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Appraisal of Water Quality in Sungai Johor Estuary using Three-dimensional Hydrodynamic Modelling

Al-Amin Danladi Bello, Noor Baharim Hashim, Mazna Binta Ismail

Abstract—Sungai Johor is considered the main river in Johor that flows roughly north-south direction and empties into the Johor Strait, thereby affects the water quality in the Strait due to high pollutant inflow along the river. For modelling the hydrodynamic and water quality, Environmental fluid dynamic code (EFDC) is used. As water quality model linked to hydrodynamic characteristics of the river, the EFDC is configured to simulate time varying surface elevation, velocity, salinity and water temperature. These time series records are used in the simulation of physical transport processes for the water quality model which cover Dissolve Oxygen (DO), Dissolved Organic Carbon (DOC), Chemical Oxygen Demand (COD), Ammoniacal Nitrogen (NH_3-N), Nitrate Nitrogen (NO_3-N), Phosphate (PO_4) and Chlorophyll *a*.The model is calibrated using the data obtained in the site between January to June 2008. It is observed the simulated water temperature, salinity and DO showed a relatively good agreement with the observed data because the correlation coefficients between the simulated and observed temperature and salinity are lower compared to water level. A sensitivity analysis conducted for the input parameters for hydrodynamic properties showed that the bottom roughness is sensitive to water surface elevation at the upper Sungai Johor River and for the water quality, the DO regime is moderately sensitive to sediment oxygen demand (SOD) but not sensitive to nitrification rate. This implies that, DO is consumed at the benthic level than at the surface. It is anticipated that the development of the model be continued to synthesize additional field data into the modelling process.

Index Terms—Dissolve Oxygen (DO), Estuary, EFDC, Hydrodynamic, Sungai Johor, Water Quality

1 INTRODUCTION

Estuaries face a host of common challenges. As more people flock to the shore, we are upsetting the natural balance of estuaries and treating their health. We endanger our estuaries by polluting the water and building on the lands surrounding them. These activities can contribute to unsafe drinking water and beach, closing of shellfish bed, harmful algal blooms, declines in fisheries, loss of habitat, fish kills, and a host of other human health and natural resource problems.

The Sungai Johor river basin is located at the southeastern tip of Peninsular Malaysia as shown in Fig. 1. Sungai Johor has a total length of about 122.7 km with catchment area of 2636 km2. The river originates from Gunung Belumut and Bukit Gemuruh in the north and flows to the southeastern part of Johor and finally into the Straits of Johor. The major tributaries of Sungai Johor are Sungai Sayong, Sungai Linggiu, Sungai Semanggar, Sungai Lebam, Sungai Seluyut and Sungai Tiram. A great amount of pollutants from various sources, such as the sewerage network of the Johor Bahru, Pasir Gudang, Ulu Tiram, and Kota Tinggi cities, Industrial wastewaters from many industries in the surroundings, and agricultural wastewater containing fertilizers and pesticides are discharged into the Sungai Johor.

Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia
**Corresponding Author Email: ask4alamin@gmail.com*

The catchment is irregular in shape. The maximum length and breadth are 80 km and 45 km respectively. About 60% of the catchment is undulating highland rising to a height of 366 m while the remainders are lowland and swamps. The highland in the north is mainly jungle. In the south, a major portion had been cleared and planted with oil palm and rubber. The highland areas have granite soil cover consisting of fine to coarse sand and clay. The alluvium consists of fine sand and clay. The catchment receives an average annual precipitation of 2470 mm while the mean annual discharge measured at Rantau Panjang (1130 km^2) were 37.5 m^3/s during the period 1963-1992. The temperature in the basin ranges from 21 ºC to 32ºC.

Due to the tidal influence, the Sungai Johor is an ideal study area for research on model implementation and the prediction of hydrodynamics and water quality in tidally influenced areas. River and marine water quality monitoring in Malaysia has been conducted by Malaysian Department of Environment (DOE) since 1978. Primarily to establish the status of water quality, detect water quality changes and identify pollution sources. In 2007, there was a total of 1063 water quality monitoring stations located within 143 river basins throughout Malaysia. This involves routine monitoring at predetermined stations, in-situ and laboratory analysis, and data interpretation in terms of their physic-chemical and biological characteristics. River water quality appraisal is based on Water Quality Index (WQI) involving parameters such as Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Ammoniacal Nitrogen (NH3N), Suspended Solids (SS) and pH. The WQI serves as a basis for assessment of a water course in relation to pollution categorization and designated classes of beneficial, uses in accordance with the Proposed Interim National Water Quality Standards for Malaysia (INWQS). The DOE maintains 39 monitoring stations for Sungai Johor river basin. DOE (2007) reported that there were a total of 51 marine water quality monitoring stations located at Johor estuary and coastal area. A significant increase of freshwater inflow into the estuarine areas during flash flood at *Kota Tinggi* has affected the aquatic life for up to three weeks. Many of the fish die or swim to other river resulting in dwindling catch for the local fishermen. The nutrient level of the water samples collected from the Straits of Johor showed there was a risk of algal bloom in the region. There is an increasing concern of oversupply of nutrients from multiple sources in Sungai Johor estuary. This has ecological effects on the shallow coastal and estuarine areas. These effects include decrease in dissolved oxygen, impacts on living resources and loss of aquatic habitat. Degraded water quality has adverse effects on critical habitats in Sungai Johor estuary such as seagrass, which is an essential food for dugong and many herbivorous fish (Land Clearing, Sand Mining Affect Rivers, 2007, April 16). Hence, there is the need for comprehensive and intensive baseline studies of the water quality in the Sungai Johor estuary in order to assess the impact of all existing and future developments on the ecology of the Sungai Johor estuarine and coastal waters.

