Applied Ocean Research 55 (2016) 59–65

Contents lists available at ScienceDirect

Applied Ocean Research

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

Technical Note

Conceptual hydrodynamic-thermal mapping modelling for coral reefs at south Singapore sea

Jaan Hui Pu

School of Engineering, Faculty of Engineering and Informatics, University of Bradford, Bradford DB7 1DP, UK

ARTICLE INFO

Article history:
Received 7 June 2015
Received in revised form
30 September 2015
Accepted 30 November 2015
Available online 22 December 2015

Keywords:
Coral reefs
Hydrodynamics
Singapore coastal waters (SCW)
Thermal map

ABSTRACT

Coral reefs are important ecosystems that not only provide shelter and breeding ground for many marine species, but can also control of carbon dioxide level in ocean and act as coastal protection mechanism. Reduction of coral reefs at Singapore coastal waters (SCW) region remains as an important study to identify the environmental impact from its busy industrial activities especially at the surrounding of Jurong Island in the south. This kind of study at SCW was often being related to issues such as turbidity, sedimentation, pollutant transport (from industry activities) effects in literatures, but seldom investigated from the thermal change aspect. In this paper, a computational model was constructed using the Delft3D hydrodynamic module to produce wave simulations on sea regions surrounding Singapore Island. The complicated semi-diurnal and diurnal tidal wave events experienced by SCW were simulated for 2 weeks duration and compared to the Admiralty measured data. To simulate the thermal mapping at the south Singapore coastal waters (SSCW) region, we first adapted a conversion of industrial to thermal discharge; then from the discharge affected area a thermal map was further computed to compare with the measured coral map. The outcomes show that the proposed novel thermal modelling approach has quite precisely simulated the coral map at SSCW, with the condition that the near-field thermal sources are considered (with the coverage area in the limit of 20 km × 20 km).

1. Introduction and motivation statement

Singapore is regarded as one of the busiest island countries connecting the world by its shipping and haulage activities. In recent years various industrial activities have boomingly growing at Singapore and causing various environmental impacts to its surrounding waters. Thus an in-depth hydrodynamic understanding of the surrounding sea and coastal area of Singapore Island is crucial in seeking solution to the rising environmental issues. In the research of Singapore coastal waters (SCW) hydrodynamic numerical modelling, there are a numbers of difficulty that were constantly suggested in various studies [3,19,22,25,33], especially for the modelling surrounded Strait of Singapore. They include: (1) the effects diurnal to semi-diurnal tides that occur in between Singapore, Malay Peninsula and Indonesian Sumatra; (2) the huge amounts of small islands exist around Singapore (that causes difficulty in numerical meshes assignation); and (3) the effect from seasonal flow, such as Monsoon season. These difficulties couple with the grids resolution restrictions in various parts of SCW post a great challenge in the search of a numerically robust approach to reproduce its tidal currents.

During the development of hydrodynamic models for SCW, published studies using various software packages (i.e. Delft3D, MIKE, POM and FVCOM) have been intensely conducted since last two decades. Among them, most studies were done using either 2D [4,19,27,28] or 3D models [3,30,31]. Among those models, the most common meshing method involved orthogonal or regular rectangular grids (as the fully unstructured grid model is computationally too demanding to apply for large-scale coastal flow application as suggested in [29]); and the boundary conditions were usually set by effective water depth. Those 2D and 3D modelling studies have proven that both local and regional models surrounded SCW can be constructed to precisely capture its tidal situation. The above-mentioned comparison from different studies also further proved that the 2D model can achieve satisfactory results and comparable accuracy with 3D model to reproduce large-scale tidal currents simulation, while giving a more efficient and hence practical tidal computational time.

Some advancements have also been proposed such as boundary-fitted [25,32] and grid-alignment approaches [19] to obtain better accuracy in simulating the 2D tidal currents in SCW. However, the improvement in accuracy was usually restricted to only small simulated area (showed in [25,32]) or was not obvious in tidal current and water level simulations (showed in [19]). In comparison, by refining the local mesh resolution according to the local geometry

E-mail address: J.H.Pu1@bradford.ac.uk

0141-1187/$ – see front matter © 2015 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2015.11.011

can effectively improve the water levels and tidal currents simulation as proven in various studies (refer to studies by [9,21]), which it is also suggested to be a crucial element in the sensitivity analysis of SCW tidal simulations conducted by Kurniawan et al. [22] and Sun et al. [27].

In terms of the coral reefs mapping at SCW, it was estimated that around 60% of the SCW coral reefs have been lost in the last six decades due to its coastal development activities [7]. The common approach to study their disappearance/growth was either by investigating the factors of: (1) sedimentation and turbidity [28]; (2) penetrating light-intensity due to sedimentation [12,18]; or (3) anthropogenic activities near to coral colony such as dredging, land-reclamation, industrial activities and pollutant transport effects [6,13,17,20]. Comprehensive studies from different perspectives of coral reef survival (i.e. from physical and biological perspectives by Erftemeijer et al. [14], Fabricius [15], and Rogers [24], respectively) have also been conducted. The conclusion from those studies showed that even though the terrestrial sedimentation can affect the coral mapping, its effect to the shallow SCW is not obvious due to its tidal currents system and heavy mixture of marine waters that can dilute the fluvial sediment sources from their influence towards the coral reef grow [28]. Besides, the observed low sedimentation rates on coral area located at SCW (typically 5–20 mg/cm^2/day) was found to have minimal impact towards the coral reefs [12,13], which it showed that the true reason of SCW coral map shrinking is still inconclusive. For this reason, a different coral reefs modelling study has to be conducted to determine the exact reason for coral map shrinking at SCW.

