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Modeling of tide in the Java sea coastal area between Jakarta and Cirebon, Indonesia: bathymetric data source and sensitivity tests due to bottom roughness and boundary condition

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Abstract. With the on-going construction of deep water port in Patimban area, a more dense marine traffic is expected to occur in the coastal belt between the ports of Jakarta and Cirebon. Precise prediction of tide is inevitably becoming more important in order to maintain safe navigation. The purpose of this work is carrying out a dedicated tidal simulation for the area in question. The presented result contains primarily the selection of bathymetric data for the development of computational domain and sensitivity tests due to bottom roughness and the quantity of elevation points along the model's open boundaries. For the purpose of constructing computational domain, we assess the suitability of global and national bathymetry data. Data from two water level stations in Sunda Kelapa and Cirebon ports are used to verify the model output, for example surface elevation due to tide. The simulation of tide is carried out using two-dimensional horizontal numerical model facilitated by Delft3D software. Sensitivity tests considering two bottom roughness values and three scenarios of boundary conditions are carried out. It is found that the short-term tidal simulation indicates reasonable agreement against tidal data from Sunda Kelapa and Cirebon stations. It seems that bottom roughness does not provide significant control to the resulting magnitude. We have learned that an optimum number of tidal elevation points along the boundary condition must be set. Despite of the demands in improving the tidal phase, our present results indicate promising milestones toward a precise tidal simulation for the domain in question.

1. Introduction

Tide prediction has an important role for activities based in marine areas, some of the benefits of tide data are to support development in coastal areas such as port. Tide prediction is important to be considered in the infrastructure development process. In addition, tide data is also needed for navigation safety and the efficiency of the port [1]. Tide prediction is used to predict high tide phenomenon, by knowing this phenomenon, authorities can mitigate tidal flooding [2]. Tide prediction is also can be used to predict oil spill movement in the ocean [3].

Until now, there have been several tide models that have been carried out, including the global tide model [4, 5, 6, 7, 8] and the regional tide model [7, 9] These models are performed using altimetry satellite data. There is a study on the development of a regional tidal model by assimilating altimetry data into a regional barotropic tidal model, this is done for areas with complex topography such as the Indonesian seas [9]. Also, tidal model with good agreement results can be achieved because it has a well defined modeling parameters such as bathymetry and boundary conditions [10]. Several studies on tide modeling in the Java Sea have been conducted by [11] and [12] with a resolution of 2' x 2' and bathymetry data from World Ocean Topography Data (ETOPO). These studies shows that the Java Sea is dominated by tidal constituent K1 originating from the Pacific Ocean and M2 originating from the



Indian Ocean which is the same result as Ray, et al. (1999) [5]. Koropitan, et al. (2008) [11] suggested making a model with a better resolution to describe tidal mixing in the Java Sea.

Bathymetry data is important and can affect the tidal model. According to [13], the improved bathymetry dataset can reduce errors in tidal residuals. Therefore, by using a high resolution bathymetry data, a more precise prediction of the tidal elevation around the questioned area can be obtained [14]. Beside the bathymetry data, bottom roughness is also important for tidal modeling. According to [14], bed variability in an area can cause a strong effect on the tide model. It becomes important to define the type of sea bed and its roughness coefficient. The open boundary conditions are crucial to the representation of tidal model in an area [15]. The open boundary conditions are placed at several points on the open boundary of the model domain, while other points will be approximated by linear interpolation along the open boundary.

This study aims to obtain a tidal model in the Java Sea coastal area, between Jakarta and Cirebon with numerical modeling methods using Delft3D software. This model uses a structured grid with a resolution of 1 km (0.5'). The bathymetry data used is BIG's BATNAS data, this data is selected based on the results of DoD calculations. The other data used are tidal harmonic constituents from TPXO-9 tidal model and observation data from BIG Tidal Station. This modeling process includes sensitivity testing on two scenarios of the bottom roughness value parameter and three scenarios of the number of open boundary conditions points. The expected result of this research is that defining the number of boundary condition points optimally in the western part of the modeling domain will produce tide prediction that is similar to the observed data.

2. Materials and Method

The details of data used in this study can be seen in Table 1.

Table 1 Details of Data.

No.	Types of Data	Source of Data	Notes
1.	National Bathymetry (BATNAS)	Geospatial Information Agency (BIG) [16]	- Resolution: 180 m (6 arc-second)
2.	Tidal Harmonic Constituents	Tide Model Driver [17]	- Model: TPXO-9 - For open boundary conditions
3.	Tidal Station Observation Data	Geospatial Information Agency (BIG) [18]	- Interval data: 3 minutes - 2 station: Sunda Kelapa and Cirebon

Bathymetric data is data required as input data in the modeling process which will be interpolated in accordance with the model grid resolution, that is 1 km (0.5'). Bathymetric data used in this study is BATNAS, this data is provided by Indonesian Geospatial Information Agency (BIG). The spatial resolution of BATNAS is 6 arc-second or about 180 m.