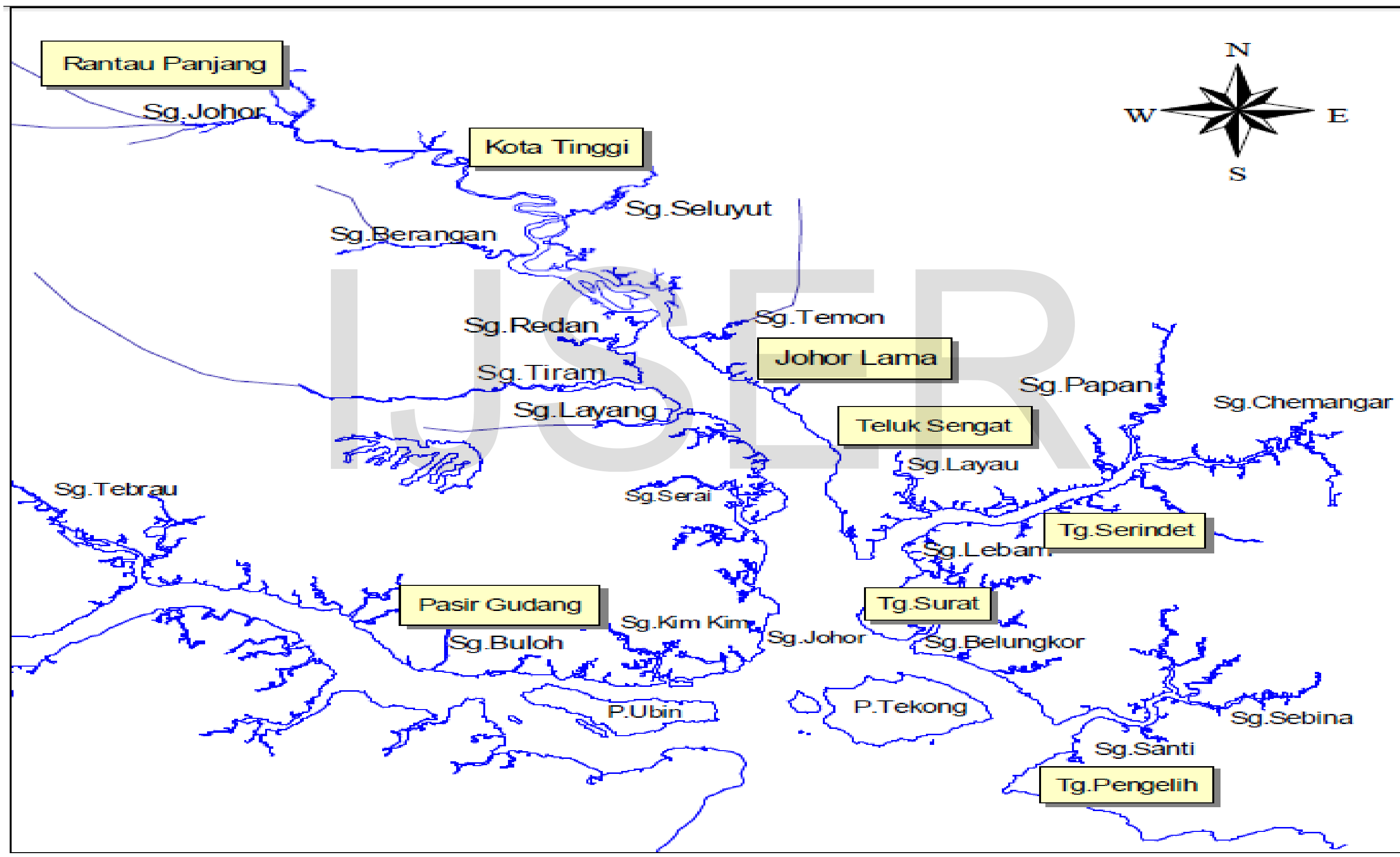

Fig. 1. Map of Sungai Johor study area.

Estuarine flow and DO distribution are three dimensional in nature. To simulate these completely, a three dimensional model with time dependent momentum and continuity equations, mass balance equations with details description of the biochemical kinetics, and sources and sinks of all dissolved constituents are necessary. It seems that the state of the art computer technology enables us to do three dimensional simulations, particularly of hydrodynamics [6]. The current sampling capacity, however, cannot provide us with the quantity and quality of field data that are indispensable for the calibration and verification of the model, particularly the water quality model. This hydrodynamic model was applied in the study to simulate the flow field and salinity distribution, and the corresponding water quality model was employed to simulate the distributions of DO and other related water quality parameters.

The primary purpose of the study is to apply hydrodynamic model and water quality model to Sungai Johor estuarine system using EFDC. The objectives of the study are listed as follows:

i. To calibrate the model utilizing historical data and field data collection.

ii. To do sensitivity analysis of input parameters of hydrodynamic and water quality model.

2 MATERIALS AND METHODS

The concept of deterministic models for the water column conditions that is based on mass balance equations for dissolved and particulate substances in water column, which consists of physical transport (advective and turbulent diffusive transport) processes and biogeochemical Processes is employed. Information on physical processes is very important and is usually obtained by applying the hydrodynamic models. Depending on the characteristics of a system, one may choose an appropriate hydrodynamic model. For a large coastal system where both horizontal and vertical gradient are significant, one needs to apply a three dimensional hydrodynamic model. Therefore the Environmental Fluid Dynamic Code, EFDC [13], is selected for the model build up. An intensive field observation surveys is conducted by the UTM research group during January- June 2008. Field data are required to specify the initial conditions, boundary conditions, and forcing function distributions in time and space for the calibration, verification and application of a three-dimensional hydrodynamic and water quality model of the study area. Historical water quality and quantity data collection was conducted in the Sungai Johor basin and its tributaries. While some of the data are also obtained from other resources such as government departments and private agencies.

The model domain, as indicated in Fig. 2, defines the Sungai Johor estuarine system and major surrounding tributaries that provide fresh water inflow into the estuary. The curvilinear-orthogonal horizontal model grid for the Sungai Johor estuary system was comprised of approximately 6613 active quadrilateral water cells, with each cell divided into 10 layers to capture the vertical variations of simulated constituents. The grid systems were constructed by using GEFDC program. GEFDC is a preprocessor system, which can generate either Cartesian or curvilinear orthogonal grids [33,35]. There are 48 downstream (seaward) boundary cells located at *Tanjung Pengelih*. The upstream boundary cells include *Sungai Seluyut*, *Sungai Berangan*, *Sungai Redan*, Sungai *Temon*, *Sungai Tiram*, *Sungai Layang*, *Sungai Layau*, *Sungai Papan*, *Sungai Lebam, Sungai Pelepah, Sungai Serai,* and several unnamed tributaries.

