Sea-level prediction for early warning information of coastal inundation in Belawan coastal area using Delft3D model

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Abstract. Coastal inundation has a great impact on the environment, such as damage to infrastructure and pollution of land and water. One of the efforts to prevent coastal inundation is to predict the water level. Delft3D is a hydrodynamic model that's able to simulate the water level. Coastal inundation research using the Delft3D model is still rarely done in Indonesia, especially on the east coast of Sumatra. This research is conducted in Belawan coastal area by simulating the water level that caused the coastal inundation using the Delft3D model. The best bathymetry for the prediction of water level and the magnitude of the wind effect was obtained from the simulation. The final step is to predict the water level in Belawan coastal area. The result of this research shows that the Delft3D model can simulate the water level which causes the coastal inundation in the Belawan coastal area. The correlation of the Delft3D model is 0.9, and the RMSE of GEBCO bathymetry is 0.39 meters and the RMSE of NOAA bathymetry is 0.46 meters. The GEBCO bathymetry is better than NOAA bathymetry in describing the water level in the Belawan coastal area. The wind effect on the water level simulations is not significant because the coefficient of determination is 0.47%. Besides, the Delft3D model with GEBCO bathymetry input can predict the water level which causes the coastal inundation with correlation reaches 0.92 and RMSE is 0.39 meters.

Keywords: coastal inundation, tidal flood, sea level, Delft3D

1. Introduction

Global sea levels were expected to increase over the next century with the global average increase approaching 1 meter by 2100 [1]. In Marfai and King [2], Barth and Titus explain that the serious impacts of sea-level rise are coastal erosion, tidal flooding, and land changes, as well as increased salinity in estuary and aquifer areas. Tidal flooding has a major impact on the environment, such as damage to infrastructure, damage to agricultural land and ponds, as well as soil and water pollution [3].

The problem of tidal flooding in Indonesia has been widely researched in the northern coastal areas of Java [3–5]. Factors that influence tidal flooding include long-term sea-level rise, land subsidence, tides, and dynamic meteorological factors [5]. Ward et al. [4] used a GIS-based model to produce inundation maps for tidal flood events in the Jakarta area. Habibi et al. [5] researched in the Semarang area regarding tidal flooding using 2D hydrodynamic models and verification using IKONOS satellite image data to determine the inundation area. Tidal flooding was also studied in the coastal area of Pekalongan by Marfai et al. [3] in 2013 by mapping tidal floods in the area.

Tidal flood prevention and identification of coastal environmental problems are some of the initial efforts to formulate a coastal management plan based on coastal disasters [4]. One of the mitigation efforts for tidal flooding is predicting tidal flooding by modeling. Many hydrodynamic models are used to simulate the sea level that causes tidal flooding. One of the hydrodynamic models that can be used to analyze and predict tidal flooding is Delft3D. The Delft3D modeling system is designed to simulate the propagation of waves, currents, sediment transport, morphological developments, and aspects of water
quality in coastal areas, rivers, and estuaries [6]. Research conducted by Elias et al. [7] in Egmond, the Netherlands showed that the Delft3D model can perform hydrodynamic measurements well when compared with observational data. In another study on tides, the results of the Delft3D model around the front coastline of PLTU Tarahan, Lampung have a high correlation value after being verified with tidal observation data obtained using the AOTT Kempton strip chart [8].

Tidal flood research using the Delft3D model is still very rare in Indonesia. Tidal flood research is still mostly focused on the northern coast of Java, whereas in other areas, such as the coast of Sumatra, it is also prone to tidal flooding [9–11]. The tidal flooding often occurs on the Medan Belawan sub-district. Tidal flooding can be predicted with historical analysis through tidal flood events that have occurred. Therefore, the author wants to research the coastal area of Medan Belawan by predicting the sea level that causes tidal flooding using the Delft3D model.

2. Methods

2.1. Research time and location

The research area was on the coast of Medan Belawan. The research time was from 30 December 2017 until 6 January 2018, when the supermoon phenomenon occurred, i.e. on 12-19 June 2018, 10-17 July 2018, and also 8-15 August 2018 when the new-moon phenomenon occurred. The selection of these events was based on the closest distance of the moon to the earth during the supermoon and new-moon phases in 2018, which caused sea-level rise on the coast of Medan Belawan. Sea level simulations used the Delft3D model in the supermoon phase (from 30 December 2017 until 6 January 2018) as well as two new-moon phases (10-17 July 2018 and 8-15 August 2018) and predictions were made on 12-19 June 2018 in the new-moon phase.

