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# Hydrologic Models for Coastal Environments in the Context of *RACE*

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**Abstract.** This paper discusses the hydrodynamics in Selat Johor in the context of *Rapid Appraisals for Coastal Environment* (*RACE*). Computer simulations of Selat Johor using a simple model *ABADI* were compared with results from hydraulic models such as *DYNHYD5*, data from Admiralty Chart No.2586 (AC No.2586) and results from previous studies. Comparison results indicate that *ABADI* gives good approximations with approximately 20% of error. Thus the simple model *ABADI* can be used for the purpose of getting a fast and timely assessment of hydrodynamic conditions in the area of study which is of interest to the researchers in the context of *RACE*.

## 1. Introduction

Estuaries and coastline hydrodynamics such as those found in Selat Johor are fascinating, diverse and complex water system. The ebb and flow of tides, the salinity intrusion from the ocean and the influx of nutrients from upstream drainage all contribute to a unique aquatic ecosystem. Therefore a good understanding of the hydrodynamics of the water body is important as these water movements will affect greatly the water quality of such bodies of water.

Modeling hydrodynamics of water bodies using hydraulic models can be complicated. In developing countries like Malaysia and in the third world countries this could pose a problem as the use of these hydraulic models require levels of technological understanding and sophistication which may not be possible in traditional rural culture. In addition, it can be time consuming as it may take some time to be able to learn and use these models. Due to these reasons, a simple hydrologic model *ABADI* is developed in the context of *RACE* [8] so that the hydrodynamic conditions in coastal areas or estuaries can be assessed quickly with reliable results within a short time frame and without the need to acquire sophisticated technological knowledge of the hydraulic models.

Hence, it is the purpose of this paper to develop a simple model, *ABADI* in the context of *RACE*. It is hoped that *ABADI* will be able to be applied to solve problems such as those found in Selat Johor to obtain a quick preliminary assessment of the hydrodynamic conditions before further research are done using more complex tools.

## 2. *RACE*

*RACE* is an approach used to provide timely and reliable information for coastal environment in developing countries especially in rural areas where sophisticated technologies are not available. *RACE* is a concept that has its origin from *RRA (Rapid Rural Appraisal)*. *RRA* represents one particular combination of techniques for information collection and approaches to learning about rural conditions [9].

*RACE* uses a narrow set of explanatory indicators to pinpoint key issues and major problems found in the area under study for coastal environments. It also aims to provide timely and reliable information useful for coastal zone management plan [4,8]. However it should be emphasised that results from these studies are only suitable for initial assessment of the problem due to the narrow set of indicators used which may not reflect all actual detailed conditions. Further research using standard research methodology is necessary to provide a thorough and detailed study of the problem.

## 3. Mathematical model

There are broadly two types of models involved in modeling the hydrodynamics of the water bodies that is the hydraulic models and the hydrologic models. The use of hydraulic models such as *DYNHYD5* [1], explicit finite difference method [7] and finite element method [3] can be complicated technically and time consuming as these are complex formulations based upon both mass balance and momentum/energy principles. Hydraulic models cannot be solved analytically and require numerical methods for solutions. Hydrologic models are models that consist of simple formulations of mathematical equations based upon mass balance. The momentum/energy principles are approximated by other simple empirical formulations that are measurable [2,4]. Hence the remaining part of this chapter will describe the mathematical formulations used to develop *ABADI*.

The tidal hydrodynamics in this study is generally described by the two-dimensional depth averaged shallow water wave equation. This implies that pressure varies hydrostatically and horizontal velocities are uniform throughout the depth. The model consists of the mass balance continuity equation (1) that relates the inflow and outflow of the tidal motion to the change in storage within a small segment of the channel. The model also consists of approximations for the momentum/energy principles by other measurable empirical formulations such as the length and width of the channel and the tidal elevations as function of time.

Hence, the mass balance for *ABADI* at segment ⓘ (see Figure 1) implies

$$\frac{\partial Q}{\partial x} = -\frac{\partial A}{\partial t} \tag{1}$$

where $A$ = cross-sectional area, $m^2$
$Q$ = flow, $m^3/s$.

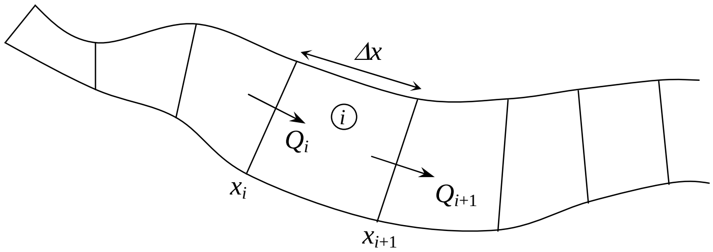


Figure 1. Mass balance at segment (i).