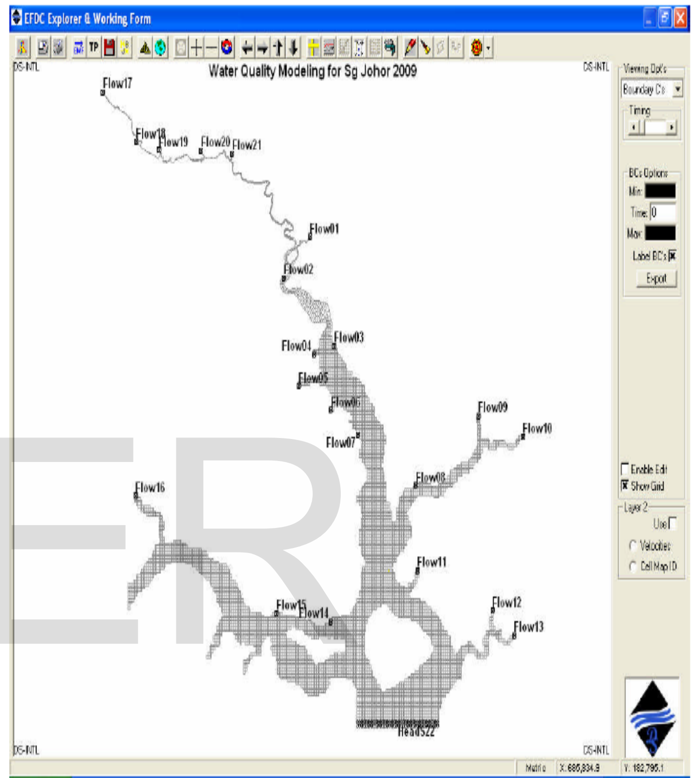

Fig. 2. The curvilinear orthogonal horizontal model domain of Sungai Johor estuary

The bathymetric data of Sungai Johor estuarine system and its surrounding areas were obtained from the Malaysian Navy navigational chart. Overall bathymetric features are illustrated in Fig. 3.

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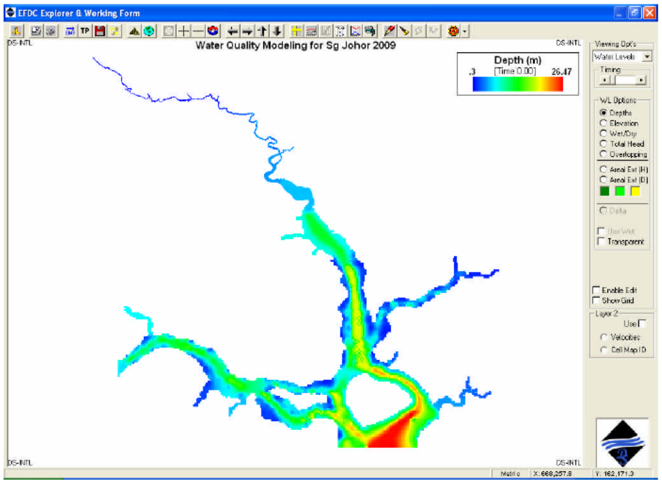


Fig. 3. The model bathymetry incorporated data from bathymetric data

As a condition to the numerical solution of the equation used to predict the four variables, values for salinity, velocity, temperature and water elevation must be specified at the model boundaries. Conditions at the Sungai Johor estuary seaward boundary was defined by water elevation, temperature, and salinity time series. Conditions at the upstream boundary was defined by averaged daily river flow and freshwater (zero salinity).

The model is capable of reading separate input files for time series specifications of tidal height as well as salinity at the seaward boundary and freshwater discharges at upstream and tributaries locations. The downstream boundary point for the model is located at *Tanjung Pengelih*. This downstream seaward boundary was forced by a tidal elevation series as measured at *Sungai Belungkor*. The upstream boundary of Sungai Johor is located outside the tidal influence, allowing the use of a simple flow time series boundary condition at *Kampung Rantau Panjang*. A flow condition is defined by the Department of Irrigation and Drainage (DID) data.

Information on wind speed and direction was obtained from the *Senai* Airport meteorological stations to define wind conditions within the model domain. The boundary conditions of surface water elevation, wind speed and direction, air temperature, atmospheric pressure, and solar radiation are used for calibration period.

According to DOE (2007), a total of 51 marine water quality monitoring stations were set up throughout the Johor State and 29 river water quality monitoring stations were set up in the Johor river basin. Under the Malaysia Singapore Joint Committee on the Environment (MSJCE) monitoring program, 20 stations were also 51 monitored in 2007. Locations of DOE River and marine water quality monitoring stations are shown in Fig. 4. Water quality data from 1997 to 2006 is available from DOE.

