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Performance Evaluation of the Delft3D-FLOW Hydrodynamic Model for Simulating Tidal Dynamics and Sea Level in the Pekalongan Coastal Area

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Abstract

Tidal dynamics and sea level variations are important components of coastal hydrodynamic studies, requiring numerical models capable of accurately representing field conditions. This study aims to evaluate the performance of the Delft3D-FLOW hydrodynamic model in simulating tidal dynamics and sea level in the Pekalongan coastal area during the period of 14–31 December 2024. The simulation was conducted using ERA5 atmospheric data, BATNAS bathymetry, and TPXO tidal harmonic data, and was subsequently verified against tidal observation data obtained from the Indonesian Geospatial Information Agency (BIG). Model performance was evaluated through time series analysis, spatial distribution analysis of sea level, and statistical verification using the correlation coefficient (r), coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). The results indicate that the model successfully reproduced the observed tidal pattern, with an r value of 0.793, an R^2 value of 0.629, an RMSE of 0.120 m, and an MAE of 0.091 m. The tidal regime in the study area is classified as mixed tide prevailing diurnal, while the spatial distribution reveals tidal propagation from east to west. Although the model slightly underestimated sea level during High Highest Water Level (HHWL) conditions, overall, Delft3D-FLOW demonstrated good performance and is suitable for coastal hydrodynamic analysis and coastal condition assessment in the Pekalongan coastal area.

Keyword: Deflt3D-Flow, Hydrodynamic Model, Sea Level, Tides.

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INTRODUCTION

Image processing allows extracting the meaning of an observed scene from the acquired information. Nowadays, there is a great interest in image processing algorithms able to work on mobile platforms (Abbasipayam & Mokrova, 2022). Indeed, incorporating image processing capabilities on mobile devices open new opportunities in different application contexts such as augmented reality, visual search, object recognition, and so on. However, the high computational complexity of some image processing algorithms and both their long processing time and energy consumption prevent them from being effectively used in real-time mobile applications. Thus, the practice of these algorithms on such a device is still a challenging task since these devices are typically limited by: power supply, battery capacity, energy consumption, computational power, RAM amount, etc. Tidal dynamics and sea level variations are important hydrodynamic processes that play a significant role in controlling oceanographic conditions in coastal areas. Variations in sea level elevation are influenced by the interaction between astronomical factors, such as the gravitational forces of the Moon and the Sun, and meteorological factors, including wind and atmospheric pressure. The combination of these factors can affect tidal patterns and changes in sea level, which in turn have implications for various coastal phenomena, such as tidal flooding, coastal erosion, sedimentation, and shoreline changes (Daud et al., 2025; Leatherman & Nicholls, 1995; Small & Nicholls, 2003; Smith, 1979). Therefore, understanding tidal dynamics and sea level variations is essential for coastal area management and disaster risk mitigation.

Numerical hydrodynamic modeling has become an effective approach for representing the dynamics of coastal waters. Compared with field observations, which are often limited in spatial and temporal coverage, numerical models are capable of simulating the spatial and temporal distribution of hydrodynamic parameters, thereby providing more comprehensive information. One of the widely used modeling platforms is Delft3D, a hydrodynamic modeling system developed by Deltares to simulate currents, tides, waves, sediment transport, and changes in sea surface elevation through the numerical solution of fluid flow equations in shallow-water environments (Deltares, 2014). The reliability of a numerical model largely depends on its ability to accurately represent observed conditions. Therefore, evaluating model performance against observational data is an essential step before the model is applied to further analysis or decision-making.

Several studies have demonstrated that Delft3D performs well in representing coastal hydrodynamic processes in Indonesia. (Hermawan et al., 2020) used Delft3D to model tidal flooding hydrodynamics along the Sidoarjo coast, while (Pratama, 2019) demonstrated that

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the model was capable of representing increases in sea level in Pekalongan associated with land subsidence. In addition,)(Gloria et al., 2023) reported that the combination of the FLOW and WAVE modules was capable of estimating inundation depth and extent with a high level of accuracy. Nevertheless, evaluations of Delft3D model performance in the Pekalongan coastal area remain limited, particularly under the hydrodynamic conditions and data availability examined in previous studies.

Since these studies were conducted, the Pekalongan coastal area has continued to undergo changes due to land subsidence, variations in hydrodynamic characteristics, and recurrent high-tide events, including those occurring in December 2024. These changing conditions highlight the need to reassess model performance using recent observational data to determine the model's ability to represent tidal dynamics and sea level variations under more current coastal conditions. In addition to serving as a model validation process, such an evaluation can provide information on the spatial characteristics of sea level elevation that can be used as a basis for further coastal hydrodynamic studies.

Based on these conditions, this study aims to evaluate the performance of the Delft3D-FLOW hydrodynamic model in simulating tidal dynamics and sea level variations in the Pekalongan coastal area during the period from 14 to 31 December 2024. The evaluation was conducted by comparing the simulation results with tidal observations from the Geospatial Information Agency (Badan Informasi Geospasial, BIG) using the correlation coefficient (r), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). In addition, the spatial distribution of simulated sea level elevation was analyzed to identify patterns of sea level variation during the study period. The results are expected to provide information on the reliability of Delft3D-FLOW in representing coastal hydrodynamic conditions and to serve as a reference for the application of numerical models in coastal dynamics studies in the Pekalongan area.