Equation (1) can be further modified to (2):

$$Q_{i+1} = Q_i - \frac{\partial A}{\partial t} \cdot \Delta x \tag{2}$$

where $\Delta x = x_{i+1} - x_i$ = segment length, m.

However, $A = W \cdot H$

where $W$ = segment width, m

$H$ = tidal height as a function of time, m

$x_i$ = distance, m

$t$ = time, s.

Hence,

$$Q_{i+1} = Q_i - W_i \frac{\partial H_i}{\partial t} \cdot \Delta x_i \tag{3}$$

and (3) can be written as

$$Q_j = Q_o - \sum_{i=1}^{j} f_i \tag{4}$$

where $f_i = W_i \frac{\partial H_i}{\partial t} \cdot \Delta x_i$, $Q_o$ = initial flow at $(x_o = 0,\ t = 0)$, and $Q_j$ = flow at segment $j$, $m^3/s$. Therefore the computer model is developed based on (4) with $H_i$, $W_i$, $\Delta x_i$ as input for tidal height, segment width and length and $\Delta t$ as input for time step. Verification of this model is done by comparing the results with the analytical solution.

Assuming that a progressive wave is moving along a channel with both ends open at velocity $u\ ms^{-1}$. The analytical solution which is the shallow water wave equation is a result of both the continuity and momentum principles. The continuity equation (1) can be rewritten as

$$W \frac{\partial h}{\partial t} = -\frac{\partial (uWH_o)}{\partial x} \tag{5}$$

where $h = H_o + \eta$

$h$ = tidal surface elevation, m

$H_o$ = mean depth, m

$\eta$ = instantaneous elevation from mean sea level, m.

Therefore from (5),

$$\frac{\partial \eta}{\partial t} + H_o \frac{\partial u}{\partial x} = 0 . \tag{6}$$

The momentum equation (7) is given by the local acceleration due to gravitational forces only with the assumption that there is no advection, frictions, wind stress and eddy viscosity for model simplicity

$$\frac{\partial u}{\partial t} = -g \frac{\partial h}{\partial x} . \tag{7}$$

Thus,

$$\frac{\partial u}{\partial t} + g \frac{\partial \eta}{\partial x} = 0 . \tag{8}$$

Solving (6) and (8) together will give (9) and (10) which is the analytical solution for the shallow water wave equation for a progressive wave propagation

$$\eta = a \cos(\sigma t - kx) \tag{9}$$

$$u = \sqrt{\frac{g}{H_o}}\, a \cos(\sigma t - kx) \tag{10}$$

where $a =$ tidal amplitude, m
$\sigma =$ frequency, $s^{-1}$
$k =$ wave number, $m^{-1}$
$t =$ time, s
$x =$ distance, m
$u =$ tidal velocity, $ms^{-1}$
$g =$ gravitational acceleration, $ms^{-2}$
$H_o =$ mean depth, m

and $k = \frac{\sigma}{\sqrt{gH_o}}$, $\sigma = \frac{2\pi}{T}$ where $T =$ tidal period, hour .

Hence, (9) and (10) are analytical solutions for progressive wave with no friction.

With the assumptions that one end of the channel is closed and a complete reflection of the wave moving along the channel with velocity $u$ $ms^{-1}$ occurs in the channel, we will obtain (11) and (12). Thus, (11) and (12) are the results of two progressive waves of equal amplitude $a_o$ and period $T$ superimposed with one another, one travelling in the positive and one travelling in the negative direction. The result is a standing wave propagation with an amplitude of $2a_o$, which will be applied to the case of Selat Johor. The reasons for choosing these two equations as the analytical solutions in Selat Johor will be explained in Input Parameters.

$$\eta = \frac{a}{\cos k\ell} \cos \sigma t \cos kx \tag{11}$$

and

$$u = \sqrt{\frac{g}{H_o}} \frac{a}{\cos k\ell} \sin \sigma t \sin kx \tag{12}$$

where $\ell$ = length of channel, m.

## 4. Input parameters

This section discusses briefly some important parameters required as input for *ABADI* as mentioned previously to simulate the tidal hydrodynamics, with particular reference to the tidal hydrodynamics of Selat Johor. Hydrology data were obtained from AC No.2586 (Admiralty Chart No.2586). *ABADI* requires as its input parameters the length, $\Delta x_i$ and width, $W_i$ of the segments as well as the tidal elevations (tidal heights), $H_i$ as a function of time. In *ABADI*, the tidal elevation, $H_i$ is an input at each time step and it is assumed that the water level, $H_i$ throughout the channel is interpolated from known measured values. This assumption is valid for shallow water wave equation where the wave length is long compared to the depth of the channel. The water levels at both ends of the channel do not differ much as the water level changes very slowly and slightly throughout the whole channel.