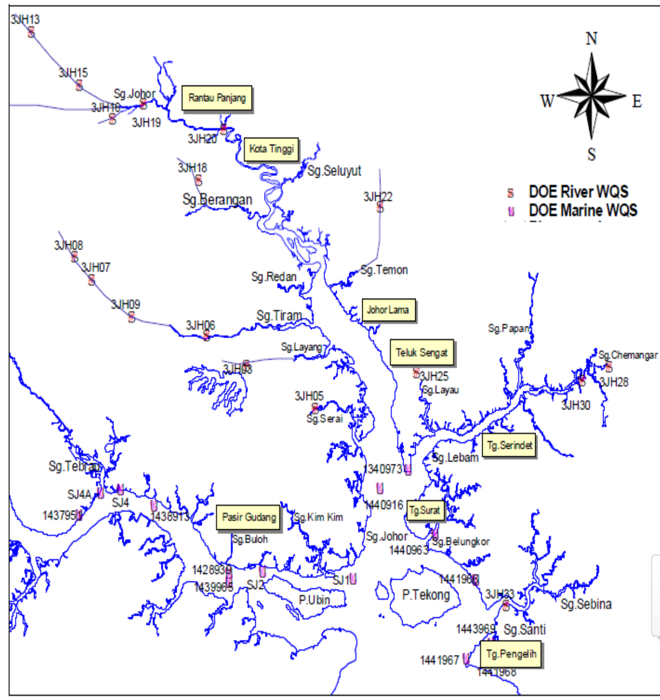
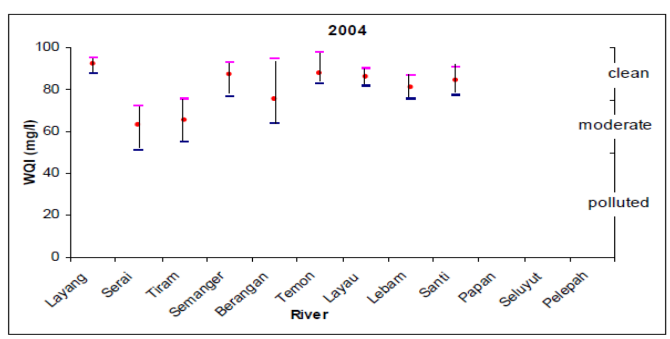


Fig. 4. Locations of DOE River and marine water quality stations.

The rivers' water quality generally deteriorated towards the estuaries, indicating multiple inputs of pollutants along the river systems [9]. As shown in Fig. 5 and 6, stations 3JH19 and 3JH20 are categorized as clean or Class II except in June 1997 and the year 2000, which have been categorized as polluted river and Moderate River, respectively. Station 3JH20 is located near Kota Tinggi bridge and station 3JH19 is approximately 7 kilometers upward from station 3JH20. Stations 3JH13 and 3JH15 are categorized as clean river or Class II. Station 3JH13 is located near *Kampung Rantau Panjang*, *Kota Tinggi* and station 3JH15 is located approximately 5 kilometers downward of station 3JH13.



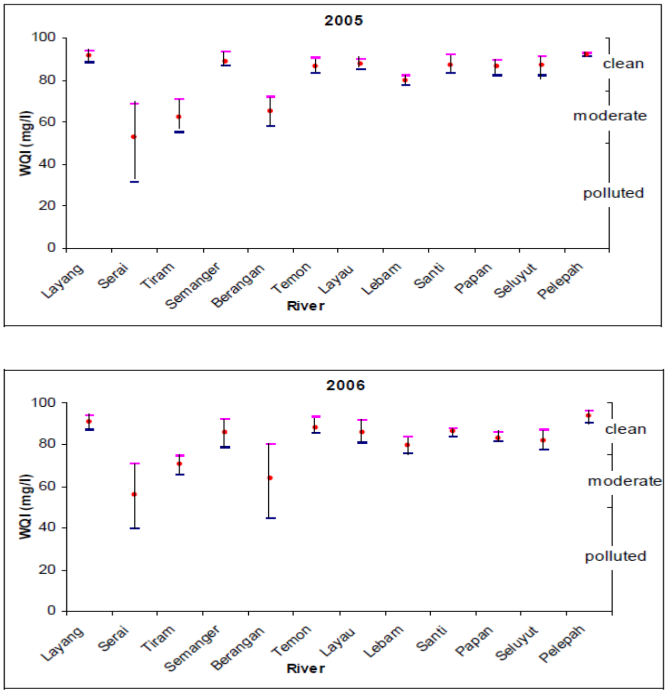


Fig. 5. Range of WQI for selected rivers along Sungai Johor

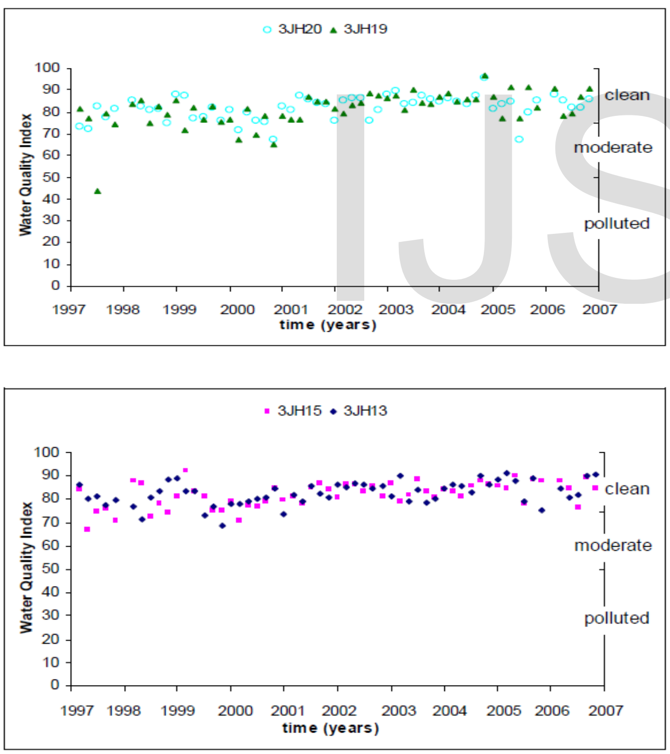


Fig. 6. Water quality trends at DOE river monitoring stations

Initial conditions for EFDC water quality model include initial concentrations, as well as solid transport field for each solid in each segment/ grid. In this study, the initial concentrations of ammonia nitrogen, nitrate nitrogen and dissolved oxygen was based on the depth averaged conditions. Linear interpolations are made on the available water quality sampling stations to initialize the concentrations of water quality parameters throughout the water quality segments. The decay of the pollutants and the oxygen uptake amount in the system is determined based on the measured data and standard water quality modeling assumptions.

By showing how the model behavior responds to changes in parameter values, sensitivity analysis is conducted to ensure effective model building as well as model evaluation. Basic comparative statistics and their associated tests [2], [31] are used to validate the EFDC model.

