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ESTIMATING DISSOLVED OXYGEN DEPLETION IN INNER WESTERN JOHOR STRAIT, MALAYSIA USING A THREE DIMENSIONAL WATER QUALITY MODEL

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Abstract: Characterization of changes in inner Western Johor Strait (WJS) of monitoring works was successfully carried out. Eight water quality data sets collected in this area from Second Link to Causeway Link. An extensive dissolved oxygen (DO) data set was used to develop a statistically meaningful way of estimating mean DO from discrete measurements in inner WJS. Relationships among bottom water DO, vertical stratification, and the factors responsible for stratification-destratification in this narrow stretch of water along the WJS with some recent continuous monitoring data. Therefore, it is imperative that the environmental of reclamation and dredging works, municipal or industrial discharge, marine aquaculture and shipping activities in this area be effectively controlled and managed. The purpose of this study was to assess the water quality condition in the Inner Western Johor Strait and the estimating the spatial variable ties of the mean salinity, temperature and dissolved oxygen conditions in WJS. An application of the three dimensional water quality model Environmental Fluid Dynamic Code (EFDC) was developed for the inner WJS to investigate the DO depletion along the strait and surrounding areas. The twenty-one state variable water quality model available in EFDC included multiple dissolved and particulate organic carbon constituents, as well as organic and inorganic nutrients, DO, and three phytoplankton constituents.

Keywords: *Oxygen depletion, tidal range, estuarine circulation*

1.0 Introduction

Johor Strait is located along the south shore of Peninsular Malaysia and separates the island of Singapore from Peninsular Malaysia over a distance of about 50 km between the estuaries of Sungai Pulai to the west and Sungai Johor to the east. The strait is divided by the Causeway linking Singapore to mainland Malaysia. Figure 1 shows the location of Johor Strait with the western and eastern portions of the strait, respectively.

The significant problems of water pollution in coastal waters as a result of the discharge of large amounts of pollutants into the coastal environment resulted from human activities in South Johor and Singapore are a direct consequence of rapid development and industrialization in South Johor, Malaysia. The discharges of waste from human activities in South Johor and Singapore are directly sent to the Johor Strait. The waste discharges of the Johor Bahru Municipality, Pasir Gudang Industrial Estate and also, the Skudai and Tebrau river discharges which flow through the areas in South Johor with a big population. The inside portion of the Johor Strait that includes the stretch of coastal waters from the estuary of Skudai to the estuary of Tebrau requires special attention based on the above observations. Besides, fisheries and recreation activities are evident in this area. The bulk of the waste load that is discharged into the Strait is sent to the Inner Johor Strait. The presence of the Causeway that has caused the blockage of the normal flow of the Strait and led to the propagation of a standing wave with no flow at the Causeway has aggravated the situation (Kuo *et al*., 1991).

Generally, in aquatic ecosystem, dissolved oxygen depletion or hypoxia is the low oxygen in water where dissolved oxygen (DO) concentration is less than 5 mg/l. A complete lack of oxygen (0 mg/L) is called anoxia (Stanley, 1992; Liu *et al*., 2007, 2008, 2009 & 2010). There are some definition of hypoxia defined by various institution and committee. Based on nutrients levels from field data and modelling results in the Straits of Johor and Singapore Straits, Cheong (2001) noted the likelihood of algal bloom in the region. The loss of dissolved oxygen from the decay of phytoplankton bloom is most likely in the Johor Straits because of the high biomass (>40µg/l chl-a) blooms that frequently occur in this eutrophic waterway. Small fish kills do occur, especially in or near the small scale aquaculture farm that exist along this waterway, although there is no direct evidence of this cause.

In December 2009, a toxic bloom hit Singapore waters along East Johor Strait causing massive fish kills and great economic losses. In 2012, there are 160 tons of dead fish are found in fish farm along Straits Johor. Oxygen level near the bottom of Johor Straits can fall to less than 2 mg/l in some parts of Johor Straits. Hypoxia is much less likely in the less nutrient enriched and better mixed waters of the Singapore Straits.