Selat Johor (Figure 2) is located around latitude $1^\circ 26' \mathrm{N}$ and from longitude $103^\circ 35' \mathrm{E}$ to longitude $104^\circ \mathrm{E}$. It has a length of over 50 km with the eastern and western part of the strait separated by the Causeway. Since the end of the Causeway is closed due to the shutting of the balancing culverts across the Causeway, the normal flow at the Causeway's end is zero, resulting in a standing wave propagation [3]. The tidal regimes in Selat Johor are influenced by the astronomical tide that is predominantly semidiurnal, with tidal period of 12.42 hours. The stretch of Selat Johor under study, which is the eastern part, has a width that varies from 0.9 km to 1.2 km and a length of approximately 19 km from the Causeway to Punggol. Eastern Selat Johor has a mean depth of 10 m. The tidal elevations for spring tide ranges from 0.4 m to 2.7 m and for neap tide ranges from 1.0 m to 2.0 m. The tidal elevation for both spring and neap tides were used as input for simulations in *ABADI*. Simulations using time steps of 15 minutes and one hour were also carried out.

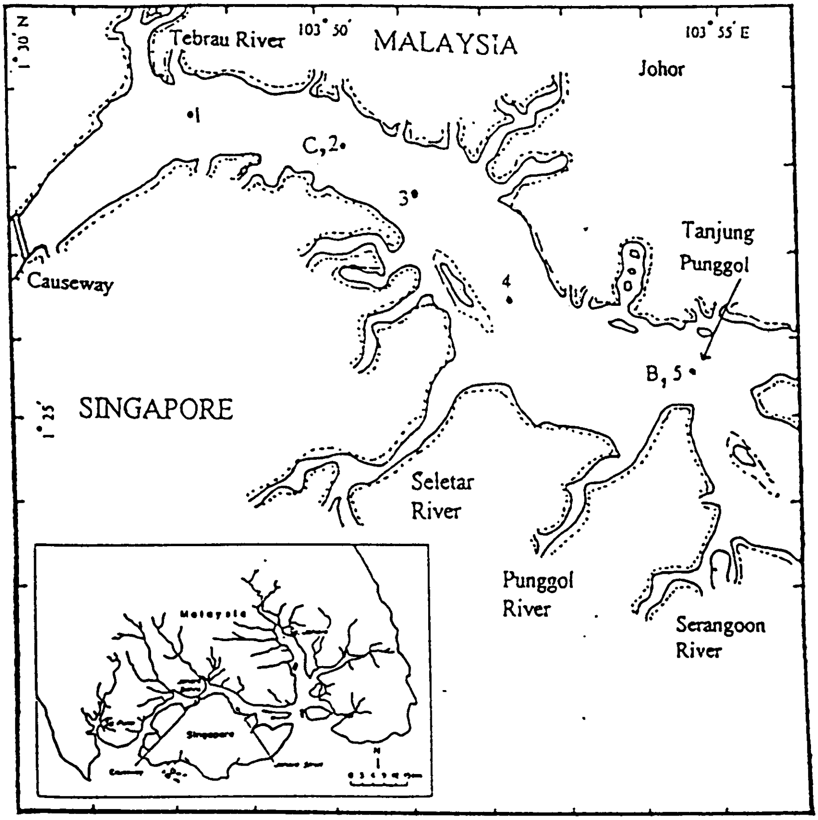


Figure 2. Location map of Selat Johor and Stations 1-5.

Simulations were carried out at five positions. The positions of these stations are as given (see Figure 2):

(a) Derman Shoal denoted as Station 1;
(b) Sembawang Shipyard denoted as Station 2 (or Station C as in AC No.2586);
(c) Lavis Buoy denoted as Station 3;
(d) Near Seletar river mouth denoted as Station 4; and
(e) Punggol denoted as Station 5 (or Station B as in AC No.2586).

## 5. Simulation results

The simulation results for *ABADI* are as shown in Figures 3-10. Table 1 is taken from AC No.2586 on tidal velocities and directions during spring tide (Sp) and neap tide (Np) at two stations, that is Punggol (Station B or Station 5) and Sembawang Shipyard (Station C or Station 2) at Selat Johor. Figures 3 and 4 give the tidal patterns at both stations according to AC No.2586.