In addition to bathymetry data, there are another data needed as input in the tide modeling process, these data are tidal harmonic constituents at certain points of the model's open boundary as boundary conditions. The boundary condition is prescribed at two points which divide a complete boundary into several segments. Points that lie in between these two points are calculated by linear interpolation of the forcing at both ends [19]. The harmonic constituent data used are obtained from TPXO-9 tidal model.

There are 8 primary harmonic constituents (O_1 , K_1 , P_1 , Q_1 , K_2 , N_2 , M_2 , and S_2) entered in each point as boundary condition. The distribution of boundary condition points can be seen in the Figure 1 marked in green color

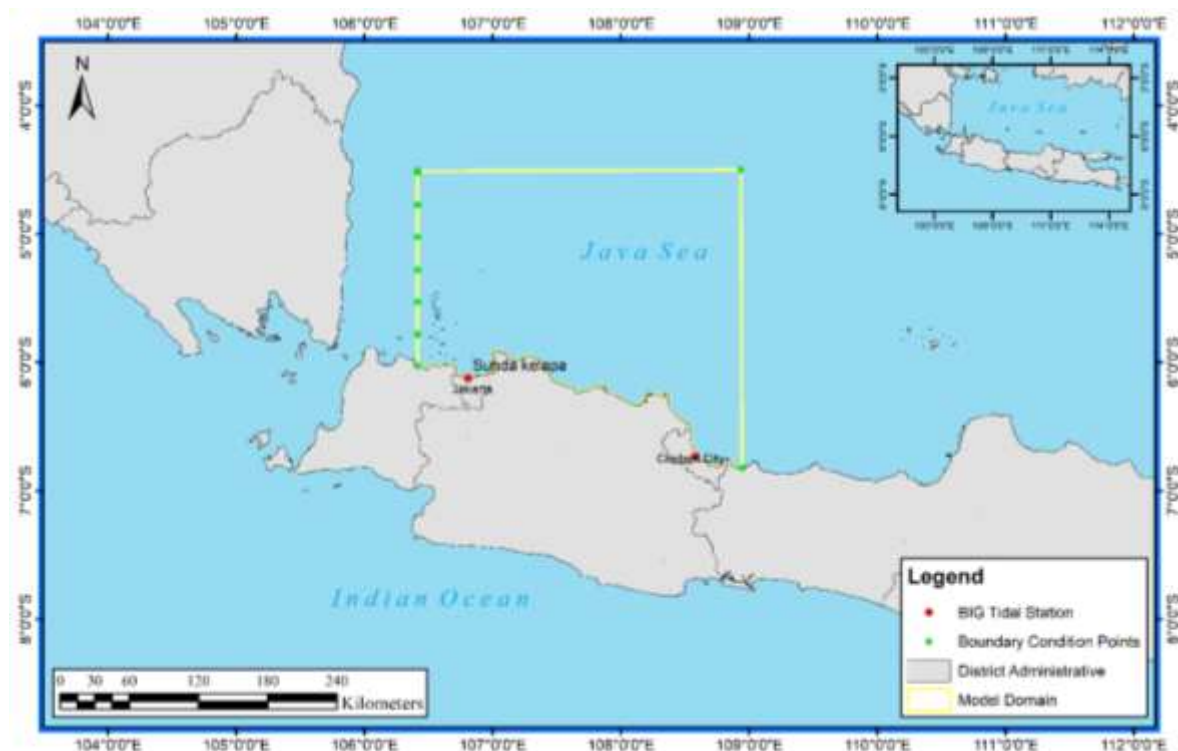


Figure 1. Map of Study Area

The next data is tidal observation data from the BIG tidal station verification process of the tide model. This is conducted to know the quality of the tidal model and the difference between the model and the observed data. Verification is done by calculating the Root Mean Square Error (RMSE) and also by comparing the phase between the model and the observation data. The data used for verification purpose is observation data at two stations, that are Sunda Kelapa Station in the west of the modeling area and the Cirebon Station in the east of the modeling area. The data used at the Sunda Kelapa Station is data taken on January 17th – January 31st, 2020. While the Cirebon station uses data taken from January 1st – January 31st, 2020. The difference in the observation time span is due to the difference of completeness data at each station.

2.1 Methods

This research is conducted by doing DEM of Difference Calculation for the bathymetry data, sensitivity test for the setting of model's parameter, and the verification of the model by comparing the model results with observation data, it can be seen in Figure 2.