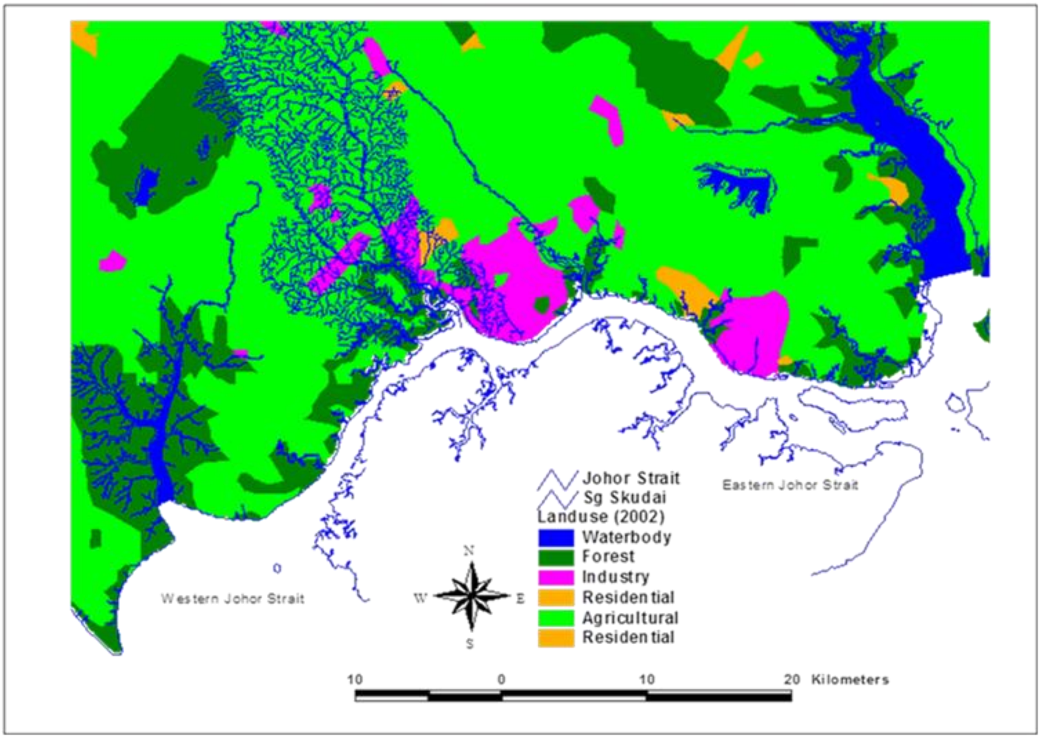


Figure 1: Location of study area

2.0 Model Description

2.1 Water Quality Component

Environmental Fluid Dynamic Code (EFDC) is composed of a hydrodynamic model and a water quality model combined internally. A water quality eutrophication model, functionally equivalent to Corps of Engineers Integrated Compartment Water Quality Model (CE-QUAL-ICM) (Cerco and Cole, 1993) is integrated into the model (Hamrick and Wu, 1997; Park *et al*., 1996).

The eutrophication module in EFDC model solves mass balance equations for the 21 state variables in water column, which included three algal groups, various component of carbon, nitrogen, phosphorus, and silica cycles, dissolved oxygen dynamics, and fecal coliform bacteria as shown in Figure 2 (Hamrick and Wu, 1997; Wang *et al.*, 1999). Figure 2 illustrates the interactions among those variables, atmosphere and sediment. The diagram shows that the whole eutrophication process is composed of physical, chemical and biochemical reactions. In the figure, each box represents a state variable and the symbol denotes sediment phase. The arrows represent kinetic interactions among state variables.