Figure 5 is a comparison between tidal velocities simulated using *ABADI* and those from AC No.2586 during spring tide at Sembawang Shipyard (Station 2) while Figure 6 is a comparison between simulation from *ABADI* and velocities during spring and neap tides from AC No.2586 at Punggol (Station 5). Comparison from Figure 5 shows that simulation from *ABADI* gives good agreement for spring tide at Station 2. For Figure 6, comparison between *ABADI*'s neap tide and neap tide at Station 5 from AC No.2586 shows large difference. The same result is observed for spring tide. This may probably be due to the bottleneck effects at Punggol, which *ABADI* did not take into considerations in order to keep the model simplicity.

Figures 7 and 8 are simulation results from *ABADI* using different time steps. Velocities are simulated at every 15 minutes and at every 1 hour. These simulation results were then compared with the analytical solutions. Results show that simulations at smaller time steps are more accurate but longer simulation time required.

Table 1. Tidal streams referred to highwater (HW) at Singapore.

| | Hours | Station B | | | Station C | | |
|---|---|---|---|---|---|---|---|
| | | Direction | Rate (m/s) | | Direction | Rate (m/s) | |
| | | | Sp | Np | | Sp | Np |
| Before HW | 6 | 312 | -0.10 | -0.05 | *Slack* | *Slack* | *Slack* |
| | 5 | 277 | -0.36 | -0.21 | 280 | -0.05 | -0.05 |
| | 4 | 267 | -0.51 | -0.26 | 284 | -0.10 | -0.05 |
| | 3 | 267 | -0.67 | -0.36 | 284 | -0.15 | -0.10 |
| | 2 | 277 | -0.82 | -0.46 | 293 | -0.15 | -0.10 |
| | 1 | 277 | -0.72 | -0.41 | 297 | -0.10 | -0.05 |
| | HW | 275 | -0.21 | -0.10 | *Slack* | *Slack* | *Slack* |
| After HW | 1 | 91 | 0.15 | 0.10 | 90 | 0.10 | 0.05 |
| | 2 | 100 | 0.77 | 0.41 | 96 | 0.15 | 0.05 |
| | 3 | 97 | 0.82 | 0.46 | 101 | 0.21 | 0.10 |
| | 4 | 92 | 0.82 | 0.41 | 114 | 0.21 | 0.10 |
| | 5 | 90 | 0.57 | 0.26 | 122 | 0.10 | 0.05 |
| | 6 | 52 | 0.10 | 0.05 | *Slack* | *Slack* | *Slack* |

Table adapted from Admiralty Chart No.2586 (AC No.2586).

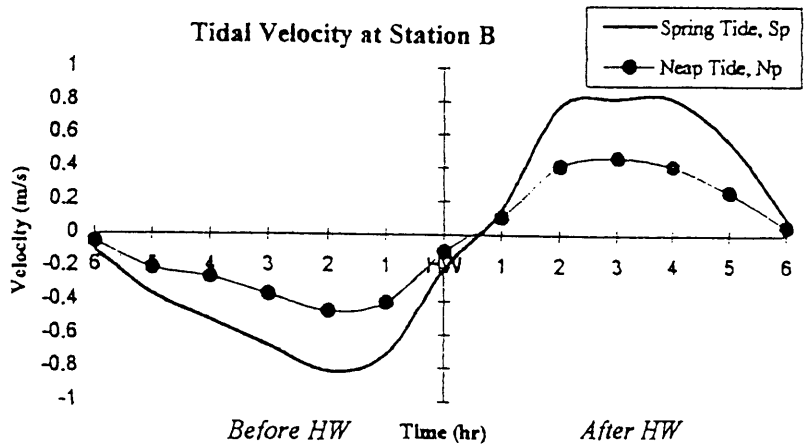


Figure 3. Tidal velocity patterns during spring and neap tide at Station B, Punggol, Selat Johor from AC No.2586.

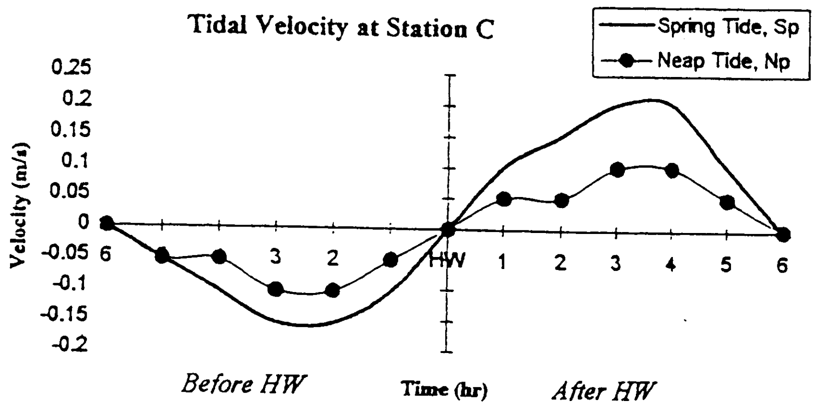


Figure 4. Tidal velocity patterns during spring and neap tide at Station C, Sembawang Shipyard, Selat Johor from AC No.2586.