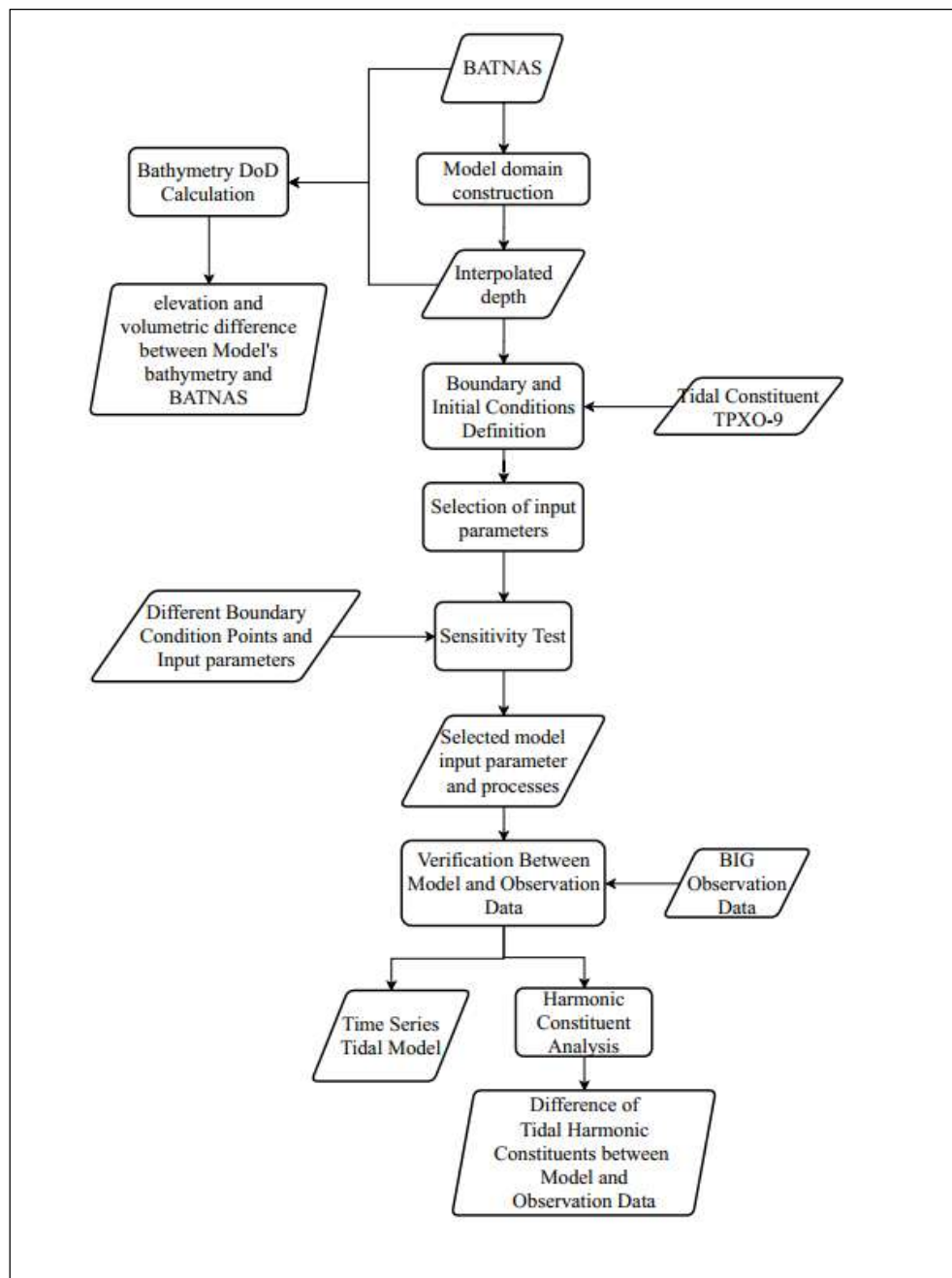


Figure 2. Workflow of the Research

2.1.1 DEM of Difference (DoD). During modeling, the bathymetry data that entered into the model will be interpolated according to the grid used for modeling, which produce bathymetry with different resolution from the original bathymetry (BATNAS). This will also affect the quality of the model result. Therefore, the process of calculating the difference between the interpolated bathymetry in the model and the original bathymetry (BATNAS) is quite important to see what affects the quality of the model.

The process of DEM of Difference will start by calculating mean elevation difference by using equation (1).

$$\Delta h_j = \frac{1}{N} \sum_{i=1}^N |h_{j,i} - h_{mod,i}| \quad (1)$$

After obtaining the result of the mean elevation difference with each of the same surface area, the volume of the result of the elevation difference can be determined using equation (2)

$$\Delta Vol_j = \sum_{i=1}^N (dA_i) |h_{j,i} - h_{mod,i}| \quad (2)$$

Note: $i = 1, N$ (number of bathymetry point in model)

$j = \{\text{BATNAS}\}$

mod = interpolated bathymetry from Delft3D model

The result of DEM of Difference process will be shown in a visual of elevation difference and the volumetric difference value between the two bathymetry data.