![Figure 1. Map of the research area](image_url)

2.2. Research Data

The data used in this study are:

a) the Final Analysis (FNL) wind data and the Global Forecast System (GFS) from National Center for Environmental Prediction (NCEP) as input for the Delft3D model, this research used the wind components (u, v, and mean sea level pressure or MSLP). These FNL and GFS data have the spatial resolution 0.25°x0.25° and temporal resolution of 6 hours. The FNL data downloaded from [https://rda.ucar.edu/datasets/ds083.2/](https://rda.ucar.edu/datasets/ds083.2/) and the GFS from [https://rda.ucar.edu/datasets/ds084.1/](https://rda.ucar.edu/datasets/ds084.1/).

b) bathymetric data for the region 98°-99°30’E and 3°30’-5°N obtained from the General Bathymetric Chart of the Ocean (GEBCO) with the spatial resolution of 0.0042°x0.0042° and the
National Oceanic and Atmospheric Administration (NOAA) with the spatial resolution of 0.0167°x0.0167°.

c) sea-level data from the Geospatial Information Agency (BIG) and tidal harmonic constants (K1, O1, P1, M2, S2, N2, K2, M4, and MS4) the observation point of the sea level station observation of BIG Belawan.

2.3. Research methods

This research simulated the sea level on the coast of Medan Belawan using the Delft3D model. The output from the Delft3D model was compared with sea-level observation data from the BIG. Then, analyzed the sea level (water level) to describe the pattern of sea-level at the time of the supermoon and new-moon events using GEBCO and NOAA bathymetry input. The best bathymetry was obtained for predicting sea level and the magnitude of the wind factor from the simulation. The final step was to predict sea level in the coastal area of Medan Belawan.

The FNL and GFS data whose extension GRIB2 was converted to .amp extension for pressure, .amu for u-wind, and .amv for v-wind. Then creating the grid domain model on the Delft3D-RGFGRID tool, which was the service area of A.05 Belawan Maritime Meteorological Station in the central part of the Malacca Strait. The grid used in the simulation is in spherical coordinate form (Figure 2).

![Figure 2. Research model domain](image)

In this research, simulations were carried out by running for supermoon and two new-moon events with FNL wind data and without FNL wind data (pure tides). After the simulation was complete and the results can be downloaded, then verified the Delft3D model output. Then determine the meteorological factors from the reduction of sea level results from the Delft3D model with-wind and without-wind (purely tidal). Furthermore, tested to predict the sea level by using the best bathymetry obtained from the three simulations and the wind used was the GFS wind. Finally, the Delft3D model output as sea-level prediction verified using the sea level observation data from BIG.

The following is the model set-up used in the Delft3D model in this research (Table 1).

| Description       | Value       |
|-------------------|-------------|
| Module            | GRID-FLOW   |
| Bathymetry        | GEBCO / NOAA|
| Simulation period | 7 days      |
| Time-step         | 1 minute    |
The following equations were used to verify the output of the Delft3D model against sea-level observation data by BIG.

\begin{equation}
  r = \frac{(n \sum xy - (\sum x)(\sum y))}{\sqrt{(n \sum x^2 - (\sum x)^2)(n \sum y^2 - (\sum y)^2)}}
\end{equation}

\begin{equation}
  RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - y_i)^2}
\end{equation}

where \( r \) is the correlation, \( x, y \) are the variables being compared, \( n \) is the number of data, \( x_i \) is the \( i \)-th model output (forecast), and \( y_i \) is the \( i \)-th observation data.

3. Result and Discussion

3.1. Selecting the bathymetry data for Delft3D configurations

Batubara [12] states that tidal flooding in Belawan generally occurs when the sea level is more than 1.52 above the mean sea level (MSL). Overall, using both GEBCO and NOAA bathymetry inputs, the incidence of tidal flooding during the supermoon and new-moon in Medan Belawan can be simulated by the Delft3D model.