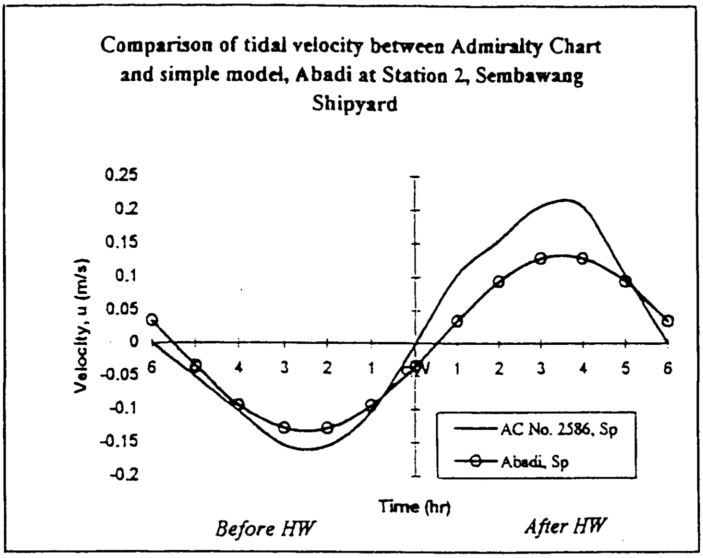


Figure 5. Comparison between tidal velocities simulated using simple hydrologic model, *ABADI* and AC No.2586 at Station 2, Sembawang Shipyard, Selat Johor.

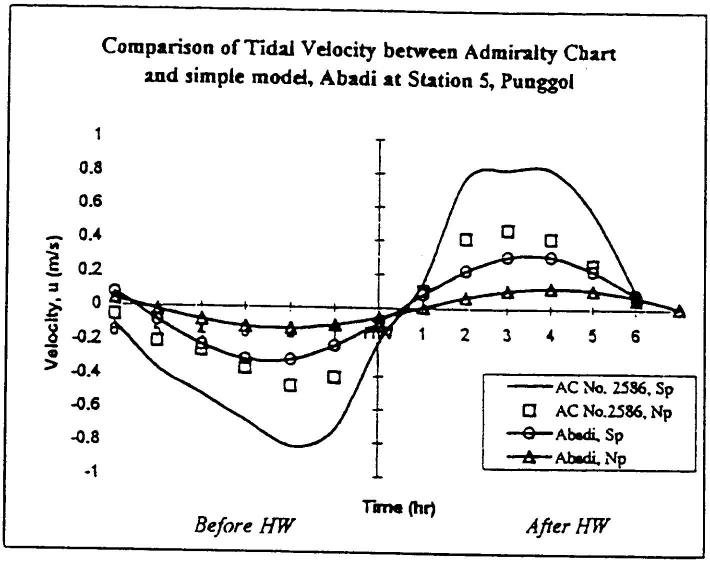


Figure 6. Comparison between tidal velocities simulated using simple hydrologic model, *ABADI* and AC No.2586 at Station 5, Punggol, Selat Johor.