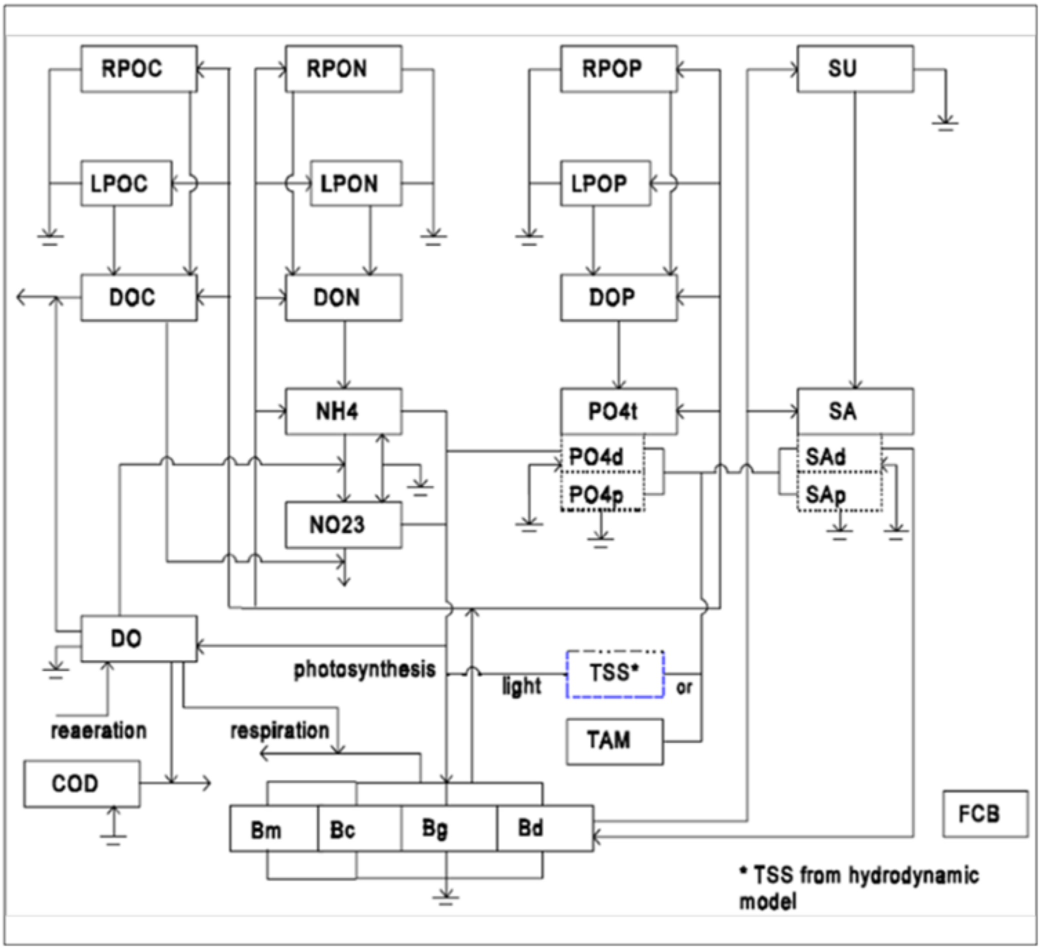


Figure 2: Schematic diagram of EFDC water quality model structure (Hamrick and Wu, 1997)

$$\frac{\partial}{\partial t}\left(m_x m_y HC\right) + \frac{\partial}{\partial x}\left(m_y H\mu C\right) + \frac{\partial}{\partial y}\left(m_x HvC\right) + \frac{\partial}{\partial z}\left(m_x m_y \omega C\right) =$$

$$\frac{\partial}{\partial x}\left(\frac{m_y H A_x}{m_x}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{m_x H A_y}{m_y}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(m_x m_y \frac{A_z}{H}\frac{\partial C}{\partial z}\right) + m_x m_y H S_c \qquad (1)$$

Where C is concentration of a water quality state variable: *u*, *v*, *w* are velocity components in the curvilinear, sigma x-, y- and z-directions, respectively; A_x, A_y, A_z are turbulent diffusivities in the x-, y-, z-directions, respectively; S_c is internal and external sources and sinks per unit volume; H is water column depth and m_x, m_y are horizontal curvilinear coordinate scale factors.

In the governing mass balance equation (Eq.1), last three terms on the left-hand side account for the advective transport, and the first three terms on the right-hand side account for the diffusive transport. These six terms for physical transport are analogous to, and thus the numerical method of solution is the same as, those in the mass-balance equation for salinity in the hydrodynamic model (Ji et *al.*, 2007). The last term in (Eq.1) represents the kinetic processes and external loads for each of the state variables. The present model solves (Eq.1) using a fractional step procedure which decouples the kinetic terms from the physical transport terms.

3.0 Model Application

3.1 Data Description

Hypoxic events happened in Western Johor Strait near Causeway Link and surrounding areas. During the hypoxic events, the water body became smelly, dissolved oxygen depletion and reduction in harvestable fish and shellfish. As a result, the landscape functions of the strait decreased rapidly.