The correlation value of the two bathymetries is very high reaching more than 0.9 (Table 2). If the two bathymetric inputs are compared, it is found that the Delft3D model with GEBCO bathymetry input is better at simulating the sea level causing tidal flooding in Medan Belawan than the NOAA bathymetry input. GEBCO is said to be better than NOAA because the tidal flood simulation with GEBCO bathymetry input has a smaller RMSE value than NOAA. According to Prihantono [13], if the error between the model and the measurement results is small enough, the model can be used, but if the error between the model and the measurement results is large enough, it is necessary to adjust the model input parameters to obtain a small error between the model and measurement. So the smaller the error value between the model and the measurement, the better the model. Therefore, the Delft3D model using the GEBCO bathymetry input is considered to be better at describing sea level in the Medan Belawan area than the NOAA bathymetry.

| Supermoon | New-moon event-1 | New-moon event-2 |
|-----------|------------------|------------------|
| GEBCO     | NOAA             | GEBCO           | NOAA           | GEBCO          | NOAA          |
| Correlation | 0.91           | 0.91           | 0.93         | 0.92          | 0.94          | 0.93          |
| RMSE (m) | 0.32            | 0.40           | 0.41         | 0.49          | 0.43          | 0.49          |
The following are the graphs of simulated sea level for 30 December 2017 - 6 January 2018 for supermoon events (shown in Figure 3), on 10-17 July 2018 for new-moon events-1 (shown in Figure 4), on 8-15 August 2018 for new-moon events-2 (shown in Figure 5).

**Figure 3.** The sea level at the time of the supermoon event was based on observational data (red dots), Delft3D model data with GEBCO bathymetry input (orange line), and Delft3D model data with NOAA bathymetry input (blue line) at the observation point of the sea level station observation of BIG Belawan for 30 December 2017 - 6 January 2018; the tidal flood event occurred on 3-4 January 2018 (black box).

The tidal flood occurred on 3 and 4 January 2018 when the sea level was more than 1.52 meters from MSL. The highest sea level reached 1.54 meters on 3 January 2018, at 02:00 LT, while on 4 January 2018, the highest sea level reached 1.53 meters which occurred at 03:00 LT. The results shown by the Delft3D model show that the GEBCO bathymetry input has a correlation of 0.91 and an RMSE of 0.32 meters. While the results of the Delft3D model with NOAA bathymetry input have a correlation of 0.91 and an RMSE of 0.40 meters. Based on these aspects, it can be seen that the sea level pattern resulting from the Delft3D model, both using GEBCO and NOAA bathymetry inputs, is following the sea level pattern in BIG observations except at the beginning of the simulation time. BIG sea level observation data from 30 December 2017 to 6 January 2018, shows that in one day there are two high tides and two low tides (semi-diurnal). The tides of the semi-diurnal type can be well simulated by the Delft3D model.

BIG noted that the highest sea level on 3 January 2018, was 1.54 meters which occurred at 02:00 LT. On the same date, the Delft3D model with GEBCO bathymetry input showed the highest sea level occurred at 02:00-03:00 LT at 1.40 meters. Meanwhile, the Delft3D model that uses NOAA's bathymetry input produces the highest sea-level value on that date of 1.76 meters which takes place at 02:00-03:00 LT. On 4 January 2018, the highest sea level recorded by BIG observations of 1.53 meters occurred at 03:00 LT. For the Delft3D model with GEBCO bathymetry input, it shows that the highest sea level on 4 January 2018, occurred at 03:00 LT at 1.37 meters. From these two dates, the GEBCO bathymetry shows lower model results than the BIG observation data at the time of the highest sea level occurrence. Unlike the GEBCO bathymetry, the Delft3D model with NOAA bathymetry input simulates a higher sea level than the BIG observation data on 3 and 4 January 2018 when the highest sea level
occurred. Because on 4 January 2018, the simulated sea level reached 1.71 meters which occurred at 03:00 LT.

![Figure 4. The sea level at the time of the new-moon event-1 was based on observational data (red dots), Delft3D model data with GEBCO bathymetry input (orange line), and Delft3D model data with NOAA bathymetry input (blue line) at the observation point of the sea level station observation of BIG Belawan on 10-17 July 2018; the tidal flood event occurred on 13-18 July 2018 (black box)](image-url)