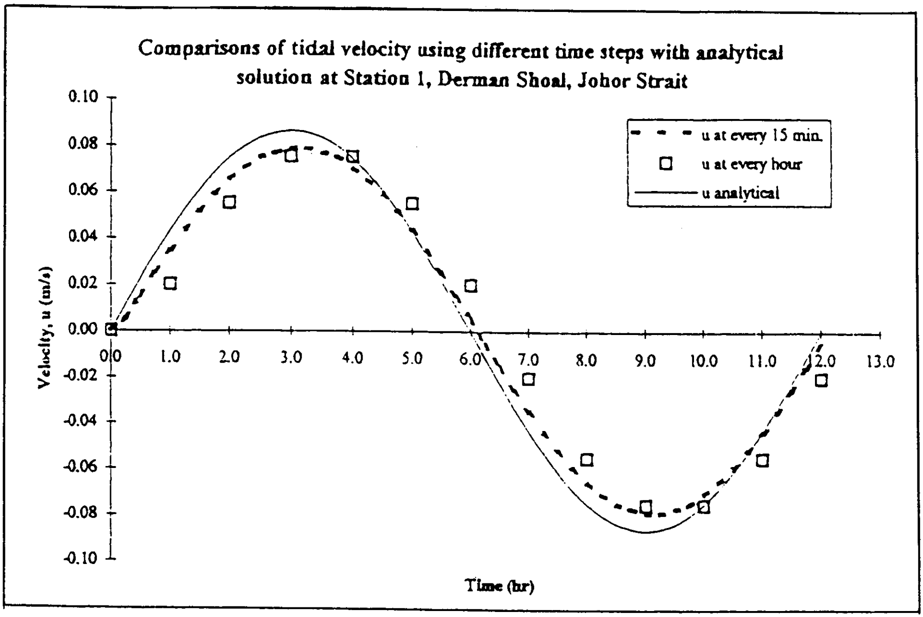


Figure 7. Comparisons of tidal velocity using different time steps with analytical solution at Station 1, Derman Shoal, Selat Johor.

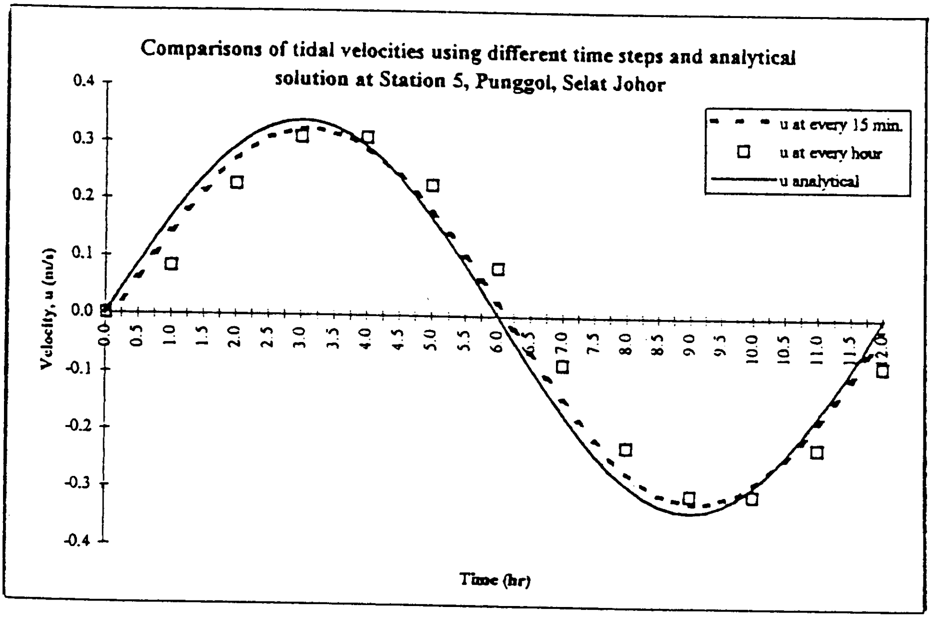


Figure 8. Comparisons of tidal velocity using different time steps with analytical solution at Station 5, Punggol, Selat Johor.

Figures 9 and 10 are comparison results between *ABADI*, a hydraulic model (*DYNHYD5*) and the analytical solutions at Station 2 and Station 5 respectively. Again results show that *ABADI* shows an accuracy with error of approximately 20% against results from the hydraulic model. A comparison between *DYNHYD5* with the analytical solutions shows approximately 5% error from analytical solution. From these comparisons it is quite clear that the larger error from *ABADI* as compared to *DYNHYD5* is due to the approximations of the momentum principles by measurable empirical formulations. In *ABADI*, the flow at each segment is given by the initial flow at the first segment and the total changes of flow at each subsequent segment due to changes in width, length and tidal elevation, $H_i$ at time $t$ of each segment. It is through these empirical formulations of the flow that the momentum principles are approximated.