2.1.2 Numerical modeling. The tide simulation model is carried out by numerical modeling method using Delft3D-FLOW module by Delft3D software. Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid [19]. For tidal modeling, Delft3D uses 2 equation, that are momentum equation and continuity equation.

The continuity equation is derived from the law of conservation of mass or the Lomonosov-Lavoiser law (1743-1749). The Law of Conservation of Mass explains that the mass of a system (fluid) from one point to another will be the same. The continuity equation can be seen in the equation (3) [19].

$$Q = \frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}} \frac{\partial[(d + \zeta)U\sqrt{G\eta\eta}]}{\partial \xi} + \frac{1}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}} \frac{\partial[(d + \zeta)V\sqrt{G\xi\xi}]}{\partial \eta} \quad (3)$$

Q representing the contributions per unit area due to the discharge or withdrawal of water, precipitation and evaporation:

$$Q = H \int_{-1}^0 (q_{in} - q_{out}) d\sigma + P - E \quad (4)$$

with q_{in} and q_{out} in equation (4) are the local sources and sinks of water per unit of volume, respectively. P is for precipitation and E is for evaporation [19]

The momentum equation is a statement of Newton's Second Law and relates the sum of the forces acting on an element of fluid to its acceleration or rate of change of momentum [20]. The momentum equation can be seen in the equation (5) and (6) [19].

$$\begin{aligned} \frac{\partial v}{\partial t} + \frac{u}{\sqrt{G\xi\xi}} \frac{\partial u}{\partial \xi} + \frac{u}{\sqrt{G\eta\eta}} \frac{\partial u}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial u}{\partial \sigma} - \frac{v^2}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}} \frac{\partial \sqrt{G\eta\eta}}{\partial \xi} + \frac{uv}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}} \frac{\partial \sqrt{G\xi\xi}}{\partial \eta} - fv \\ = -\frac{1}{\rho_0 \sqrt{G\xi\xi}} P\xi + F\xi + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left(uv \frac{\partial u}{\partial \sigma} \right) + M\xi \end{aligned} \quad (5)$$

and

$$\begin{aligned}
& \frac{\partial v}{\partial t} + \frac{u}{\sqrt{G\xi\xi}} \frac{\partial v}{\partial \xi} + \frac{u}{\sqrt{G\eta\eta}} \frac{\partial v}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial v}{\partial \sigma} - \frac{uv}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}} \frac{\partial \sqrt{G\eta\eta}}{\partial \xi} + \frac{u^2}{\sqrt{G\xi\xi}\sqrt{G\eta\eta}} \frac{\partial \sqrt{G\xi\xi}}{\partial \eta} + fu \\
& = -\frac{1}{\rho_0\sqrt{G\xi\xi}} P\eta + F\eta + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left(uv \frac{\partial v}{\partial \sigma} \right) + M\eta
\end{aligned} \tag{6}$$

2. The selection of the input parameters for this model have been determined. It can be seen in Table 2.

Table 2. Selected Input Parameters

Parameter Type	Parameter Value
Simulation Time	Start: January 1 st , 2020 End: January 31 st , 2020
Time Step	1 minute
Bottom Roughness Formula	Manning
Bottom Roughness Value	0.02
Boundary Conditions	10 Boundary Conditions.

2.1.3 *Sensitivity test.* Sensitivity analysis is the process of defining how the input parameters take effect on the output results. This is important for decision making and modeling process [21]. In this study, the sensitivity test is done for two parameters, bottom roughness values and the number of boundary condition points. The detail scenarios of the sensitivity test can be seen in Table 3.

Table 3. Sensitivity test scenarios

ID	Types of Parameter	Parameter Input Values
B1	Bottom Roughness Value	Manning 0.02
B2	Bottom Roughness Value	Manning 0.04
C1	Boundary Point	4 Points
C2	Boundary Point	6 Points
C3	Boundary Point	10 Points

3. Result and Discussion

3.1. Bathymetry

This process has been done previously to two types of bathymetry data, that is GEBCO (global bathymetry data) [22] and BATNAS (national bathymetry data) [16]. These two bathymetry data are compared to local bathymetry data obtained from the field surveys. This step is done to determine the suitable bathymetry data for this study. The results show that BATNAS has a smaller volumetric difference than GEBCO, it's because of the resolution of BATNAS is higher than GEBCO. So, BATNAS is more suitable for this study.

By determining the suitable bathymetry data for this study (BATNAS), the study can be continued by calculating the DoD between BATNAS and the Delft3d model's bathymetry, which is the model's bathymetry that has been interpolated to the grid model. The result of the DoD calculation between the Delft3D model's bathymetry and the national bathymetry (BATNAS) shows that the lowest elevation difference between the two bathymetric data is 2.4×10^{-5} m and the highest elevation difference between

the two bathymetric data is >15 m (can be seen in Figure 3.) with a volumetric difference amount $80.6 \times 10^9 \text{ m}^3$.