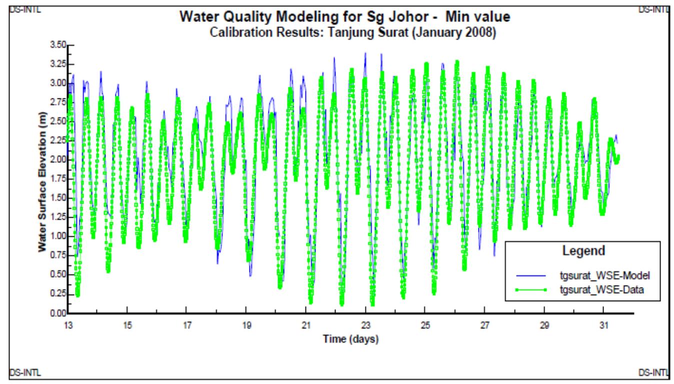


Fig. 7. Observed and simulated water surface elevations at Station Tanjung Surat

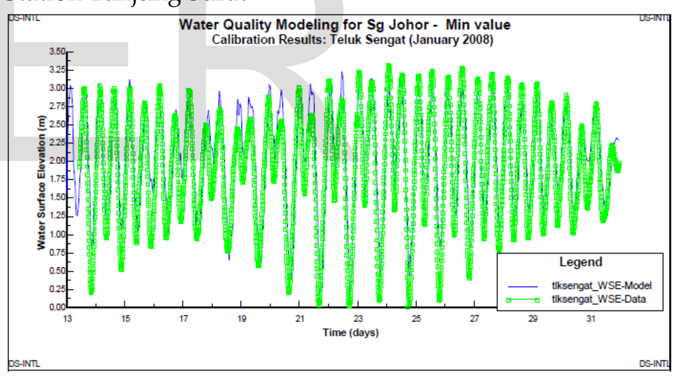


Fig. 8. Observed and simulated water surface elevations at Station Teluk Sengat

TABLE 1
ERROR ANALYSIS FOR OBSERVED AND SIMULATED WATER SURFACE ELEVATIONS

Station	Average error difference	Average absolute error difference	Root Mean Square difference
Tanjung Surat	0.141	0.249	0.321
Teluk Sengat	0.136	0.231	0.281
Kota Tinggi	0.002	0.421	0.500

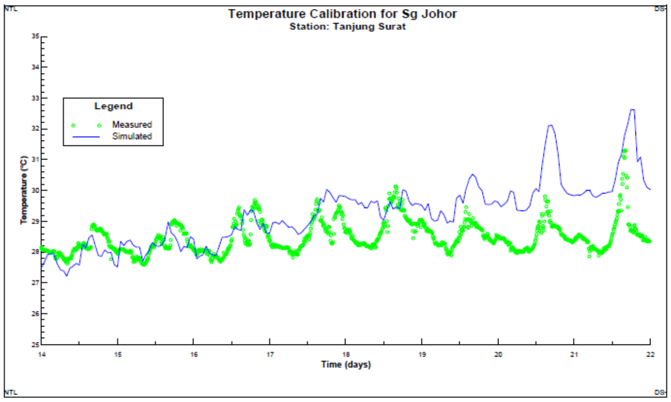


Fig. 9a. Observed and Simulated Temperatures at Station Tanjung Surat

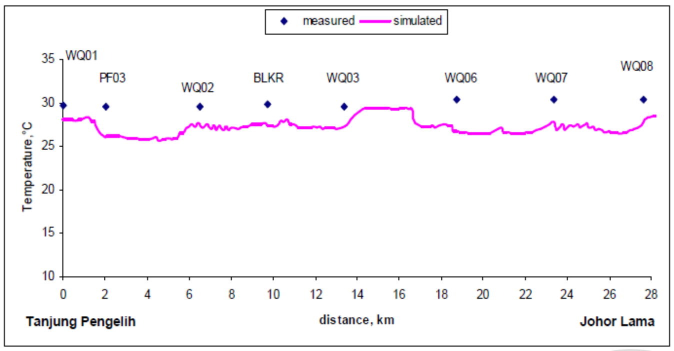
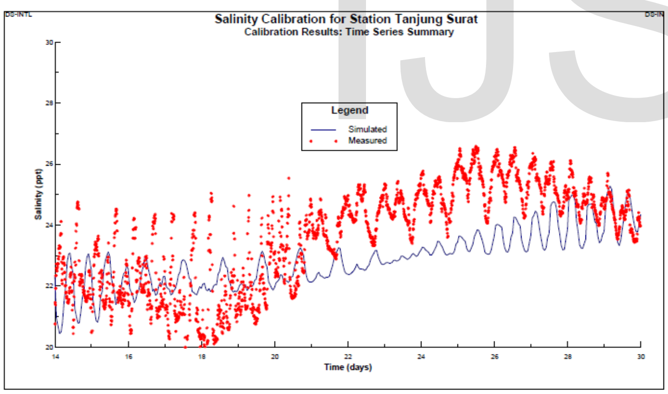