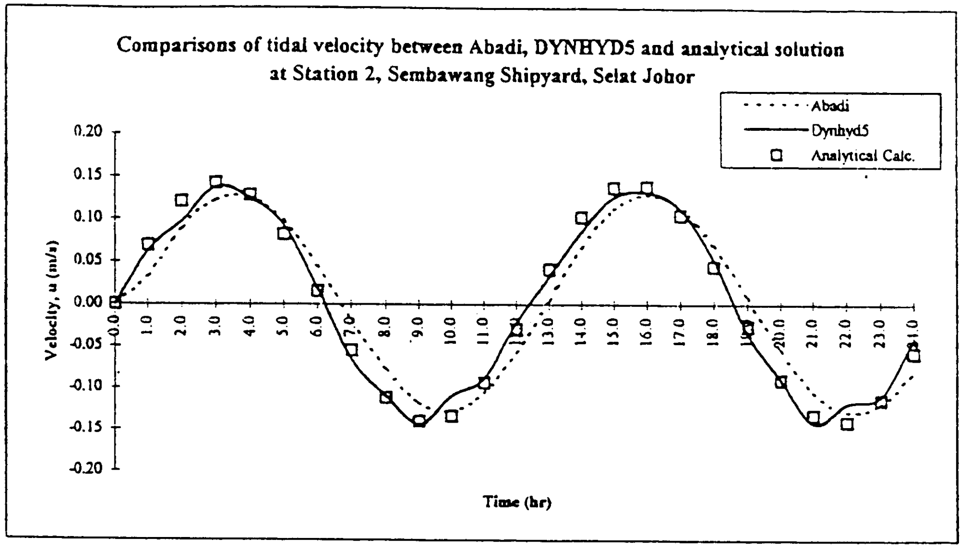


Figure 9. Simulations of tidal velocity at Station 1, Selat Johor using *ABADI*, *DYNHYD5* and analytical solution.

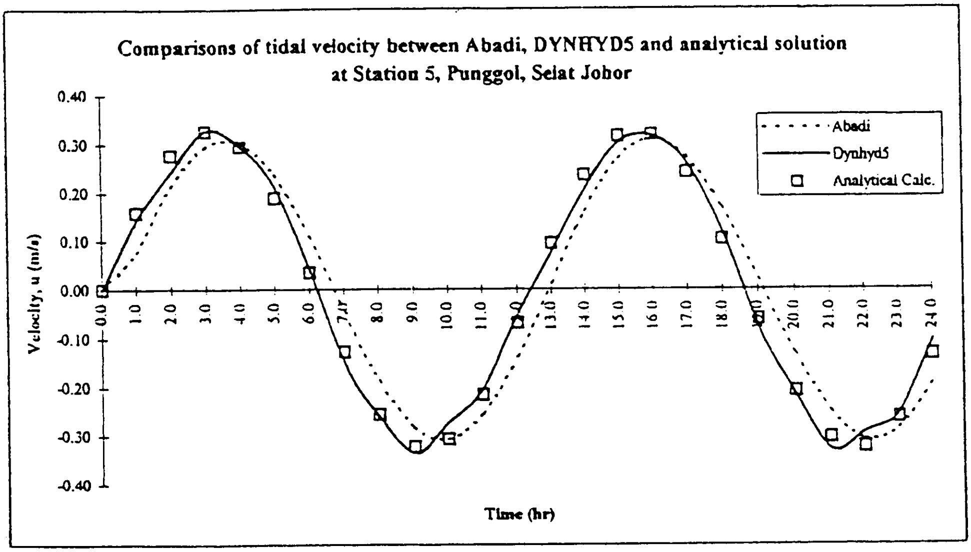


Figure 10. Simulations of tidal velocity at Station 5, Selat Johor using *ABADI*, *DYNHYD5* and analytical solution.

Finally, Table 2 and Figure 11 show the maximum tidal velocities that were simulated and measured at all five stations in Selat Johor – Stations 1-5 during spring tide. From the graph plotted at Figure 11, it can be observed that tidal velocities simulated using *ABADI* corresponds well with the results simulated using the explicit finite difference formulation at Stations 1, 3 and 5 which were conducted by Patarapanich *et al.* [7].

The simulated maximum velocities by *ABADI* at Station 2 were also found to correspond well with the tidal streams data obtained from AC No.2586 with an error ranging between 20%-30% during flood and ebb tide which is still within the acceptable range of 15%-30% as mentioned by Patarapanich *et al.* [7]. At Station 5 (Punggol), the difference between computed velocities from *ABADI* and those from AC No.2586 were slightly higher. In another comparison at Stations 4 and 5 with measured data from Lim [5] during flood tide shows that the simple hydrologic model gives a good representation of the actual velocities in Selat Johor but during ebb tide the error between *ABADI* and the measured data from Lim [5] is approximately 50% for both stations. It can be observed from here that at Stations 4 and 5, the model is accurate during flood tide but no longer accurate during ebb tide. The higher velocities recorded by AC No.2586 at Station 5 (Punggol) and the higher velocities measured by Lim [5] at Stations 4 and 5 during ebb tide could be due to various reasons.

