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Calibration of Hydrodynamic Modeling in Western Part of Johor Strait, Malaysia

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ABSTRACT: The Johor Strait is an estuarine system located on the coast of the state of Johor in Malaysia. The Western Part of Johor Strait is a shallow estuarine located between Causeway and Pulai River. A hydrodynamic model was calibrated based on the Environmental Fluid Dynamic Code (EFDC) from 4th to 17th of October, 2009. In this calibration, the EFDC hydrodynamic model was configured to simulate time series surface water elevation, velocity, and salinity. The model grid consisted of 2310 grid cells in the horizontal direction and four vertical layers. The model reasonably simulated the tidal range. The simulated velocity showed good agreement with observations data. The predicted salinity model Salinity compared the surface layer with observed data. Results of model showed that changes of salinity from surface to depth were uniform and this condition implied rapid vertical mixing of the water in the system. The calibration model can be used for water quality and sediment modeling and for studying water age modeling.

Key words: Hydrodynamic, EFDC, Salinity, Johor Strait, three-dimensional

INTRODUCTION

Estuaries are highly variable in biological, physical, and chemical properties (Yang *et al.,* 2013; Sravanthy *et al.,* 2013; Gholamalifard *et al.,* 2013; Sadatipour *et al.,* 2012; Piccini *et al.,* 2012; Pillay and Pillaym 2013; Tisseuil *et al.,* 2013). Freshwater inflows and tides are the two main external forcing mechanisms that control estuarine processes. The tides produce periodic landward and seaward transport, while the freshwater inflows lead to a net seaward transport. The freshwater tends to float on denser seawater, but tidal mixing reduces this stratification. The hydrodynamic response of an estuary to variations in freshwater inflow depends on the specification of the estuary. The time scale of the response is often illustrated by the flushing time of the estuary (Ji, Hu, Shen, *et al.,* 2007). Estuary stratification and non-stratification are a well-known phenomenon. The level of stratification in the water column is crucial in governing the intensity of vertical mixing and the vertical fluxes of water properties (Prandle, 2004) . The stratification plays an essential role on nutrient transportation in estuaries. Understanding the development and breakdown of layered in shallow estuaries will provide better understanding of the dynamical process of the estuary and its impact on living resources. In a partially layered estuary, estuarine layered–mixing process is often controlled by its spring-neap tidal cycles (Haas, 1977) . The intensity of layered depends on the buoyancy input and the mixing produced by wind stirrings and tides. Studies of estuarine layered showed that the freshwater buoyancy input is one of the most influential mechanisms of estuary circulation (Schroeder, Dinnel and Wiseman, 1990, Simpson, Brown, Matthews, *et al.,* 1990).

The EFDC is one of the most widely used the hydrodynamic models and has been tested in more than 60 modeling researches(Ji, Morton and Hamrick, 2001). The EFDC modeling has been successfully applied to simulate the hydrodynamics in lakes (Jin, Hamrick, and Tisdale, 2000, Seo, Sigdel, Kwon, *et al.,* 2010), rivers (Jiang, Shen and Wang, 2009), reservoir, harbors (Liu, X., Kabiling and Bratos, 2013, Tetra Tece, 2004, Zhang, You and Liu, 2013), wetlands , coastal seas(Xia, Craig, Wallen, *et al.,* 2011), and estuaries (Liu, X., 2007, Xu, Lin and Wang, 2008, Camacho and

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Martin 2013). The majority of EFDC applications has been carried out in estuaries (Moustafa and Hamrick, 2000, Shen and Kuo, 1999, Wool, Davie and Rodriguez, 2003).Zarillo (1998) developed a three dimensional hydrodynamic and transportation model to the Indian River Lagoon. Huang et al (2002) examined wind effects on sub tidal salinity in Apalachicola Bay. Huang (2007) applied a three dimensional hydrodynamic model to St. Andrews Bay to evaluate residence time in response to freshwater inflows. Liu et al. (2007) developed the hydrodynamic modeling and watershed using EFDC and HSPE on St. Louis Bay estuary. Huang et al. (2008) applied a three dimensional hydrodynamic model to Little Manatee River estuary. Jiang et al. (2009) investigated salinity layered in the Oujiang River estuary. In recent years, scholars to support estuarine water resource management have increasingly used the hydrodynamic modeling. A calibrated and verified the hydrodynamic model has established a correlation relationship between estuarine salinity variations and forcing functions such as tide, wind speed and direction, and river flow. Comparing with the studies on large estuarine systems, such as the San Francisco Bay and Chesapeak Bay, the processes of stratification and transportation in shallow areas and small estuaries is rather less studied. The purpose this study is the calibration of a hydrodynamic model through field observations to quantify the mixing and transportation processes in the system under tides, wind, and freshwater inflows. The model calibration was conducted using tidal elevation, velocity measurements and salinity.

