land reclamation, conversion to shrimp farming, timber and charcoal production) or because they are vulnerable to stressors (sea-level rise, insect infestation, chemical pollution) [i.e., 1]. Recognizing the benefits of mangrove forests, efforts have recently been made in various countries to protect existing mangrove ecosystems, and in many recent cases, to re-establish new mangrove forests.

The fluxes of biogeochemical materials in mangrove forests are strongly dependent upon the flow structure in the mangrove wetlands. To enable a better understanding of the role of mangroves in the nutrient cycle and the exchange of nutrients between the mangrove forests and the adjacent coastal waters for example, considerable effort has recently been placed on studying the hydrodynamic processes in mangrove swamps. Previous modeling studies focused on creek-forest interactions and the consequent tidal effect in mangrove systems [2, 3]. This required some simple parameterization of the hydrodynamic impacts of mangrove vegetation. Most analytical and numerical studies applied one- and two-dimensional modeling approaches, representing vegetation by an adjusted roughness parameter, and a simplified topography [3, 4]. Studies into tidal-scale hydrodynamics within mangroves required a more advanced approach of modeling the effect of these trees on hydrodynamics. For this purpose, Mazda [5] introduced vegetation induced drag forces into the momentum equation, related directly to a vegetation density parameter.

Recently, a 3D process-based model in Delft3D was developed to simulate tidal hydrodynamics in a mangrove creek catchment in Thailand [6]. In their study, the authors observed that, though a 2DH model cannot account for the depth-variability in the vegetated region, the depth-averaged velocities estimated from a 3D model are in accordance with a 2DH model results. Hence, it may be efficient to develop 2DH models, for quick prediction of pollutant fate in mangroves for example, instead of computationally expensive 3D models. The aim of the present study was to develop a 2DH approach for modeling flow dynamics in combination with field surveys in the Sungei Buloh Wetland Reserve in Singapore. The model is intended to simulate tidal-scale hydro- and water quality parameters in coastal mangroves and to assess their sensitivity.

2. Methodology

2.1. Model Setup

The Sungei Buloh Local Model (SBLM) was developed using the Delft3D-FLOW modeling framework to provide hydrodynamic information. The model domain covers local channels, mangrove wetlands and part of the Johor Strait as shown in Fig 1(a). The SBLM features a boundary fitted curvilinear orthogonal grid system to simulate water levels and flow patterns. The local model was nested within the Singapore Regional Model – A (SRMA) which has been extensively validated previously. The model grid consists of around 28100 grid cells, and the sizes of the grid cells vary from about 10 m in the wetland up to 100 m in the Johor Strait. The mangrove channels and its surrounding area have been given a relatively high resolution to obtain detailed hydrodynamic information in these areas. The model bathymetry is a combination of SRMA bathymetry (sampled Admiralty Chart information) and additional recent survey data for the wetland as depicted in Fig. 1(b). The mangrove channels are relatively shallow in depth (0 ~ 5 m) and are surrounded by wetlands which are inundated during high tide and become dry during low tide. Hence, the flooding scheme was activated for accurate reproduction of flooding and drying of the tidal flats in the mangrove ecosystem. Fresh water discharges based on rainfall records were also included at the upstream tips of the channels.

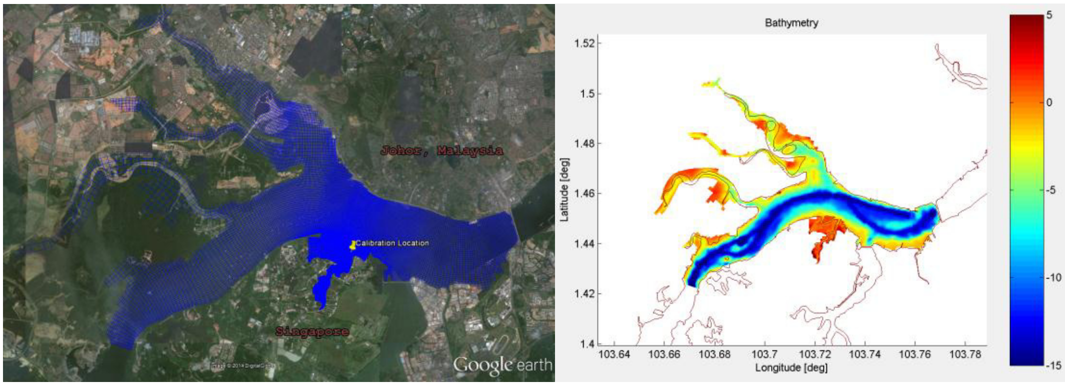

Fig. 1. (a) Model grids of the Sungei Buloh Local Model (SBLM) and (b) bathymetry of the SBLM which is based on the Admiralty chart (for Johor Strait) and survey data (for Sg. Buloh channels and surrounding wetlands).