Fig. 9b. Temperature profile along Sungai Johor



Observed and Simulated Salinity at Station Tanjung Surat

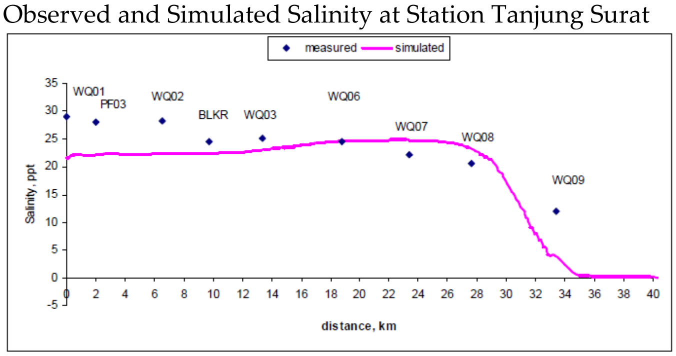


Fig. 10. Salinity profile along Sungai Johor

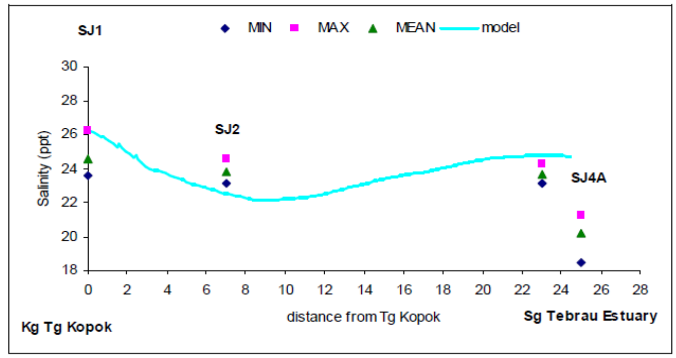


Fig. 11. Salinity profile along Johor Straits

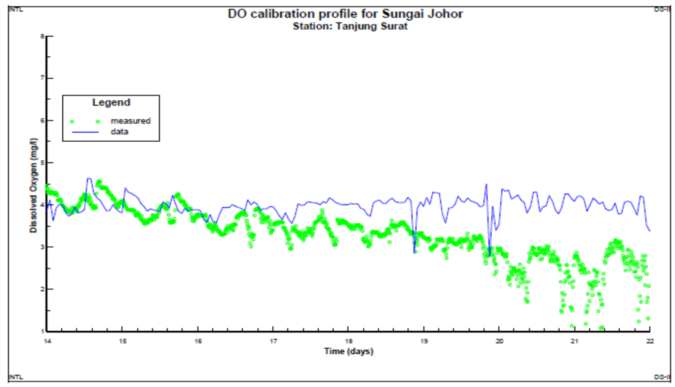


Fig. 12. Observed and Simulated DO at Station Tanjung Surat

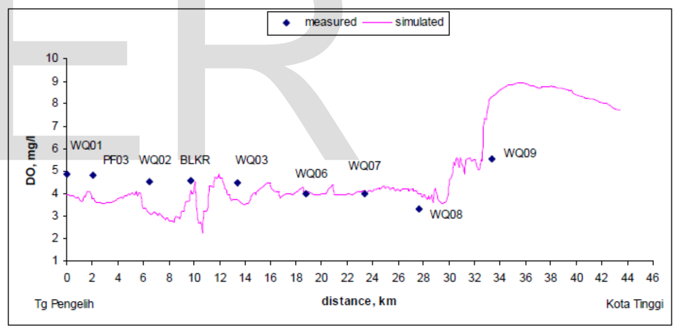


Fig. 13. DO concentration profile along Sungai Johor

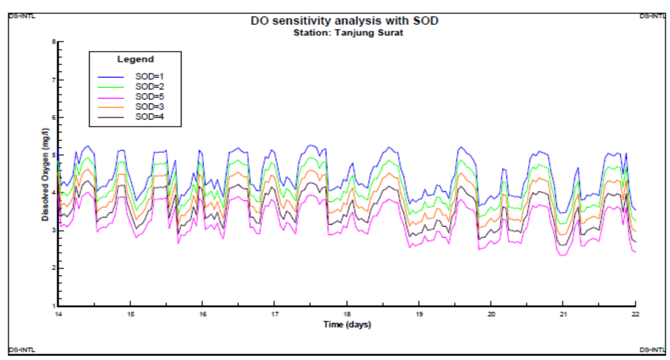


Fig. 14. Sensitivity of DO to SOD at Station Tanjung Surat

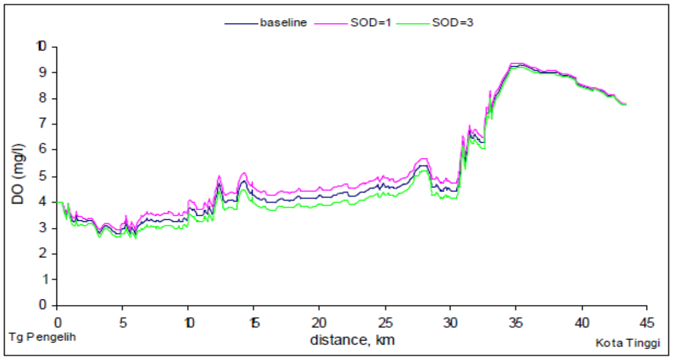


Fig. 15. Sensitivity of DO to SOD

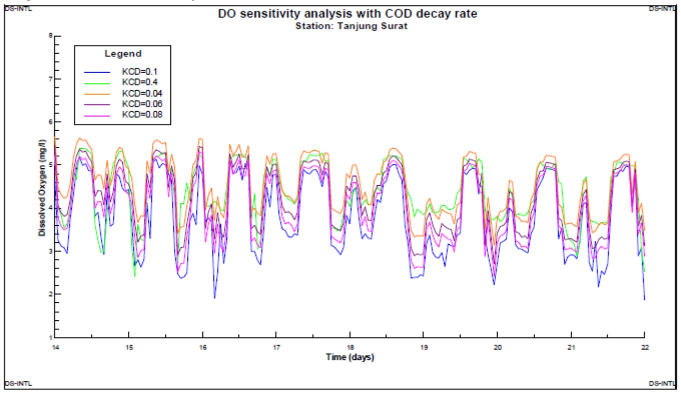


Fig. 16a. Sensitivity of DO to COD decay rate at Station Tanjung Surat

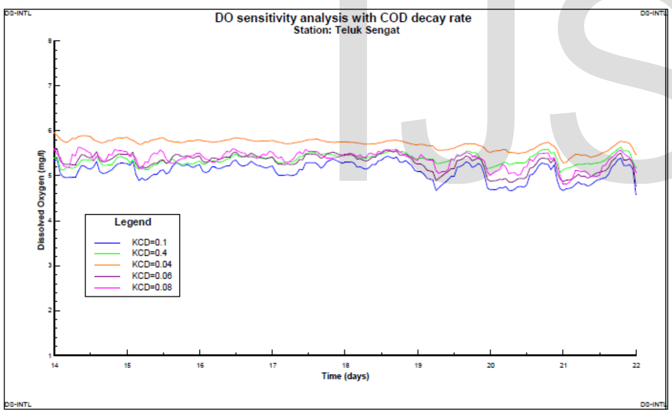


Fig. 16b. Sensitivity of DO to COD decay rate at Station Teluk Sengat

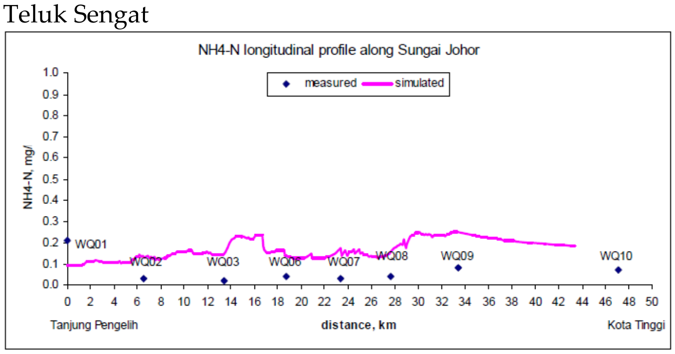


Fig. 17. Ammonia nitrogen concentration profile along Sungai Johor

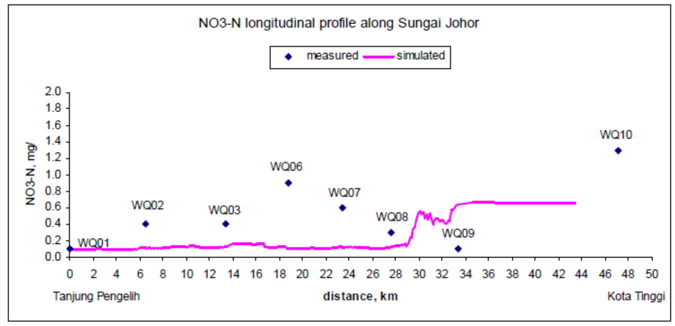


Fig. 18. Nitrate nitrogen concentration profile along Sungai Johor

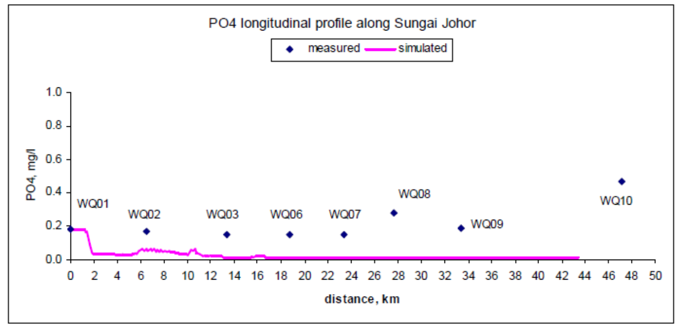


Fig. 19. Total Phosphate concentration profile along Sungai Johor

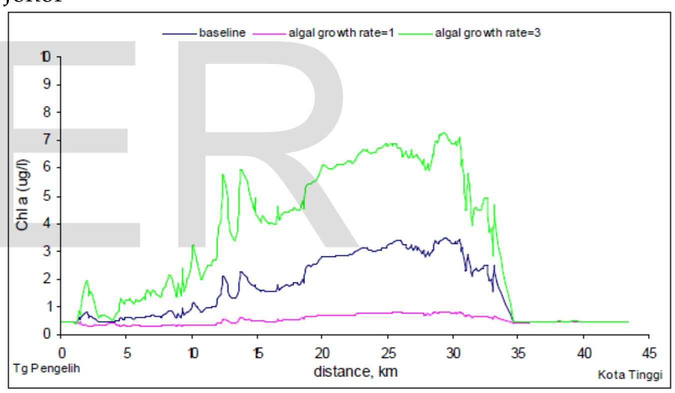


Fig. 20. Chlorophyll *a* concentration profile along Sungai Johor

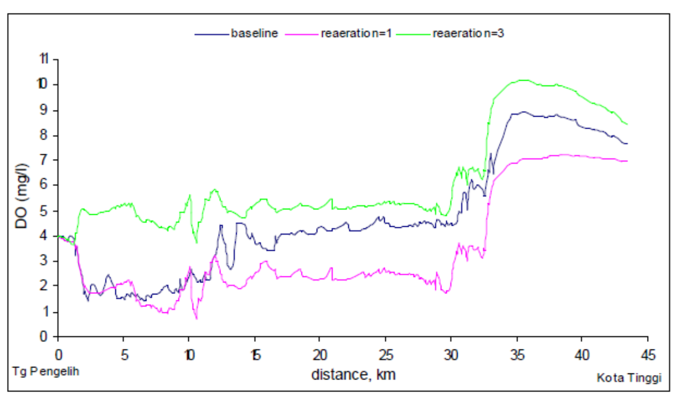


Fig. 21. Sensitivity of DO to reaeration rate

3 RESULTS AND DISCUSSION

All model coefficients should be consistent between the calibration period and the verification period. The method used in determining the values for the model coefficients is essentially one of trial and error. An intensive survey conducted in January 14-30, 2008 was used as calibration data set. This calibration data set was selected because of the availability of a comprehensive set of data and adequate description of boundary conditions during the study period.