MATERIALS & METHODS

The Johor Strait is an estuarine system located on the coast of the state of Johor in Malaysia. Johor Strait separates the Peninsular Malaysia to the north from Singapore Island to the south, and it lies between the Johor River estuary to the east and the Pulai River estuary to the west with a distance of about 53 km. The major river catchments which carry out into the Johor Strait include five rivers with their river tributaries. These rivers include the order catchments area of Johor River, Layang River, Tebrau River, Skudai River and Pulai River 51,372 Ha, 2,453 Ha, 24,877 Ha, 31,667 Ha, 31,124 Ha, respectively. Causeway has divided this strait which is linking mainland Malaysia to Island of Singapore into Western Strait and Eastern Strait of Johor. The Eastern part of the Johor Strait is located between Causeway and The Johor River estuary to a distance of about 20 km and the Western Part of Johor Strait is located between Causeway and Pulai River estuary to a distance of 33 km with a minimum width of 632 m and a maximum width of 12440m in the close estuary of Pulai (Fig. 1).

Fig. 1. Study Area

The Environmental Fluid Dynamic Code (EFDC) (Hamrick, 1992), solves the three dimensional, vertically hydrostatic and turbulent averaged equations of fluid motion in a fluid with variable density. Sigma vertical coordinates or stretched and curvilinear, orthogonal horizontal coordinates are used in the model. The code is a public domain and open source system that also includes modules of water quality and sediment transportation.

The equations of motion solved by the EFDC are derived from a vertical stretch domain that satisfies the relation given by:

$$z = \frac{(z^* + h)}{(\varsigma + h)} \tag{1}$$

Where z^* denotes the original physical vertical coordinates and $-h$ and ς are the coordinates of the bottom topography and the water surface respectively. The momentum equations using the Boussinesq approximation, and the continuity equation derived from this system are given by:

The density of fluid ρ is computed as a function of pressure, salinity, and temperature by an equation of state given by $\rho = f(p, S, T)$, while the transport of salinity and temperature is computed by the following equations:

In the above equations, the total depth $H = h + \varsigma$ at any point in the domain is computed as the sum of the depth below and the free surface displacement relative to the original physical vertical coordinate origin $z^* = 0$. u and v represent the horizontal velocity components in the curvilinear orthogonal coordinates, m_x and m_y are the square roots of the diagonal components of the metric tensor and $m = m_x m_y$ is the Jacobian or square root of the metric tensor determinant. The pressure p is the physical pressure in excess of the reference density hydrostatic pressure, $\rho_0 gH(1-z)$, is

$$\frac{\partial(mH_u)}{\partial t}+\frac{\partial(m_yH_{uu})}{\partial x}+\frac{\partial(m_xH_{vu})}{\partial y}+\frac{\partial(mwu)}{\partial z}-(mf+v\frac{\partial m_x}{\partial x}-u\frac{\partial m_x}{\partial y})H_v=-m_yH\frac{\partial(g\varsigma+p)}{\partial x}-m_y(\frac{\partial h}{\partial x}-z\frac{\partial H}{\partial x})\frac{\partial p}{\partial z}$$
$$\frac{\partial}{\partial z}(m\frac{1}{H}A_v\frac{\partial u}{\partial z})+Q_u \qquad (2)$$

$$\frac{\partial(mH_v)}{\partial t}+\frac{\partial(m_yH_{uv})}{\partial x}+\frac{\partial(m_xH_{vv})}{\partial y}+\frac{\partial(mwv)}{\partial z}-(mf+v\frac{\partial m_y}{\partial x}-u\frac{\partial m_x}{\partial x})H_u=-m_xH\frac{\partial(g\varsigma+p)}{\partial y}-m_x(\frac{\partial h}{\partial y}-z\frac{\partial H}{\partial y})\frac{\partial p}{\partial z}+$$

$$\frac{\partial}{\partial z}(m\frac{1}{H}A_v\frac{\partial v}{\partial z})+Q_v \qquad (3)$$

$$\frac{\partial p}{\partial z}=-gH\frac{(\rho-\rho_0)}{\rho_0}=-gHb \qquad (4)$$

$$\frac{\partial(m\varsigma)}{\partial t}+\frac{\partial(m_yH_u)}{\partial x}+\frac{\partial(m_xH_v)}{\partial y}+\frac{\partial(mw)}{\partial z}=0 \qquad (5)$$