To simulate the eutrophication of Western Johor Strait systematically, a field sampling was conducted from October to November 2009 with interval of 10 days. The sampling sites are shown in Figure 2. The monitoring factors included water temperature, Secchi Disc (SD), DO, and chlorophyll a concentration. The weather data were obtained from MET, which included air temperature, atmospheric pressure, relative humidity, precipitation, evaporation, solar radiation and cloud cover.

Data from intensive surveys of WJS were made to establish 8 vertical profiling stations. The measurements in this study were made with Yellow Springs Incorporated (YSI) sensors and sondes. Vertical profiles was collected and identified by distance from Second Link to Causeway Link. All sampling stations were located at the middle of navigation channels. At each station, temperature, conductivity, salinity and DO were sampled at every one meter from surface to bottom during spring and neap tide.

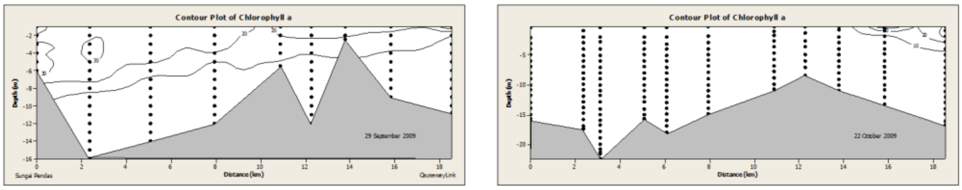
The sampling locations for this study involve eight stations located along the Western Johor Straits, between the Kelong near Second Link and the Causeway Link. These sampling stations were selected based on the criteria as the main area for fisheries and aquaculture activities. The coordinates of the sampling location is shown in Table 1.

Stations M07 and M08 are located closer to the causeway which connects the island of Singapore to the Peninsular Malaysia. There is no flow of water between the two bodies of water separated by the causeway and results in an estuary like area near the causeway itself. Stations M02, M04, M05 and M06 are located closer to the main river estuaries (Sungai Pendas, Sungai Perpat, Sungai Melayu and Sungai Skudai). The flow in the strait is relatively uniform based on the simulation forecast of the currents in the channel. Station M06 is located near the rapid development area of Iskandar Malaysia at Nusajaya. Station M08 is located at kelong between Sungai Pulai estuary and Second Link.

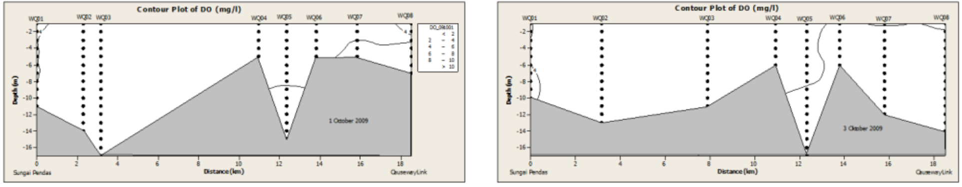
Figure 3 shows higher DO in the surface layer and the low DO in the deeper layer near Causeway Link station area. Oxygen depletion occurs near Causeway Link area. As shown in Figure 2, DO concentration in surface layer is high but at the bottom layer become less than 2 mg/l because there is no any current of water near the stations. The presence of the causeway that has caused the blockage of the normal flow of the Western Johor Strait and led to the propagation of a standing wave with no flow at the causeway has aggravated the situation (Kuo, *et al*., 1991). This area was so polluted and hypoxia occurred in the deeper layer. However, in other stations from Second Link to Sungai Skudai estuary, the higher correlation in the upper layers is no doubt because those waters are uniformly responding to air fluxes that have large spatial scales.

Table 1: Sampling Stations and Coordinates

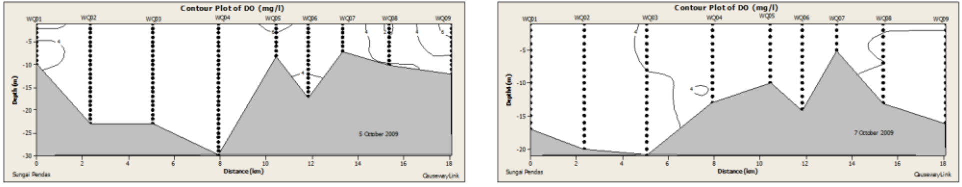
Sampling Stations	**Coordinate**
M08 – Causeway Link	1° 27.350'N 103° 45.967'E
M07- in front of Hospital Sultanah Zanariah	1° 27.317'N 103° 44.733'E
M06- Sungai Skudai estuary	1° 27.933'N 103° 43.483'E
M05– Sungai Melayu estuary	1° 27.278'N 103° 42.032'E
M04- Sungai Perpat estuary	1° 26.272'N 103° 40.682'E
M03 – Nusajaya	1° 25.167'N 103° 40.100'E
M02- Sungai Pendas estuary	1° 22.683'N 103° 38.512'E
M01- Kelong near Second Link	1° 20.448'N 103° 36.506'E