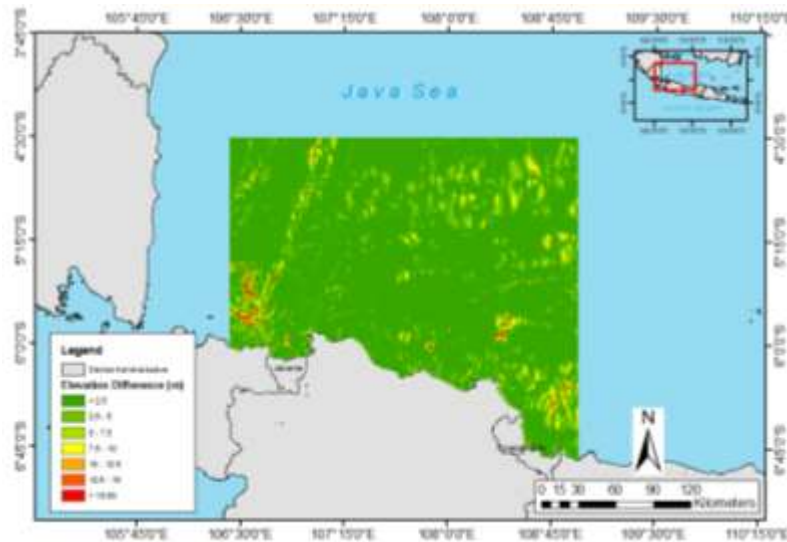


Figure 3. Elevation Difference between Model's Bathymetry and BATNAS

The highest elevation difference is in the western part of the study area, marked in red color in Figure 3. In that section, there are many small islands close to each other called Kepulauan Seribu. In the BATNAS bathymetric data, the small islands of Kepulauan Seribu are defined as land, whereas in the Delft3D model's bathymetry, most of the small islands are interpolated as oceans. This is due to the different resolutions between the two bathymetric data. BATNAS resolution (180 m) is higher than the Delft3D model's bathymetry resolution (1 km).

3.2. Bottom roughness and tidal boundary condition

The type of bottom roughness formula used in this study is Manning Formula, most of the sediment type in Java Sea, between Jakarta and Cirebon is silt [23]. According to [24] silt is a type of fine soil, with a Manning coefficient of 0.02 [25]. In this parameter, the sensitivity test is carried out using 2 scenarios, the bottom roughness value of 0.02 (B1) and 0.04 (B2).

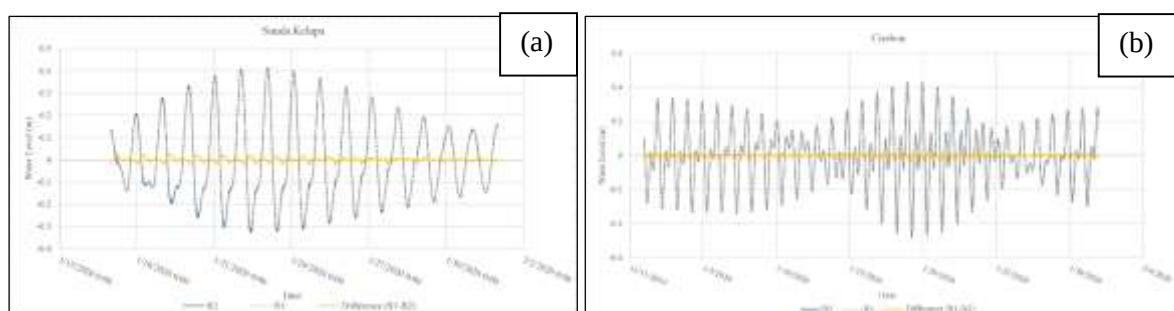


Figure 4. Sensitivity test results of scenario B1 and B2; (a) Sunda Kelapa station, (b) Cirebon station

Figure 4 shows the results of the bottom roughness value sensitivity test at two BIG stations, Sunda Kelapa Station and Cirebon Station. Visually, the orange line (B1) and the blue line (B2) show the amplitude between the two scenarios is almost the same, it also can be seen from the yellow line in the figure, which is the difference between the modeling results of B1 and B2, this line indicates the low amplitude.

The results of this sensitivity test can be tabulated in Table 4, so the maximum and minimum tidal range from both of the results can be obtained.

Table 4. Tidal range results of bottom roughness value scenarios; B1 and B2

Station	Maximum (m)			Minimum (m)		
	B1	B2	Diff	B1	B2	Diff
Sunda Kelapa	0.71	0.74	0.03	0.29	0.30	0.01
Cirebon	0.89	0.91	0.02	0.32	0.32	0.00

Based on Table 4 and Figure 4, it can be seen that there is no significant difference of the amplitude and the phase between two scenarios at each station. It can be concluded that this model is less sensitive towards the bottom roughness value.