$$\frac{\partial(m\varsigma)}{\partial t}+\frac{\partial(m_yH\int_0^1 udz)}{\partial z}+\frac{\partial(m_xH\int_0^1 vdz)}{\partial y}=0 \qquad (6)$$

$$\frac{\partial mHS}{\partial t}+\frac{\partial(m_yH_uS)}{\partial x}+\frac{\partial(m_xH_vS)}{\partial y}+\frac{\partial(mwS)}{\partial z}=\frac{\partial}{\partial z}(m\frac{1}{H}A_b\frac{\partial S}{\partial z})+Q_s \qquad (7)$$

$$\frac{\partial mHT}{\partial t}+\frac{\partial(m_yH_uT)}{\partial x}+\frac{\partial(m_xH_vT)}{\partial y}+\frac{\partial(mwT)}{\partial z}=\frac{\partial}{\partial z}(m\frac{1}{H}A_b\frac{\partial T}{\partial z})+Q_T \qquad (8)$$

divided by the reference density ρ_0. f is the Coriolis parameter. A_v is the vertical turbulent or eddy viscosity, and Q_u and Q_v are momentum source-sink terms. The buoyancy b is the normalized deviation of the density from the reference value. Q_S and Q_T are source and sink terms in the equations of transport of salinity and temperature respectively, and finally A_b is the vertical turbulent diffusivity.

EFDC uses a second order accurate spatial finite difference on a staggered or C grid to solve the equations of motion. Additionally, the model uses a second order accurate three-time-level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear or baroclinic mode of the external free surface gravity wave or barotropic mode(Hamrick, 1992).

The bathymetry data used in the hydrodynamic models was the combination of surveyed data and digitized data. The bathymetry surveys in the rivers were conducted in 2002 and 2005. The bathymetry data in the Strait of Johor has been digitized from navigation maps that the Royal Malaysian Navy published it in 1999.

The atmospheric forcing factors considered in this EFDC model included air temperature, Wind speed and direction, solar radiation, and atmospheric pressure. These data was obtained from " www.underground.com " Website at the meteorological station of Senai Airport.

Universiti Technologi Malaysia (UTM) and Clean Water Noor (CWNE) carried out the data collection work at in October 2009**.** The data were collected from the 4st to the 17th of October and consisted of flow, water level, current and salinity data. Table 1 shows the locations for where the data was collected. Water levels were measured at Perling Bridge, JB Waterfront, Lido and Nusajaya stations. Salinity data was recorded simultaneously at an interval of 10 minutes over 12 days in YSI stations (Table 1). Salinity was measured every 1m in 13 stations of vertical profiling in 6 days (Table 1).

Current data was measured by NAHRIM for both speed and direction using Acoustic Doppler Current Profilers (ADCP) at two locations, ADCP1 and ADCP2 (Table 1). These sites were selected for the deployment of the instruments based on conditions such as: appropriate distance from the navigation channel; bottom conditions suitable for the frame to be stabilized for recording data. Current data was recorded

Table 1. Location of stations

KIND OF STATION	ID	X	Y	KIND OF STATION	ID	X	Y
CURENT	ADCP1	355901.5	164344.8	**VERTICAL PROFLNG**	WQ04	357173.1	162600.4
	ADCP2	357677.6	163027.2		WQ05	357809.5	162059.6
WATER LEVEL	PERLING BRIADGE	353596.2	165849.5		WQ06	359580	161146.5
	JB WATERFRONT	362148	160638.3		WQ07	362216.1	160564.6
	LIDO	357677.6	163027.2		WQ08	356662.3	161157.3
	RINTING	355462.1	164754.3		WQ09	355293	160918.6
YSI	NUSAJAYA	350917	156192		WQ10	353072.4	158604.2
VERTICAL PROFLNG	WQ01	355462.1	164754.3		WQ11	352036.2	157229
	WQ02	355798.6	164075.3		WQ12	350211.2	154724
	WQ03	357037.5	163254.6		WQ13	350006.9	154275.7

simultaneously at an interval of 10 minutes over 12 days.

Data of flow discharge was collected daily at three stations. These stations include Skudai River at PUB, Danga at Masjid Bukit Indah, and Tebing Runtuh on the Melayu River. Fig. 2 provides the time series of daily measured flow at these stations. From this figure, flow discharges at PUB and Masjid Bukit Indah are significant with the peak flows reaching 2.7m³/s and 3.8m³/s during the observation period at PUB and Masjid Bukit Indah, respectively, while flow discharge at Tebing Runtuh is quite small.