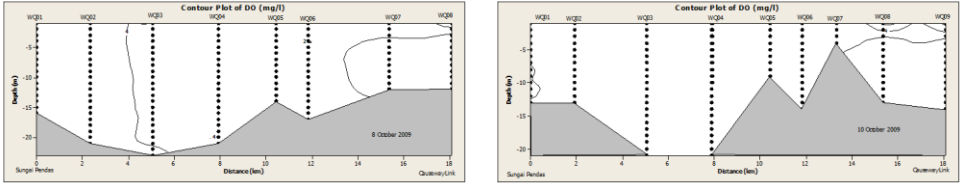
(a) 29 September 2009 (b) 22 October 2009



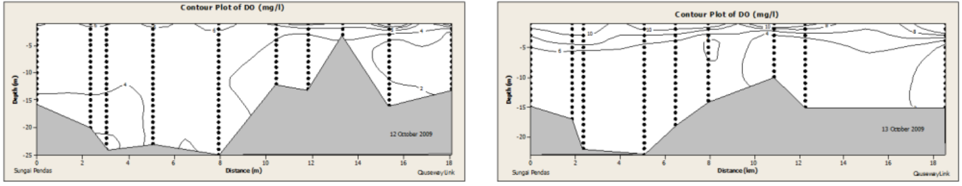
(c) 1 October 2009 (d) 3 October 2009



(e) 5 October 2009 (f) 7 October 2009



(g) 8 October 2009 (h) 10 October 2009



(i) 12 October 2009 (j) 13 October 2009

Figure 3: Vertical sections of Dissolved Oxygen and Chlorophyll a constructed with data collected on September-October 2009.

3.2 Cell Generalization and Input Conditions

On the basis of the features of the study area, curvilinear orthogonal grids were employed to represent complex geometry of the Western Johor Strait. The model grids consist of 6591 cells in the horizontal direction, with grid size ranging from 20 to 200 m (Figure 4).

After the generalization of the Western Johor Strait, a set of input files including initial concentrations and boundary conditions need to be configured to drive the EFDC model. The input files are different according to the different purpose of simulation. Table 2 lists the input files used in this study. The initial concentrations of the water quality factors were setup in wq3dwc.inp file and the boundary conditions such as inflows, atmosphere, water temperature and pollutant loadings were setup in qser.inp, aser.inp, tser.inp and wqpsl.inp, respectively.