In defining the boundary conditions in the modeling area, the amplitude and phase values of the harmonic constituents at the open boundary of the model are needed. The number and location of the boundary condition point considering the condition of the interpolated bathymetry in the west of the modeling also may affect the modeling results. Therefore, the sensitivity test is done to the number of boundary conditions in the west of the model domain by using 3 scenarios; 4 points (C1), 6 points (C2), and 10 points (C3).

Figure 5 shows the sensitivity results between three scenarios at Sunda Kelapa Station, it can be seen that visually, the sensitivity test shows the difference in amplitude of each scenario. There is no difference in the phase of each scenarios. But, for more detail, take a look to Figure 6.

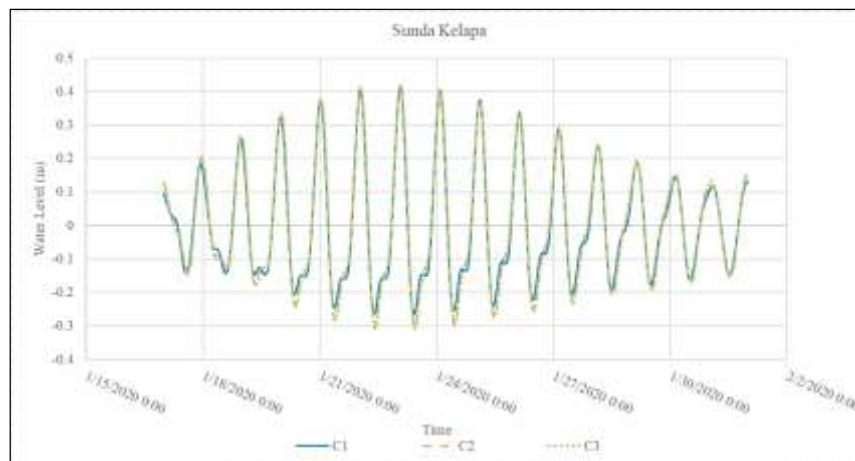


Figure 5. Boundary condition points sensitivity test results at Sunda Kelapa

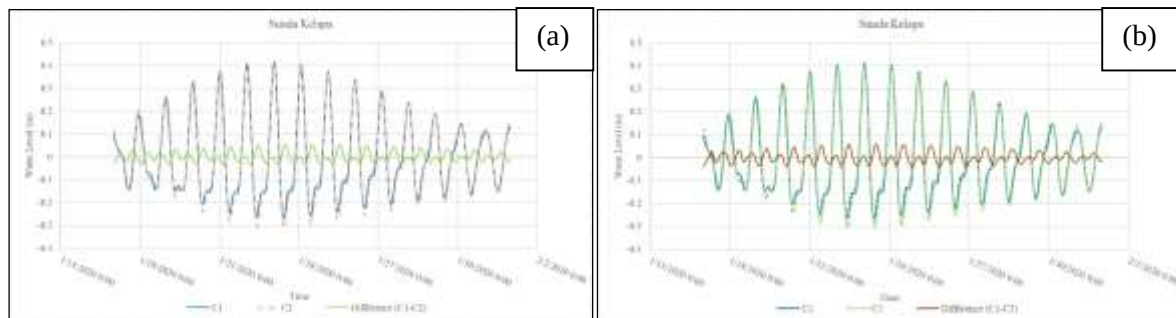


Figure 6. The difference between two boundary condition point scenarios at Sunda Kelapa station; (a) C1-C2, (b) C1-C3

From Figure 6, it is clear that each scenario produces a different amplitude, the difference of the amplitude showed by the green line in Figure 6 (a) and red line in Figure 6 (b). These lines indicate a quite high amplitude as the difference of each scenario.

In another case, at Cirebon Station, the results didn't show any difference in the amplitude, as well as the phase. The results of the boundary condition point sensitivity test in all scenarios can be seen in Figure 7. While Figure 8 shows the difference of each scenario to the base scenario (C1) in more detail. In Figure 8, it can be seen that the amplitude difference line tends to be straight at zero, the line is marked in green line (a) and red line (b).

The results of this sensitivity test can be tabulated in Table 5, so the maximum and minimum tidal range from both of the results can be obtained.