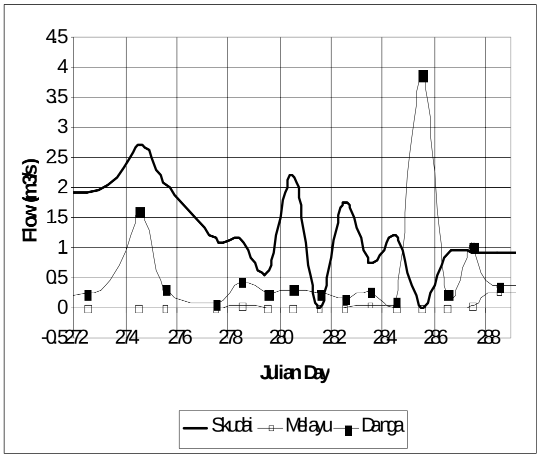

Fig. 2. Daily flow data at stations

The Western Part of Johor Strait is bounded by a complex shoreline with shallow areas. The curvilinear orthogonal grid was created with using the Delft3D package to present the complex geometry of the Western Part of Johor Strait. The model grid consists of 2310 grid cells in the horizontal direction, with grid size ranging from 20 m in rivers and up 350 m in the Strait. The model has four vertical layers (Fig. 3). For hydrodynamic modelling, the external factors that have been taken into account include stream runoff from tributaries, tidal forcing, wind speed and direction and atmospheric forcing. The hydrodynamic model was calibrated during 4th to 17th October, 2009.

Once the grid and bathymetry were determined, the boundary conditions were assigned to the appropriate grid cells based on the location and boundary condition type. The boundary types are ocean tidal forcing and inflows of water from rivers. A master input file directs the input time series to a specific cell within the model domain, and sets all time-related and space-related parameters. Fig.3 shows the EFDC model grid with the boundary conditions location identified and labelled by the boundary group. The causeway along the eastern edge of the model domain in the Strait of Johor was taken as a no-flow boundary.

RESULTS & DISCUSSION

The developed hydrodynamic model was forced by observed surface water elevation and salinity during 4th to 17th October, 2009 at open boundary. The observed and modeled water surface elevations have been analyzed using the pressure method. In calibrating the hydrodynamic model, the value of the bottom roughness height was adjusted to minimize the difference between the simulated and the observed data. A constant value of 0.02m has been used in the model for depth less than 3m and 0.005m for depth more than 3m.

The computed statistics for model calibration were mean observed, mean computed, mean error absolute,

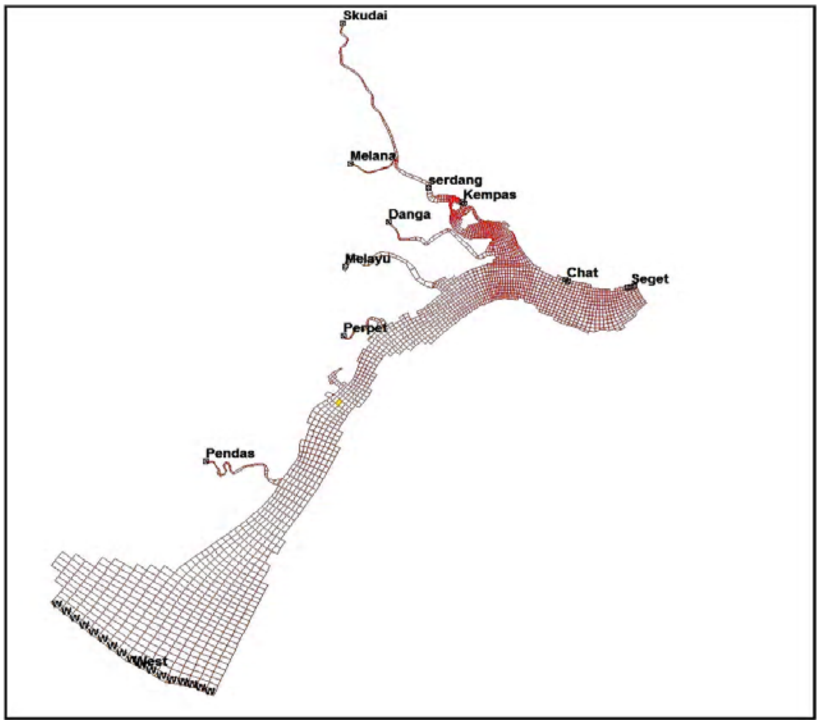

Fig. 3. Location of boundary condition in the EFDC hydrodynamic model

root mean square error absolute and relative root mean square error. The root mean squared error, average error, and average absolute error are all measurements of the size of the discrepancies between predicted and observed values. Values near zero indicate a close match. The average error is a measure of aggregate model bias, though values near zero can be misleading because negative and positive discrepancies can cancel each other. The average absolute error and the root mean squared error both accommodate the shortcoming of the average error by considering the magnitude rather than the direction of each discrepancy. Together these three statistics provide an indication of model predication accuracy (Stow, Roessler, Borsuk, *et al.,* 2003).