The local model (SBLM) has a single open boundary (west side of the Johor Strait) which was forced by the water level variation generated by the regional model (SRMA). The other end of the Johor Strait (east side) is closed by the cause-way. In the present study, the effect of vegetation and more specifically mangrove roots, on hydrodynamics was incorporated by increasing Manning's n from 0.03 $m^{-1/3}s$ (in the Johor Strait) to 0.06 $m^{-1/3}s$ (in the wetland area covered with mangrove roots).

2.2. Hydrodynamic Survey

A water level sensor was deployed in a channel within the wetland to record water levels every 15 minutes for 2 weeks to cover one spring-neap tide cycle. The collected data was used to calibrate the SBLM. In addition, current patterns (speed and direction) were recorded through ADCP surveys near the mouth of the estuary for different tidal conditions (spring/neap periods in November 2012). The survey area was divided in blocks consisting of 4~8 lines where the boat moves with a bottom mounted ADCP. Vertical profiles of current data were processed to estimate depth-averaged values. Noisy records were observed quite frequently as the surveyed areas were relatively shallow (~ 5 m water depth).

3. Results and Discussion

The 2DHmodel developed in the present study was run for 2 months (1 October – 30 November 2012), covering 4 spring and neap periods with a 0.5 min time step. The model results were compared with measured water levels as depicted in Fig. 2 for spring-neap variations.

The observed tidal range varied from 1.5 m during neap tide to 2.5 m during spring tide. The water surface fluctuations obtained from the SBLM are in good agreement with the field data though some minor discrepancies exist: the observed high waters are slightly lower than the predicted high waters; however, these differences are within 10%.

Current speeds and directions are difficult to reproduce accurately through numerical modeling since they are strongly determined by local bathymetry. Since the survey did not cover time history of a single location, it is difficult to use those for validation. However, the depth-averaged modeled velocity fields was compared with single location field data during both flood and ebb period and displayed in Fig 3. Qualitatively the single point field velocity matches well with modeled results of nearby locations. It is observed from both the comparisons that the SBLM can capture the tidal hydrodynamics successfully.

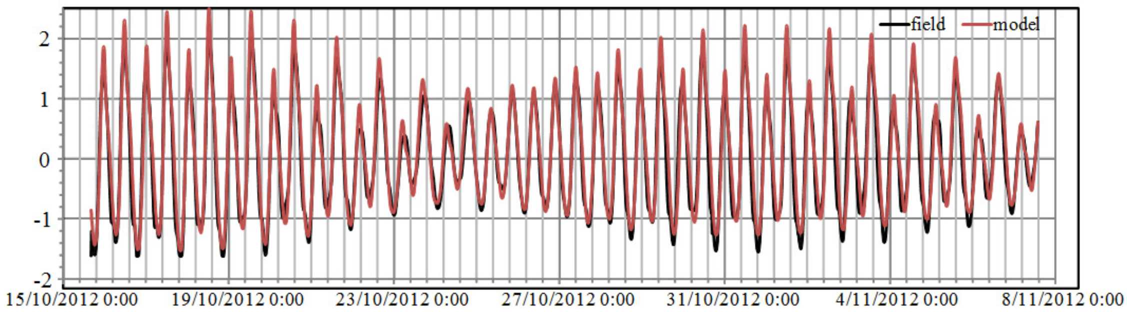

Fig. 2. Comparison of water levels between model results and field surveys covering a spring-neap period.

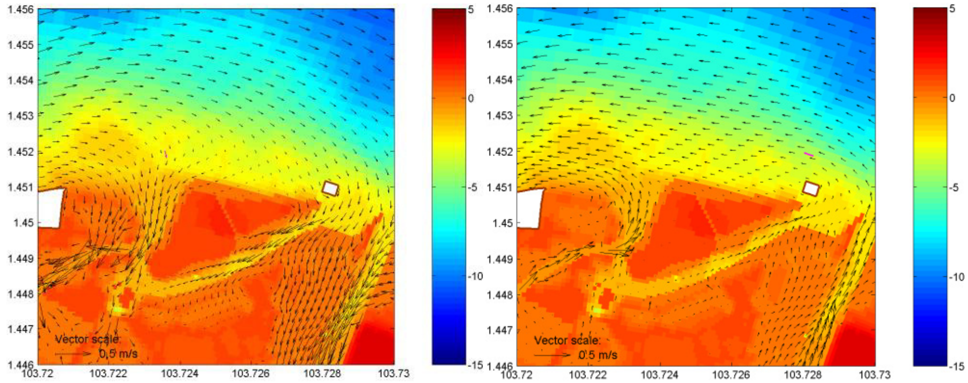

Fig. 3. Comparison between surveyed (pink arrow, single location) and modeled (black arrow) velocity field during flooding (left panel) and ebbing (right panel) condition.