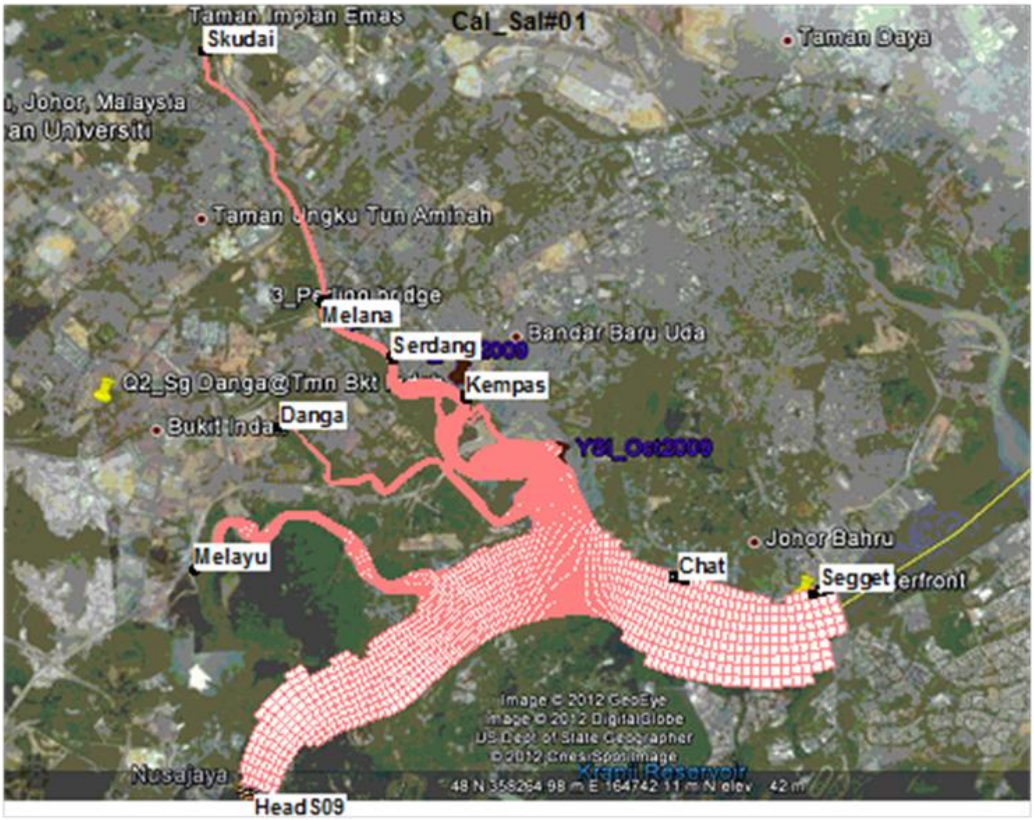


Figure 4: Sampling point and grids sketch.

Table 2: Eutrophication model input files for the Western Johor Strait.

Files Name	Files type	Files function
efdc.inp	Master input file	The information in efdc.inp provides run control parameters, output control and physical information describing the model domain and external forcing functions.
wq3dwc.inp	Water quality master input file	The information in wq3dwc.inp provides run control parameters, output control and external forcing functions for water quality simulation on the domain described by the efdc.inp file.
cell.inp	Horizontal cell type identifier file	The cell.inp file specifies the horizontal grid of cells which is defined by a cell type array: 0 Dry land cell not bordering a water cell on a side or corner 1 Triangular water cell with land to the northeast 2 Triangular water cell with land to the southeast 3 Triangular water cell with land to the southwest 4 Triangular water cell with land to the northwest 5 Quadrilateral water cell 9 Dry land cell bordering a water cell on a side or corner of a fictitious dry land cell bordering an open boundary water cell on a side or a corner
celllt.inp	Horizontal cell type identifier file	The file celllt.inp may be identical to the file cell.inp or specify a subset of the water cells in the cell.inp file
dxdy.inp	Cells information file	File specifying horizontal grid spacing or metrics, depth, bottom elevation, bottom roughness and vegetation classes for either Cartesian or curvilinear-orthogonal horizontal grids
lxly.inp	Cell information file	File specifying horizontal cell center coordinates and cell orientations for either Cartesian or curvilinear-orthogonal grids
qser.inp	Time series file	This file defines the time series for volumetric source-sink
aser.inp	Time series file	This file defines the time series for atmospheric forcing
tser.inp	Time series file	This file defines the time series for water temperature
wqpsl.inp	Time series file	This file defines the time series for point source loads
show.inp	Screen writing file	File controlling screen print of conditions in a specified cell during simulations runs
efdc.exe	Executable program	Master file executes for EFDC model

3.3 Model Calibration

The field data from October 2009, 1-16 were selected for the calibration of the eutrophication model and the data from November 2009, 1-10 for the validation. The key issue in calibrating the water quality model is to simulate the concentration of dissolved oxygen (Wang and Li, 2009; Zhang and Tang, 2009; Yin *et al*., 2004). Understanding the planktonic organisms, the effects of nutrient enrichment, and the rates and pathways of organic matter production and decomposition will determine the precision and accuracy of the model to predict the eutrophication process.

Calibration of the water quality model consists of selecting of values to represent the kinetics and constants of the model equations. Model parameter selection is an iterative process, where parameters are adjusted within a range of feasible values to find the best agreement between modelled and observed values of the state variables. There may not be a unique combination of parameter values that would be representative of the conditions in Western Johor Strait. Several possible sets of parameters may produce similar agreement between predicted and observed conditions. These model parameters were adjusted within the typical range reported in literature. Table 3 lists the rates and constants for water column parameters in the Western Johor Strait and other water bodies application of the EFDC model.