As it can be observed in Table 2. The root mean square errors for water level are 0.176, 0.199, 0.147, and 0.111 for Perling Bridge, JB Waterfront, Lido, and Nusajaya, respectively. According to guidelines for preparation of coastal engineering hydraulic studies and impact evaluation provided by Jabatan Pengairan Dan Saliran, Malaysia at 2001, the relative root mean square for n surface water levels shall not be more than 10% that for this model and are 5.765, 5.738, 4.268, and 3.313 in Perling Bridge, JB Waterfront, Lido, and Nusajaya, respectively. Generally, the model results for surface water level are in good agreement with the observations (Fig. 4).

Current measurement was carried out at two stations that were located within the model boundary in Skudai Revir, ADCP1 and ADCP2. Average error, the average absolute error, and root mean square error were close to zero. The results of model indicated that the velocity was in good agreement with observation. The relative root mean square errors are less than 30 for velocity and 45 for direction. The accuracy of velocity modeling depends on many factors, such as flow boundary conditions, wind data, the density gradient, temperature gradient, and so on. Skudai River is a very shallow estuary with water depth ranging from 0-6 m; hence, wind could have strong impacts on the velocity simulation, which has been substantiated by modeling verification tests.According, Table 2 Real RMS Error for velocity between minimum 13.45 to maximum 28.78. Fig. 5 shows variation of velocity in direction of X and Y ,velocity of magnitude in direction of XY and velocity direction for stations of ADCP 1 and ADCP 2. Generally, the model results for current are in good agreement with the observations.

The model calibration for salinity used observed data at three stations: Lido, Rinting and Nasajaya. The observed data typically was measured at 0.5 m below the surface and model results in the surface layer have been used in the model data comparisons. The statistics of model results against observations are listed in Table 2. Fig. 6 shows comparison of the

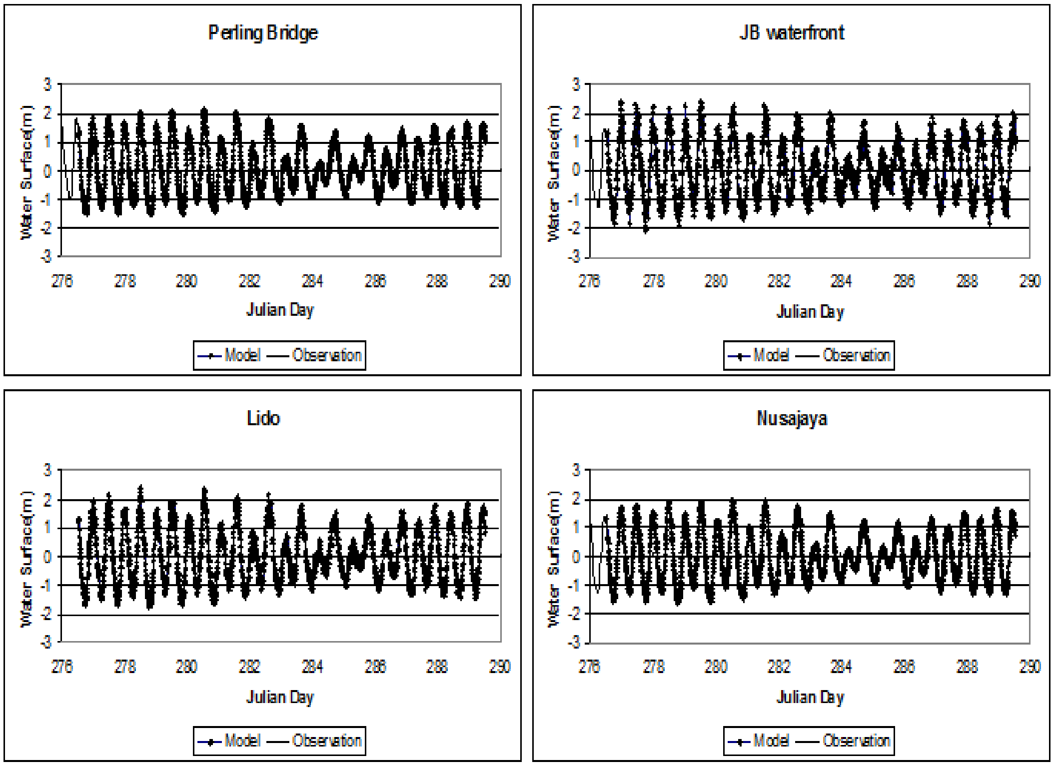

Fig. 4. Comparison of the predicted model and observed surface water level in stations