The order in which the hydrodynamic model is calibrated is performed to address issues such as bathymetry, friction, tidal volume, cross-sectional area, and heat budget before salinity is calibrated. Salinity is the predominant signal in the model to ensure that mass is being moved horizontally and vertically with the appropriate timing and direction.

During the calibration process, Bottom roughness values are adjusted until the predicted results reasonably matched the observed data. The model results were compared against observed data in the study period (January 14-30, 2008). The temporal profiles of observed and predicted tide level are compared in for the calibration period. As shown in Fig. 7 and 8, the predicted tide levels reasonably matched the observed data at two sampling stations: *Teluk Sengat* and *Tanjung Surat*. These figures indicate that the model reasonably simulated the tide range and phase at a number of locations throughout Sungai Johor estuary. The simulated water level showed a good and fairly good agreement with observations, indicated by the low values of root mean square as shown in Fig. 7 and 8 respectively. Bottom roughness is very sensitive to water surface elevation at upper Sungai Johor and insensitive to lower Sungai Johor

Temperature is the hydrodynamic parameter with the least calibration. The temperature data is used at *Tanjung Pengelih* for the downstream boundary. The pattern of water temperature along Sungai Johor is observed from *Tanjung Pengelih* to *Johor Lama (*see fig. 9*)*. The simulated water temperature showed good and fairly good agreement with observations, as indicated by the low values of root mean square. The simulated water temperature is also compared with DOE marine water quality data at Station SJ1, SJ2, SJ4 and SJ4A.