4.0 Conclusion and Discussion

This paper introduced EFDC model in the Western Johor Strait for dissolved oxygen simulation and hypoxia prediction. A field sampling was conducted in October 2009 to collect data for model application. After calibration and validation based on field data, the modelled results showed that the EFDC water quality model can be used to predict the trend of hypoxia on the whole area of Western Johor Strait. The application of EFDC model is mainly focused on the simulation of hydrodynamic process, salinity, water temperature, transport of toxic contaminant, dye tracer, sediment and heavy metals, cycles of carbon, nitrogen and phosphorus.

While oxygen depletion is not the only environmental issue of concern along the Western Johor Strait, it is certainly one of the most important. There are potential links between low oxygen and kills of fish and commercially valuable shellfish. Field observations indicated that bottom DO concentrations decreased when neap tidal events occurred. Limited water exchange with open ocean in semi enclosed intertidal water of Western Johor Strait which increased in flushing time and created a lot of anthropogenic pollutants via riverine inputs. In this period, stratification was still present and the vertical mixing was suppressed, which suggests that the DO supply in the bottom layer due to coastal water intrusion accompanied by estuarine circulation.

5.0 Acknowledgements

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References

Cerco C.F. and Cole T.M. (1993) Three-dimensional eutrophication model of Chesapeak Bay, *ASCE J.Environ.Engr.Div*. 119(6) pp. 1006-1025

Cheong, H. F., Shankar, N., Ong, C. E., *et al.* (2001). Baseline study of water quality in Singapore coastal waters. 182-188.

Hamrick, J. M., and T. S. Wu, (1997) Computational design and optimization of the EFDC/HEM3D surface water hydrodynamic and eutrophication models. Next Generation Environmental Models and Computational Methods.

Ji, Z.-G., Hu, G., Shen, J., *et al.* (2007). Three-dimensional modeling of hydrodynamic processes in the St. Lucie Estuary. Estuarine, Coastal and Shelf Science. 73 (1–2): 188-200.

Kuo, A. Y., Park, K. and Moustafa, M. Z. (1991). Spatial and temporal variabilities of hypoxia in the Rappahannock River, Virginia. Estuaries and Coasts. 14 (2): 113-121.

Liu, Z., Choudhury, S. H., Xia, M., *et al.* (2009). Water quality assessment of coastal Caloosahatchee River watershed, Florida. Journal of Environmental Science and Health Part A. 44 (10): 972-984.

Liu, Z., Hashim, N. B., Kingery, W. L., *et al.* (2010). Fecal coliform modeling under two flow scenarios in St. Louis Bay of Mississippi. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering. 45 (3): 282-291.

Liu, Z., Kieffer, J. M., Kingery, W. L., *et al.* (2007). Watershed modeling of dissolved oxygen and biochemical oxygen demand using a hydrological simulation Fortran program. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering. 42 (13): 2023-2032.

Liu, Z., Kingery, W. L., Huddleston, D. H., *et al.* (2008). Assessment of water quality conditions in the St. Louis Bay watershed. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering. 43 (5): 468-477.

Park, K., Kuo, A. Y. and Neilson, B. J. (1996). A numerical model study of hypoxia in the tidal Rappahannock River of Chesapeake Bay. Estuarine, Coastal and Shelf Science. 42 (5): 563-581.

Stanley, D. W. and Nixon, S. W. (1992). Stratification and bottom-water hypoxia in the Pamlico River estuary. Estuaries and Coasts. 15 (3): 270-281.

Wang, P. F., Martin, J. and Morrison, G. (1999). Water Quality and Eutrophication in Tampa Bay, Florida. Estuarine, Coastal and Shelf Science. 49 (1): 1-20.

Wang, Y. and Li, X. (2009). 3D Hydro Environmental Model of Dissolved Oxygen Distribution in Yangtze Estuary

Zhang, C. and Tang, H. (2009) Advances in Water Resources and Hydraulic Engineering Tsinghua University Press: Springer Berlin Heidelberg. 680-682.

Yin, K., Lin, Z. and Ke, Z. (2004). Temporal and spatial distribution of dissolved oxygen in the Pearl River Estuary and adjacent coastal waters. Continental Shelf Research. 24 (16): 1935-1948.