Table 2. Computed statistics for October, 2009

Parameters	Statistics	Number of observation	Mean predicted	mean observed	AE	AAE	RMSE	Rel. RMSE
Water Level	Perling Bridge	1737	0.124	0.198	-0.074	0.134	0.176	5.765
	JB Waterfront	1870	0.01	-0.012	0.022	0.158	0.199	5.738
	Lido	1870	0.011	0.09	-0.079	0.121	0.147	4.268
	Nusajaya	311	-0.001	0.002	-0.003	0.077	0.111	3.313
Vx	ADCP1	1049	-0.015	0.007	-0.022	0.052	0.068	13.458
	ADCP2	797	-0.007	0.035	-0.042	0.134	0.162	19.278
Vy	ADCP1	1033	0.039	-0.049	0.088	0.204	0.234	17.35
	ADCP2	797	0.018	0.003	0.015	0.09	0.108	14.772
Vmag.	ADCP1	1590	0.094	0.232	-0.138	0.161	0.205	18.105
	ADCP2	798	0.07	0.2	-0.13	0.136	0.166	28.78
Salinity	Rinting	1651	11.o12	13.961	-2.949	4.063	4.822	20.891
	Lido	1868	21.169	22.225	-1.056	2.163	2.553	17.067
	Nusajaya	1710	23.251	23.593	-0.343	1.895	2.2	20.891