Station 4 and Station 5 (Punggol) is situated right before Pulau Ubin where there is a narrowing of the channel geometry. Therefore, flow velocities are higher here due to the bottleneck effects especially during ebb tides as can be observed from the AC No.2586 data and from measured values by Lim [5]. According to Lim [6], Eastern Selat Johor can be hydrologically divided into the inner and outer area with Punggol as the division boundary. The outer area is more turbulent especially during flood tide [6]. This too contributes to the higher river flow variations at Punggol. Lim [5,6] also shows that there is a salinity intrusion effect which results in a complicated two-layered flow where the net surface flow is flowing outward but the net bottom flow which is more saline and slightly lower in temperature is flowing inward. However, the model *ABADI*, is a one-dimensional tidal motion using continuity equation and relevant approximations for its momentum equation. Therefore *ABADI* do not take into considerations factors such as the bottleneck effects due to a change in the channel geometry and the salinity intrusion effects. As such, *ABADI* fails to simulate accurately the flow at the outer stations but for Stations 1-3 simulation results were good as can be seen from Table 2.

Table 2. Maximum velocities (m/s) in Selat Johor during spring tide, simulated and measured.

| Station | Max. u from ABADI (Sp tide) | Max. velocity from explicit FD method (Sp tide) | Max. u from AC No.2586 (Sp tide) (flood) | Max. u from AC No.2586 (Sp tide) (ebb) | Measured max. u (flood tide) | Measured max. u (ebb tide) |
|---|---|---|---|---|---|---|
| 1 – Derman Shoal | 0.08 | 0.11 | | | | |
| 2,C – Sembawang Shipyard | 0.13 | | 0.15 | 0.21 | | |
| 3 – Lavis Buoy | 0.16 | 0.18 | | | | |
| 4 – Sg. Seletar river mouth | 0.18 | | | | 0.20 | 0.35 |
| 5,B – Punggol | 0.31 | 0.28 | 0.82 | 0.82 | 0.30 | 0.75 |

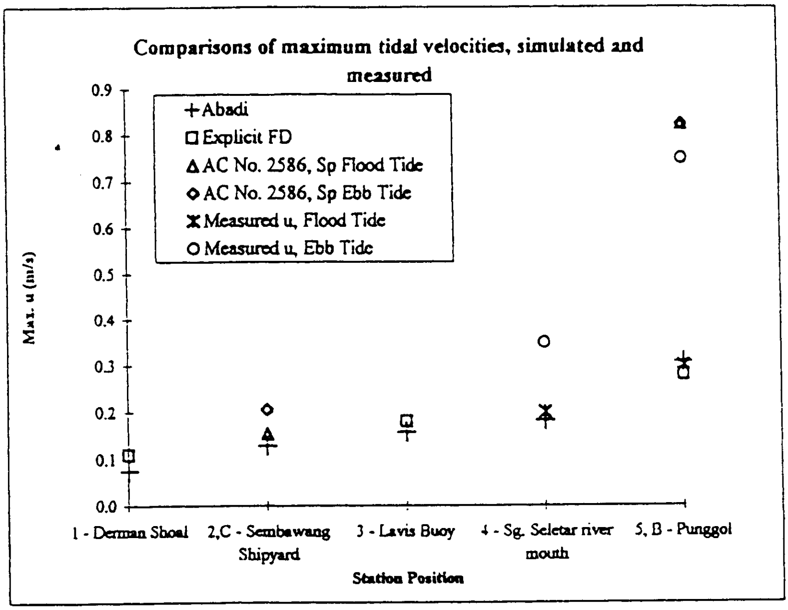


Figure 11. Comparisons of maximum tidal velocities simulated and measured at five stations at Selat Johor during spring tide.

## 6. Discussion and conclusion

Simulation results indicate clearly that *ABADI* is able to model quite accurately with an error of 20% the tidal hydrodynamics in Selat Johor even though the momentum/energy principles were approximated with other empirical formulations. Due to the simplicity of this model, *ABADI* can be used to quickly assess the hydrodynamic conditions of the study area of interest as in the context of *RACE* to obtain some preliminary results. These results can then be used for further studies, if needed, using standard research approaches such as the hydraulic models for more details of the hydrodynamic conditions in the area under research.

As a conclusion, it is found that the model *ABADI* gives a good representation of the actual flow velocities at the inner part of Selat Johor but the model is no longer accurate at the outer part of Selat Johor (after Punggol) due to bottleneck effects and salinity intrusion that the model does not consider. Hence the model *ABADI* is suitable for simple prediction and simulation of tidal velocities or tidal flows in estuaries or river mouth where there is no bottleneck effects or other complicated flow variations. Results from this model can be used as input to water quality simulations and eutrophication.

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