Due to the complicated condition with high diversity of reef environment in small SCW coastal area, its mapping determination has a crucial impact to unlock the true issue faced in order to save the coral reef species from further reduction [8,28]. The reefs surrounded SCW are mainly fringing-type corals that concentrate on its coastline [5]. These types of coral reef at SCW exhibit the exact features of the tropical corals that can be threatened by coral bleaching due to: (1) the thermal stress [2,16]; and (2) the constant exposure to wet–dry condition from the mixture of high and low tides in the shallow sea [7,26]. Therefore from the suggestions of those studies, the hydrodynamic and thermal impacts towards coral reefs are seemed to be important factors to consider in order to study the future coral map development at SCW.

In the light of the afore-mentioned studies, this work is motivated to construct a numerical approach to truly represent the coral map shrinking/growing. It starts by constructing a hydrodynamic study surrounded Singapore Island. The Delft3D hydrodynamic module used in the present study is based on the depth-averaged flow theory that coupled with wave propagation by its WAVE-FLOW module [10,11]. Then, the industrial output derived from daily industrial waste and cooling water discharges is statistically calculated and extended into 2-week simulation to model an effective thermal map surrounded south Singapore coastal waters (SSCW) region to understand the correlation of thermal effect towards the change of coral area. Two separate tests are conducted for the proposed model. First, in order to validate the hydrodynamic modelling, the wave simulation at four different parts of the SCW are compared to the Admiralty measured data for the duration of 2 weeks to prove the model representativeness of the actual semi-diurnal and diurnal tides at SCW. Second, the computed thermal map is compared to the coral map at SSCW. The comparisons show that the proposed thermal mapping approach can precisely simulate the area of coral reefs when the inspected area is limited to a near-field of 20 km × 20 km. Besides showing encouraging sign to simulate the correlated coral reef area, the proposed modelling approach also prove that thermal effect is one of the crucial factors to influence coral area grow which was constantly neglected in various SCW studies.

2. Model setup and description

In this study, the Delft3D model setup covers all surrounding sea regions of Singapore Island, which includes its boundaries with Johor (Malaysia) and Java Island (Indonesia). The relatively wide sea regions covered in this model allow the tidal currents computation in Singapore Strait without needing to prescribe them as boundary conditions, and hence can eliminate unnecessary preset conditions to influence the simulation. The grid system with bathymetry, water and land-cells, as well as land boundaries is presented in Fig. 1. The bathymetry setting of the whole model is mainly adapted from Admiralty bathymetry data; and the land boundaries are adapted from the mapping using GoogleMaps. The utilised grid (under orthogonal system) varies in size to effectively represent the local flow geometry and condition. It is set to be with higher resolution (in between 20 and 150 m) around Johor Strait to Tekong Island and center of Singapore Strait due to narrower geometry and existence of small islands, respectively; and in between 250 and 400 m at the east and west ends of Singapore Strait. These grid resolutions are tested with three different resolution settings (course, medium and fine grid resolutions) and the most optimum medium grid resolution is chosen.

In total, this model has two open boundaries (towards the east and west of Johor) and one sub-divided open boundaries that located along the coastline of Java Islands. Besides, there are also two small open boundaries located along Johor and Tebrau Rivers at the north of the model. There are a total of 11 supporting points used for setting those boundaries, and the tide conditions of modelled region consist of the semi-diurnal tidal constituents of M2 and S2 (two high and two low tides daily) generated from the directions of the Andaman and Java Seas, and the diurnal tidal constituents of K1 and O1 (one high and one low tides daily) coming from the direction of the South China Sea (with contribution from Java Sea also).

In order to model the daily industrial waste and cooling water discharges, two point-sources are identified to be the key discharge points from the Jurong Island industrial area located at SSCW (shown at points 1 and 2 in Fig. 1). The output discharge sources are calculated using the Continuous Stirred-Tank Reactor (CSTR) assumption on the existing discharge tanks at the industrial area, where their discharge and salinity output are represented as 112.5 m^3/s and 30 ppt, respectively. The ambient salinity is set to be 29.5 ppt as according to the documented data. Using these inputs, the model then produces heat flow discharges towards SSCW, where the complicated SSCW tidal currents governed by the hydrodynamic model disperse them to a wider field. By averaging temperature of the considered SSCW field over every quarter-hour for 2 weeks duration, we then find out a full thermal map propagation of the heat flow. By comparing the modelled thermal map affected area to the actual coral map, we can then study the heat flows influence on the coral reefs grow.

3. Hydrodynamic simulation: model validation

As afore-mentioned, the hydrodynamic modelling plays a crucial role to determine the accuracy of the tidal currents simulation, especially under complicated semi-diurnal and diurnal tides experienced by SCW. First to investigate the semi-diurnal to diurnal co-tide phases interaction at the Singapore Strait, the regional spatial distributed vector plots are investigated at the simulated flow region. Both amplitude and phase contributed tides, K1 and O1, as well as S2, are presented in Figs. 2 and 3, respectively.

The co-tide phases plotting taken at different times during a single day at Figs. 2 and 3 show the combined effects of open boundary's and bathymetry's driving tide forcing to the tidal currents. For K1 and O1 tides, they are mainly evolved from the tide