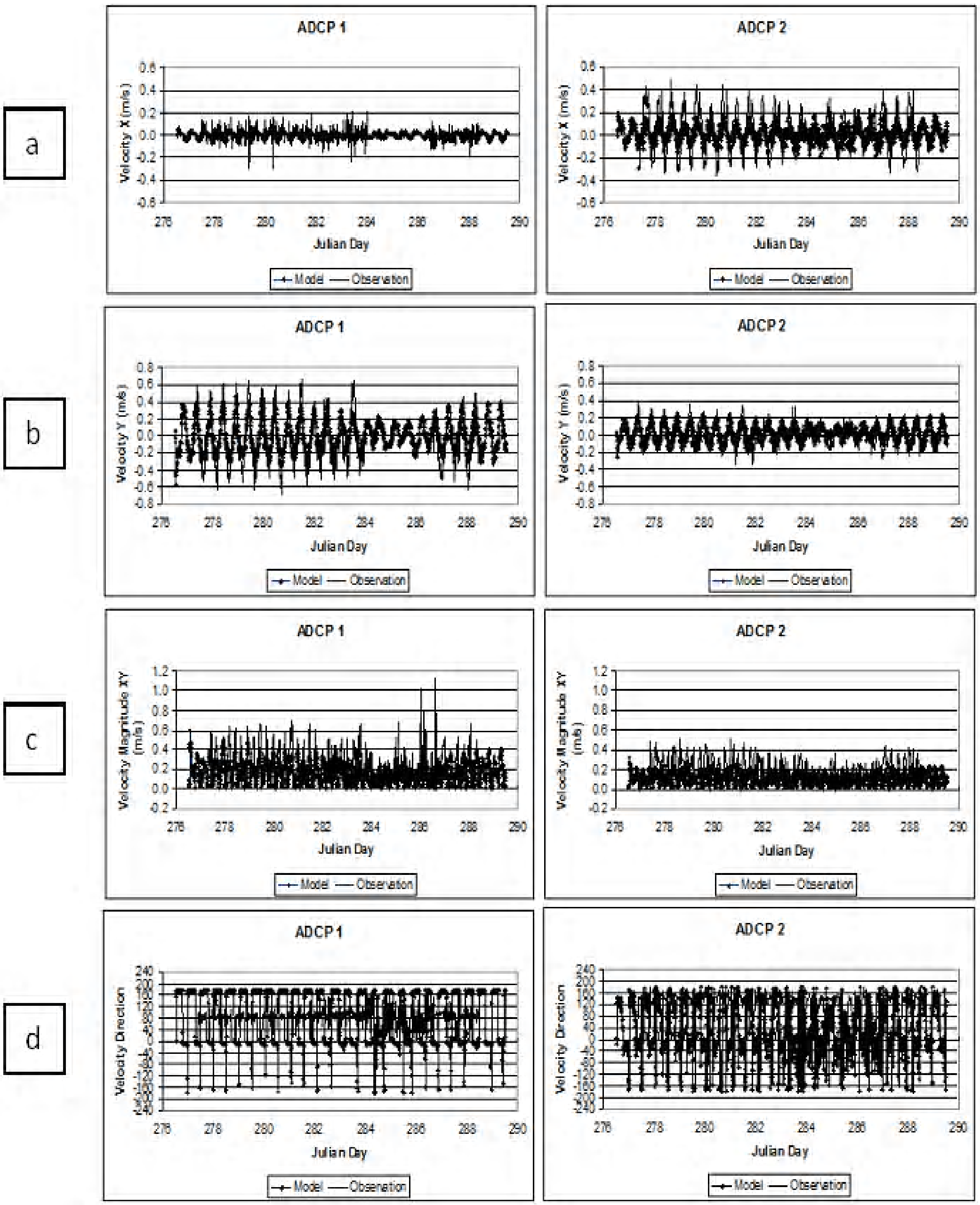

Fig. 5. Comparison of the predicted model and observed a)velocity in x direction, b) velocity in Y direction, c) magnitude velocity in XY direction, and d) direction of velocity at stations of ADCP1 and ADCP2

predicted model and observed salinity at stations. Changes of salinity in Rinting is between 0 to 22 ppt. Mean observed and mean predicted in this station is about 13.961 ppt and 11.012 ppt, respectively. According Table 2, Real RMS Error for salinity between 17.06 to 20.891.

Salinity was measured in every one meter in depth at on 5th , 7th , 8th , 10th , 12th , and 13th of October, 2009 to provide vertical profiling data in 13 stations (Table 1). Fig. 7 shows salinity stratification in depth in stations WQ05, WQ07, WQ11, and WQ12. The station of WQ05 is in estuary of Skudai River and WQ07 is near Causeway. The Calibration results showed that the model was generally able to simulate well vertical patterns of salinity between simulated values for vertical layers in October. Finally, Fig. 7 shows that salinity in direction of z direction (depth) was well-calibrated. Notice that the salinity was uniform from

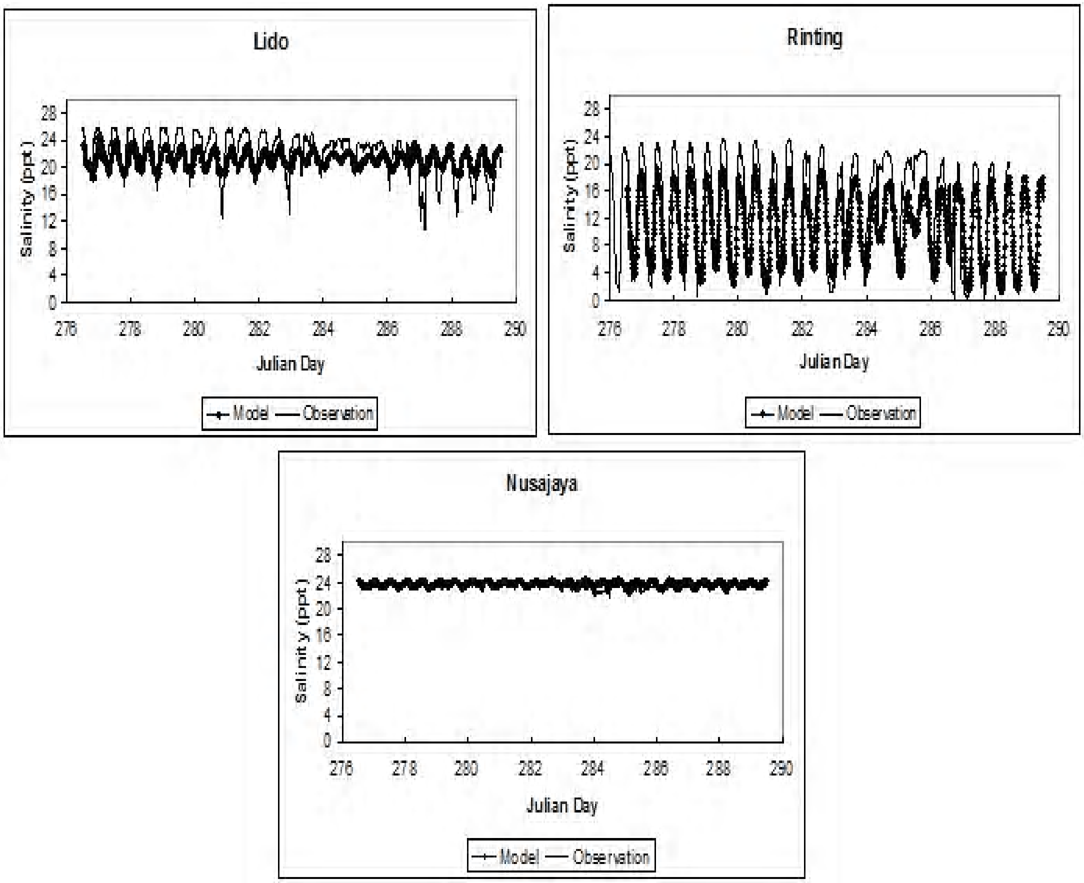

Fig. 6. Comparison of the predicted model and observed salinity at stations

surface to bottom depths. This condition implies rapid vertical mixing of the water in the system.