Based on BIG sea level observation data, tidal flooding occurred on 13-15 July 2018 when the sea level was more than 1.52 meters from MSL. The highest sea level on 13 July 2018 was 1.54 meters which occurred at 14:00 LT. Meanwhile, on 14 July 2018, the highest sea level occurred at 14:00-15:00 LT which reached 1.55 meters. On 15 July 2018, the highest sea level was 1.54 meters which occurred at 15:00 LT. The simulation results of the Delft3D model, both with GEBCO and NOAA bathymetry input, show the same pattern as the BIG sea level observation data. This can be seen from the GEBCO bathymetry correlation value which reached 0.93 and the RMSE was 0.41 meters and the NOAA bathymetric correlation value reached 0.92 and the RMSE 0.49 meters. However, at the beginning of the simulation time tends to have an irregular pattern. The GEBCO bathymetry input shows that on 13 July 2018, the highest sea level was 1.35 meters which occurred at 13:00 LT. While the results of the Delft3D model with NOAA bathymetry input indicate that the highest sea level on the same date reached 1.70 meters and occurred at 14:00-15:00 LT. Furthermore, the highest sea level was on 14 July 2018, which was indicated by the GEBCO bathymetry of 1.34 meters at 14:00-15:00 LT and the NOAA bathymetry showed that at 14:00-15:00 LT the highest sea level occurred which reached 1.73 meters. While on 15 July 2018, the results of the Delft3D model with GEBCO bathymetry input showed that the highest sea level of 1.31 meters occurred at 15:00-16:00 LT, and in NOAA bathymetry the highest sea level occurred at 15:00 LT which reached 1.69 meters.

The Delft3D model with GEBCO bathymetry input simulates a lower sea level while the NOAA bathymetry simulates a higher sea level than the BIG sea level observation data at the time of tidal flooding. However, the Delft3D model using both the GEBCO bathymetry input and the NOAA bathymetry input can simulate the sea level during the tidal flood on 13-15 July 2018, which is marked by the same pattern. In addition, the sea level can be simulated by a Delft3D model at almost the same time as the actual tidal flood in the Medan Belawan area.
Figure 5. The sea level at the time of the new-moon event was based on observational data (red dots), Delft3D model data with GEBCO bathymetry input (orange line), and Delft3D model data with NOAA bathymetry input (blue line) at the observation point of the sea level station observation of BIG Belawan on 8-15 August 2018; the tidal flood event occurred on 11-13 August 2018 (black box).

Based on BIG sea level observation data, tidal flooding occurred on 11-13 August 2018 when the sea level was more than 1.52 meters from MSL. The simulation results of tidal floods that have occurred since 11 August 2018 show the same pattern as the BIG observation data. This can be seen from the correlation value of the GEBCO bathymetry input which reaches 0.94 and the RMSE of 0.43 meters and the NOAA bathymetry input correlates 0.93 and the RMSE is 0.49 meters. However, it is the same as the previous two simulations that the Delft3D model tends to have an irregular pattern at the beginning of the simulation time.

BIG observation data shows that on 11 August 2018 the highest sea level was 1.64 meters which occurred at 14:00 LT. While the Delft3D model with GEBCO bathymetry input shows that at 14:00 LT on the same date, the highest sea level was recorded at 1.32 meters. For NOAA bathymetry, the highest sea level on 11 August 2018 occurred at 14:00 LT reaching 1.67 meters. Furthermore, the highest sea level on 12 August 2018 in BIG observation data reached 1.71 meters which occurred at 14:00-15:00 LT. For the Delft3D model with GEBCO bathymetry input, it shows that the highest sea level on 12 August 2018 occurred at 14:00-15:00 LT with a magnitude of 1.37 meters. On the same date, the results of the Delft3D model with NOAA bathymetry input showed that the highest sea level reached 1.75 meters at 14:00-15:00 LT. On the third day of the tidal flood, BIG noted that the highest sea level of 1.66 meters occurred on 13 August 2018, at 15:00 LT. On the same date, the Delft3D model with GEBCO bathymetry input shows that the highest sea level of 1.35 meters at 15:00 LT and the highest sea level reaching 1.74 meters occurred at 15:00 LT on the results of the Delft3D model with NOAA bathymetry input.

3.2. Wind factors
The influence of the wind factor on the amount of sea level in this study was obtained from the sea level of the Delft3D model where wind be diminished by the sea level of the Delft3D model without wind
(pure tides). The wind itself was a non-tidal component. The non-tidal component would be seen after taking the tidal component [14]. Figure 6 show that the magnitude of the wind factor that affects sea level at the time of the tidal flood in the Medan Belawan area in August 2018 ranged from -0.028 to 0.010 meters. This means that the sea level affected by wind factors ranges from -2.8 to 1.0 cm of the total sea level. The data in Figure 6 is used as the basis for finding the relationship between wind speed and sea level.