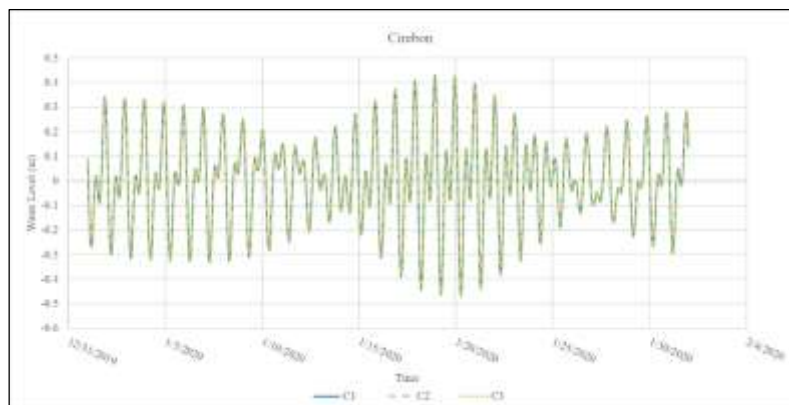


Figure 7. Boundary condition points sensitivity test results at Cirebon

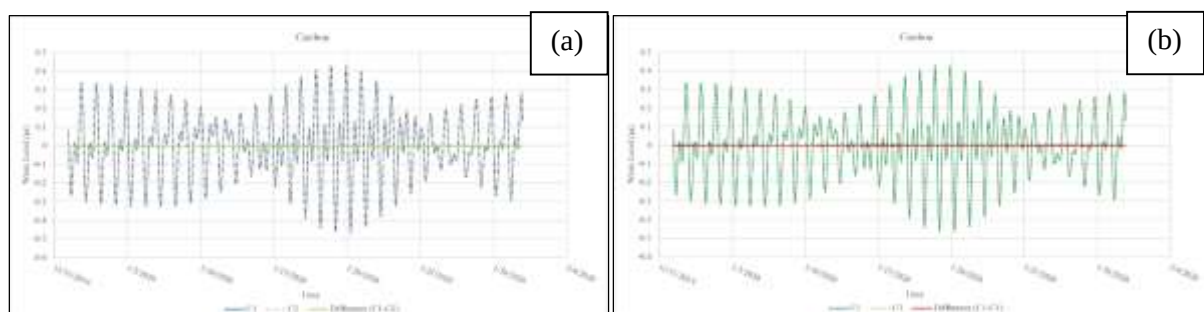


Figure 8. The difference between two boundary condition point scenarios at Cirebon station; (a) C1-C2, (b) C1-C3

Table 5. Tidal range results of boundary condition point scenarios; C1, C2, and C3

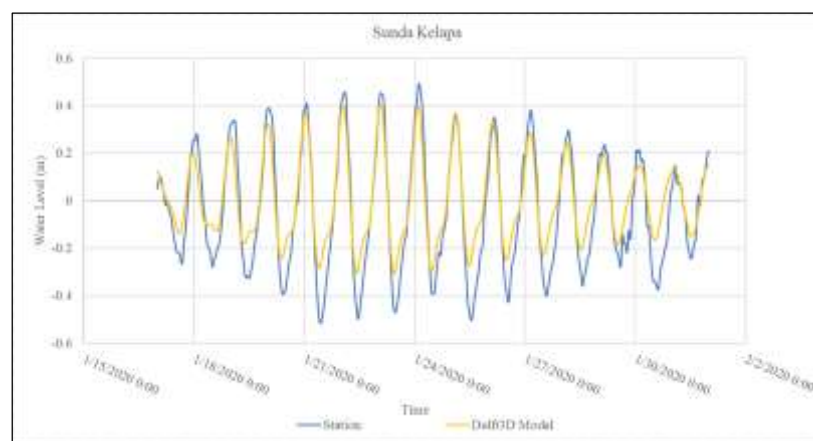
Station Name	Maximum (m)			Minimum (m)		
	C1	C2	C3	C1	C2	C3
Sunda Kelapa	0.68	0.73	0.71	0.28	0.30	0.29
Cirebon	0.89	0.89	0.89	0.32	0.32	0.32

Based on the figure and the table, it can be concluded that different quantity of boundary condition points affects the sensitivity of the model at Sunda Kelapa Station, while Cirebon Station is not. These parameters sensitivity test indicates the input parameter selection is important.

3.3 Verification

The verification of the accuracy of the simulated magnitude is conducted by comparing the time series of tide model results with observation data from two BIG tidal stations in 15 days of observation data at Sunda Kelapa station and 1 month of observation data at Cirebon station. Sunda Kelapa station is located in the west part of the model domain, while the Cirebon station is located in the east part of the model domain. Both of these BIG tidal stations are located in ports and flanking the Patimban port area.

Figures 9 and 10 show the verification results between the model and observation data at Sunda Kelapa station and Cirebon station, these figures indicate that there is a difference in amplitude between model and observation data. But visually, both of the results have the same phase and pattern of tides.