CONCLUSION

The three-dimensional model has been successfully calibrated to the Western Part of Johor Strait to characterize the salinity, surface water level and velocity. For model calibration used data in the period between 4th to 17th of October, 2009. The model parameters were adjusted until model predictions matched with observations.

Throughout understanding of the hydrodynamics of a tidal system is vital to environmental studies. Without a detailed description of how water moves through the system, any analysis of water quality issues would be incomplete. The model presented in this paper can be used as a tool for quantifying the hydrodynamic characteristics and examining the transport processes in shallow estuaries along with aiding further hydrodynamic and water quality studies and to guide field data collection programs.

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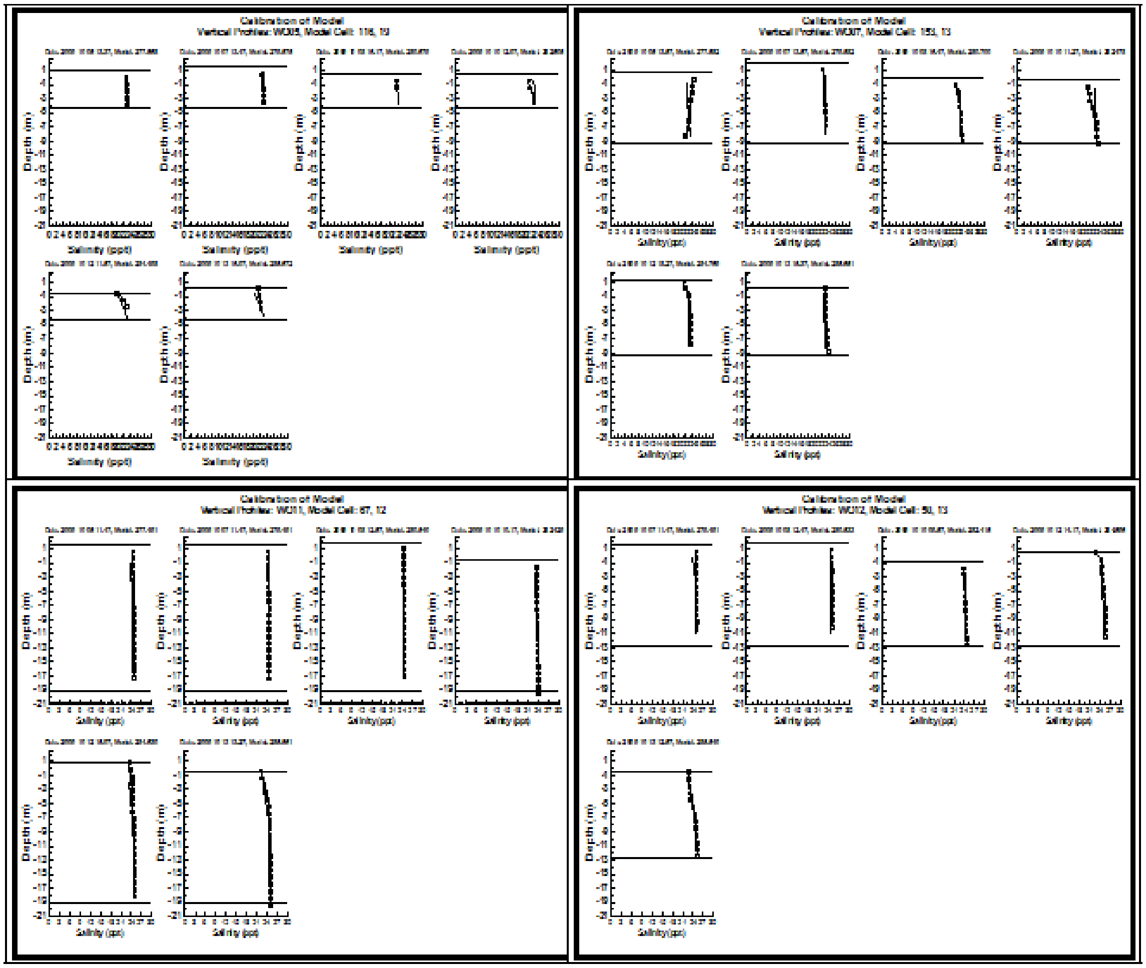

Fig. 7. Comparison of the predicted model and the observed vertical salinity profile in the station of WQ05

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