Figure 6. Graph of sea level associated with wind factor used GEBCO bathymetry input at the observation point of the sea level station observation of BIG Belawan on 8-15 August 2018

Figure 7 show the distribution value of the determination coefficient ($r^2$). The value of $r^2$ shown in Figure 6 is 0.0047 or equal to 0.47%. It means that the wind factor has no significant effect on sea level in the Medan Belawan area. In general, the conditions that affect tidal flooding in Belawan are high tides because the wind factor has no significant effect. Tidal factors affect sea level, especially when the spring tide position is in the new moon phase in June-July-August (JJA), but can occur at other times if there are cases of certain phenomena such as a supermoon that causes sea level to rise, which is higher than usual [12].
3.3. Sea-level prediction for rob floods (new-moon)

Based on the simulation results of the Delft3D model, the Delft3D model was tested in predicting sea level at the time of tidal flooding in the Medan Belawan area. The sea level that caused tidal flooding which was predicted to occur in June 2018 was precisely a tidal flood event that has taken place since 14 June 2018. The bathymetry input used in this prediction only uses the bathymetry from GEBCO. GEBCO has the lowest RMSE value compared to NOAA.

![Figure 8. The prediction of sea level in the new-moon even; the Delft3D model data with GEBCO bathymetry input (orange line) compared with observational data from BIG (red dots) at the observation point of the sea level station observation of BIG Belawan on 12-19 June 2018; the tidal flood event occurred on 14-16 August 2018 (black box)](image)

Figure 8 shows that the Delft3D model with GEBCO bathymetry input can describe the sea level at the time of the tidal flood on 14-16 June 2018. In general, the GEBCO bathymetry has a correlation value of 0.92 and an RMSE of 0.39 meters. This makes the sea level pattern the same between the BIG observation data and the results of the Delft3D model except at the beginning of the prediction time which tends to have an irregular pattern. When viewed from the value of sea level, BIG recorded the highest sea level of 1.57 meters at the time of the incident or on 14 June 2018, at 14:00 LT. Meanwhile, the Delft3D model predicts the highest sea level of 1.36 meters which will occur at 14:00-15:00 LT. On 15 June 2018, BIG observation data showed that the highest sea level reached 1.62 meters occurred at 15:00 LT while the Delft3D model predicted the highest sea level at 1.38 meters at 15:00 LT. BIG's highest sea level on 16 June 2018 was 1.55 meters which occurred at 15:00 LT. On the same date, the highest predicted sea level in the Delft3D model was 1.29 meters and occurred around 15:00-16:00 LT.
Figure 9. The prediction of sea level at the time of the new-moon event used the results of the GEBCO bathymetric as the input for the Delft3D model during the tidal flood in Belawan on 15 June 2018 at 14:40 LT.

The prediction of tidal flooding in June 2018 spatially in the A.05 service area of the Belawan Maritime Meteorological Station is shown in Figure 9. The sea level that caused the tidal flood in June 2018 was not only predicted at one point. The Delft3D model is also able to predict sea-level spatially. Figure 4.7 shows the sea level on 15 June 2018 at 14:40 LT. This time was the highest peak of tidal flooding due to higher sea levels compared to 14 and 16 June 2018. Spatially, the coastal area of the A.05 Belawan Maritime Meteorological Station has sea levels ranging from 1.1 to 1.55 meters at the time of the tidal flood in Medan Belawan. The sea level on the coast of the service area is higher than the sea level in the middle of the ocean. This is following [15] which stated that the resonance and convergence of coastal geometry caused a much larger increase in tidal amplitude at the coast compared to the tide in the open sea.

4. Conclusions
The Delft3D model was able to simulate sea level during tidal flooding in the Medan Belawan area, using both GEBCO and NOAA bathymetry inputs. In both bathymetries, the Delft3D model had a very high correlation, about 0.9. The GEBCO bathymetry had an RMSE of 0.39 meters and NOAA bathymetry has an RMSE of 0.46 meters. The GEBCO bathymetry was better in describing sea level in the Medan Belawan region than NOAA bathymetry. The wind factor had no significant effect on sea level in the Medan Belawan area. This can be seen from the coefficient of determination of only 0.47%. The Delft3D model with GEBCO bathymetry input was able to predict sea level at the time of tidal flooding in the Medan Belawan area. This is indicated by a very high correlation value, reaching 0.92, and a low error value, about 0.39 meters. In this research, the occurrence of tidal flooding is limited with a simulation time of seven days, so it is necessary to add tidal flood events to the supermoon and new moon phenomena with a longer simulation time for better prediction of sea level.

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