Velocity fields during flood and ebb tidal condition for neap and spring period are depicted in Fig 4. In the western Johor Strait, the current stream is flowing eastward during the flood tide, and westward during ebb. The flood tide is filling the Sungei Buloh Wetland Reserve and emptying during ebb as can be seen from the figures. The flow is stronger during flooding periods compared to ebbing periods. Tidal currents are shown to be dominant within the river during spring tides. The local model seems to capture the tidal dynamics within the river, the wetland area and also in the strait satisfactorily.

4. Concluding Remarks

In the present study, a preliminary 2D hydrodynamic model for the Sungei Buloh Wetland Reserve has been set up and compared with *in situ* measurements of water levels and current patterns. The model results are shown to be in good agreement with field measurements, and can be used as a base for future work. Since the ultimate goal of the project is to understand the fate of pollutants, it is proposed to next simulate the mangrove ecosystem using 3D hydrodynamic model. Further improvements of the model should investigate the use of vegetation models [i.e., 5, 6] instead of using different values of Manning roughness coefficients, to properly simulate the drag force and blockage on the flow structure in the mangrove swamp system. This should improve further the representation of relevant phenomena in mangrove ecosystems, such as the Sungei Buloh Wetland Reserve in Singapore.

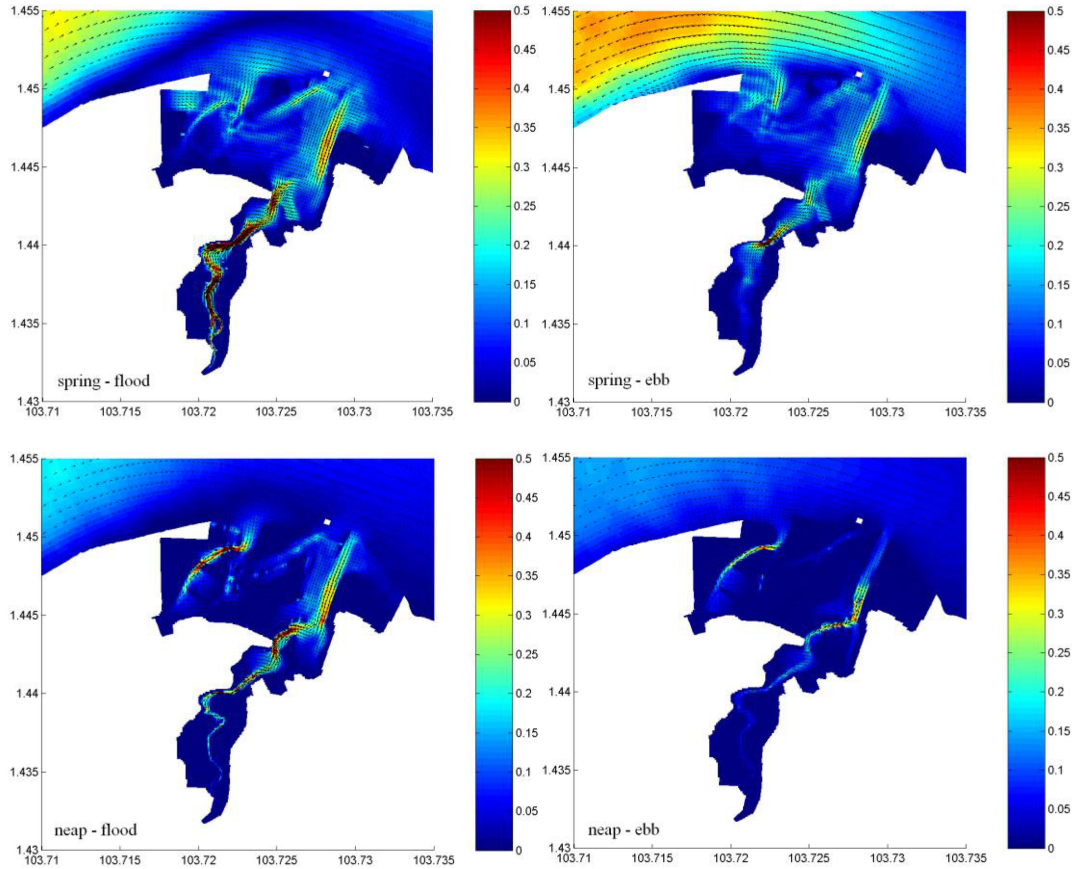

Fig. 4. Modeled depth-averaged velocity field during flood and ebb tidal condition of both spring and neap period.

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