**Figure 9.** Comparison between model and BIG observation data at Sunda Kelapa

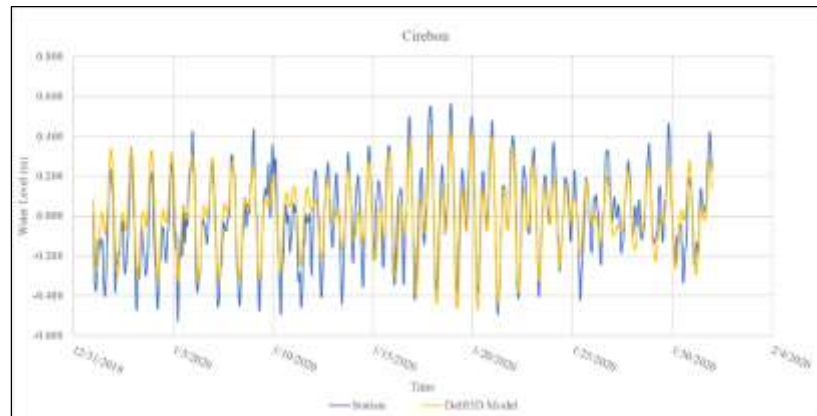


Figure 10. Comparison between model and BIG observation data at Cirebon

To ensure the phases of both of the data are the same, the time of high tide during spring tide and neap tide can be recorded so that the time shift between model and observation data are obtained. That way it can be ascertained whether the phase of the model and observation data is really the same or not, by seeing how far the time is shifted (see Table 6 and 7).

Table 6. Time shift between the model and BIG observation data in spring tide

Spring Tide Time Shift			
Station Name	Arrival Time (BIG Station)	Arrival Time (Model)	Time Shift (minutes)
Sunda Kelapa	22 January 2020, 02.15	22 January 2020, 01.00	75
Cirebon	17 January 2020, 21.30	17 January 2020, 21.00	30

Table 7. Time shift between the model and BIG observation data in neap tide

Neap Tide Time Shift			
Station Name	Arrival Time (BIG Station)	Arrival Time (Model)	Time Shift (minutes)
Sunda Kelapa	31 January 2020, 12.03	31 January 2020, 13.00	57
Cirebon	27 January 2020, 19.00	27 January 2020, 19.13	13

Based on the tables, the time shift between model and observation data at Sunda Kelapa station is quite far. While at Cirebon station the time shift is quite close, which is under 60 minutes. It can be

caused by the bathymetry condition in the west part of the model domain, where the elevation difference is high because of the grid interpolation in Delft3D. This condition of bathymetry might affect the modeling results. Besides that, the quantity of boundary condition points also can be one of the reasons. In this study, 10 points of boundary condition are the optimum numbers, because if it comes with more points, the model will overflow.

Table 8 shows the RMSE values between model and BIG observation data, The RMSE values are obtained by calculating the difference of the amplitude between two tidal data.

Table 8. RMSE values between model and BIG observation data

Station Name	RMSE (cm)
Sunda Kelapa	10.6
Cirebon	10.3

3.4 Tidal constituents

Besides doing RMSE calculations, comparative analysis of models and observation data can also be done by comparing the tidal constituents generated by the model and the observation data using T Tide program from Matlab [26]. The results of the tidal constituents can be seen in Table 9 for Sunda Kelapa Station and Table 10 for Cirebon Station.

Table 9. Tidal harmonic constituents at Sunda Kelapa

Cons.	Amplitude (cm)			Phase (degree)		
	Obs	Model	Diff.	Obs	Model	Diff.
O_1	12.58	9.13	3.45	31.02	32.56	1.54
K_1	32.26	22.33	9.93	46.88	39.54	7.34
M_2	4.9	6.33	1.43	141.52	109.99	31.53
S_2	5.38	4.49	0.89	101.45	76.12	25.33

Table 10. Tidal harmonic constituents at Cirebon

Cons.	Amplitude (cm)			Phase (degree)		
	Obs	Model	Diff.	Obs	Model	Diff.
O_1	5.90	5.99	0.09	32.99	56.56	23.57
K_1	16.73	16.82	0.09	325.09	314.19	10.9
M_2	20.14	14.74	5.40	101.67	109.25	7.58
S_2	3.35	6.26	2.91	314.11	336.35	22.24
Q_1	2.62	2.29	0.33	15.41	8.01	7.40
N_2	6.59	4.68	1.91	62.53	64.99	2.46

From Table 9 and 10, it can be determined the type of tide at each station by calculating the Formzahl number. the type of tides at Sunda Kelapa Station is diurnal tides while the type of tides at Cirebon station is mixed tide prevailing semi diurnal.

4. Conclusion

Based on this study, the model is not sensitive to the bottom roughness values at each station but sensitive to the quantity of boundary condition points at Sunda Kelapa Station

From the verification, it shows that the RMSE of the model is 10.6 cm for the Sunda Kelapa Station and 10.3 cm for the Cirebon station. with a time shift of 75 minutes at Sunda Kelapa station and 30 minutes at Cirebon Station in spring tide. While in neap tide the time shift at Sunda Kelapa Station is 57 minutes, and 13 minutes at Cirebon Station.

To get better model results it can be done by increasing the grid resolution. By doing so, the bathymetry resolution of the model will increase as well. Besides that, the open boundary condition points can be determined at each grid intersects.

Acknowledgement

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