The salinity distribution reflects the combined results of all processes, and in turn it controls density circulation and modifies mixing processes. Based on the error analysis as shown in Table 1, the model is under predicted in response to the natural system at Station *Tanjung Surat.* This might be due to the errors in the bathymetry data or the errors associated to the prescribed boundary conditions as stated [26,27]. The model reproduced seasonal trends (see Fig. 10) of measured salinity for the Sungai Johor estuarine system. Fig. 11 presents the longitudinal comparison of the simulated salinity against the DOE marine water quality monitoring data at SJ1, SJ2, SJ4 and SJ4A stations. The calibration run is made with the horizontal eddy viscosity at 25 m^2/s. This parameter was varied from 0.005 m^2/s to 75 m^2/s. The model is run for the worse case scenario during the flood event at *Kota Tinggi* in January 2007. The freshwater inflows from upstream boundary at *Rantau Panjang* have significantly changed the salinity concentrations at upper Sungai Johor estuarine system. The downstream salinity boundary was increased by 1 *ppt* and 2 *ppt* when the salinity boundary changed by 10% and 20% from the baseline run.

The measured values from the collected survey data were used for calibrating the EFDC water quality model. The data consists of dissolved oxygen, BOD, ammonia, other nutrients, and chlorophyll-*a concentrations*. Specifically, for the EFDC model calibration, dissolved oxygen concentration at Station Tanjung Surat is used. Predicted and measured DO concentration was compared at Station *Tanjung Surat* as presented in Fig. 12. To provide a quantitative assessment of the EFDC predictive capability, time series comparison underwent a simple statistical treatment. The DO calibration result shows that the response of the natural system of the DO concentration at Station Tanjung Surat was over predicted. The dissolved oxygen longitudinal profile along Sungai Johor as shown in Fig. 13 shows that DO concentration increased at upper Sungai Johor estuary and decreased at lower Sungai Johor estuary. A component analysis for DO indicated that, on average, the major source of DO was reaeration, algal production, while sinks included sediment oxygen demand (SOD) and respiration. The basic SOD value for the baseline run was 2.00 $g/m^2/day$. The variations of the parameter were 1.00 and 5.00 $g/m^2/day$ at Station Tanjung Surat as presented in Fig. 14 and while Fig. 15 shows that the DO concentration is moderately sensitive to changes in SOD along the Sungai Johor.

The basic COD decay rate for the baseline run was 0.10 *l/day*. The variations of the parameter were 0.04 and 0.40 *1/day* at Station Tanjung Surat and Teluk Sengat. With the same magnitude of variation in parameter values, the DO concentrations are sensitive to the COD decay rate (see Fig. 16a-16b)

Model prediction and simulation for ammonia nitrogen, Nitrate nitrogen and total Phosphate concentration are compared. The longitudinal profiles of simulated and observed values are shown in Fig. 17, 18 and 19. The predicted values are compared to the measured values from the sampling data in January 2008. The predicted values are within the range of observed data. The basic nitrification rate for the baseline run was 0.07 *1/day*. The sensitivity of the instream DO concentrations to the nitrification rate was analyzed by changing the value of the parameter with 0.01 and 0.10 *1/day*. DO regime in Sungai Johor estuary is not sensitive to this parameter variation.

According to DHI Water and Environment (2004), Chlorophyll *a* measurements show relatively high values (15-20 *μg/l* for Malaysian rivers and 25-40 *μg/l* for Singapore rivers) which could be due to the growth of phytoplankton in the upstream freshwater system. The nutrient levels in the same rivers are also high mixing with marine-based Chlorophyll *a* from eutropied waters is also a possible factor for the high readings. Model simulation for Chlorophyll *a* concentration along Sungai Johor is shown in Fig. 20. As indicated, the Chlorophyll *a* concentration along Sungai Johor is affected by the change of maximum algal growth rate. The basic maximum algal growth rate value for the baseline run was 2.00 *1 /day*. The variations of the parameter were 1.00 and 3.00 $g/m^2/day$. The sensitivity of DO concentration to the pollutant loads from the point sources was analyzed by changing the load of NH3-N, NO3-N, PO4, COD and DOC from the dischargers. DO concentration is sensitive to changing loads from point sources.
The effect of reaeration rate on DO distribution was analyzed by changing the value of the reaeration rate with factors of 1.00 and 3.00. Fig. 21 shows plots for the relative sensitivity of DO to the reaeration rate constant by distance from downstream boundary at *Tanjung Pengelih*. It is observed that the DO concentration is moderately sensitive to the reaeration rate coefficient.

4 CONCLUSIONS

A numerical model has been applied to study the hydrodynamic and water quality characteristics of estuary. The model was successfully applied to Sungai Johor estuarine system. Sensitivity analysis method was used in this study to identify the sensitivity of EFDC hydrodynamic and water quality parameters of the Sungai Johor model. With the available data and time constraints, reasonable results were obtained for hydrodynamic and water quality model calibration. Therefore, EFDC model proved to be quite effective in the hydrodynamic and water quality simulation of water surface elevation, water temperature, salinity, DO and nutrients concentration of Sungai Johor estuarine system. Model calibration was conducted using the field data obtained between January to June 2008 to compare the observed and simulated results using graphical comparisons, absolute mean errors, and RMSEs. There are fairly good reasonable agreement between computed and observed water level, salinity, water temperature. The water quality parameters follow the same pattern of prediction.
Coupling of the water quality model with a sediment transport model and a sediment diagenesis model is important in predicting the nutrient movement, particularly for phosphate and sediment nutrient exchanges. The mechanisms that appear to be of significant include the absorption of phosphate to sediment particles and subsequent settling, transportation of sediment in response to high freshwater flow and the release of sediment phosphate. The current calibration of the water quality model has a shortcoming in the prediction of nutrients. It was not because of the model but because of the quality and quantity of the field data used for the current calibration.

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