METHOD

Study Area and Data

This study employed a quantitative research design with a descriptive approach and was conducted in the coastal area of Pekalongan City, Central Java, Indonesia, geographically located between 6°50′42″–6°55′44″ S and 109°37′55″–109°42′19″ E. The simulation was conducted for the period from 14 to 31 December 2024, covering a period with a high potential for tidal flooding in the study area. Model verification was performed using tidal observation data from the Tidal Station operated by the Geospatial Information Agency

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(Badan Informasi Geospasial, BIG), located in North Pekalongan District at coordinates 6°51'30.528" S and 109°41'33.900" E.

The datasets used in this study included zonal wind (u), meridional wind (v), and Mean Sea Level Pressure (MSLP) data obtained from the ERA5 Hourly Data on Single Levels provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), with a spatial resolution of 0.25° and a temporal resolution of 6 hours. Bathymetric data were obtained from the National Bathymetry (BATNAS) dataset provided by the Geospatial Information Agency (BIG), while tidal boundary conditions were derived from the TPXO harmonic tidal model. The simulation results were evaluated against BIG tidal observation data provided in CSV format.

Hydrodynamic Model Configuration

Hydrodynamic simulations were conducted using the Delft3D-FLOW module with a spherical coordinate system. The modeling domain covered the coastal waters of Pekalongan City extending approximately 12 nautical miles offshore from the coastline, in accordance with the coastal waters boundary provisions stipulated in Law No. 1 of 2014 concerning the Management of Coastal Areas and Small Islands.

BATNAS bathymetric data were used to represent the seafloor conditions, while tidal boundary conditions were generated using TPXO harmonic tidal data. Meteorological factors were incorporated as atmospheric forcing, including zonal wind (u), meridional wind (v), and MSLP data from ERA5. The simulation generated sea level elevation data in both time-series and spatial distribution formats throughout the study period.

Table 1. Model Configuration

Parameters	Value
Grid size	400 x 200
Grid Cells	80,000
Time Step	60 s
Tidal Forcing	Yes
Roughness Formula	Chezy
Smoothing Time	60 min

Model Verification

Model performance was evaluated by comparing the Delft3D-FLOW simulation results

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with tidal observation data from the BIG Tidal Station. The agreement between the model results and observations was assessed using the correlation coefficient (r), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). The correlation coefficient was used to measure the strength of the relationship between the simulated and observed values, while RMSE and MAE were used to quantify the magnitude of deviations between the simulation results and observations. The corresponding equations are presented in Equations (1), (2), and (3).

$$r = \frac{\sum xy - (\sum x)(\sum y)}{\sqrt{\{n \sum x^2 - (\sum x)^2\}\{n \sum y^2 - (\sum y)^2\}}} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (2)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (3)$$

Description:

n = number of data points

x = correlation coefficient

x = variable 1

y = variable 2

y_i = model predicted data

$\hat{y}_i$ = observed data

RESULTS AND DISCUSSION

Temporal Characteristics of Sea Level

The sea level simulation results obtained using Delft3D-FLOW were evaluated by comparing them with tidal observation data from the Tidal Station of the Geospatial Information Agency (BIG) during the period from 15 to 31 December 2024.

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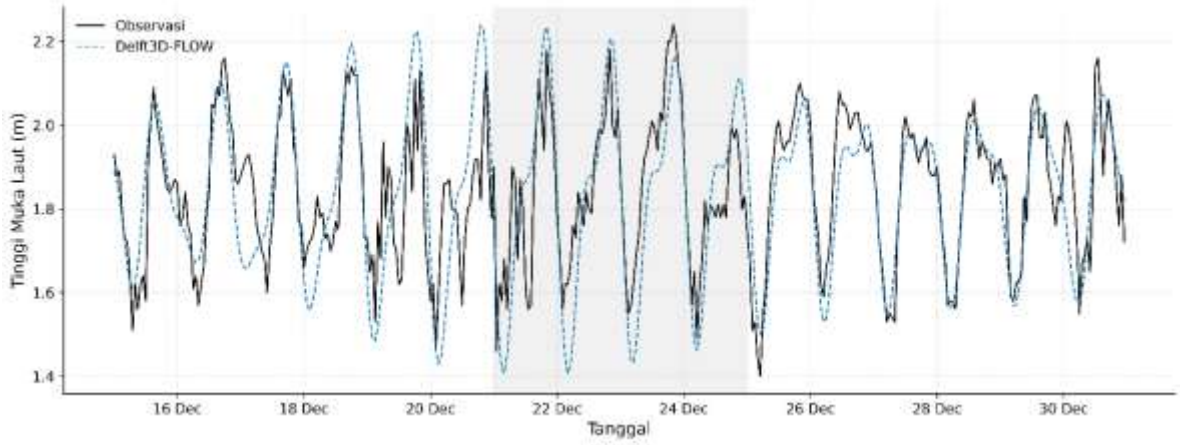


Figure 1. Time series of Delft3D simulation and observed sea level, with the tidal flooding period (gray shading)

As shown in Figure 1, the Delft3D-FLOW simulation results were able to reproduce the tidal fluctuation patterns observed throughout the study period. The model successfully represented both rising and falling tidal phases, as well as the timing of the highest and lowest tides, with patterns that were generally consistent with the observations. Nevertheless, discrepancies between the simulation results and observations were still evident during certain periods, particularly when sea level elevation changed rapidly. These differences indicate that the model was not yet able to fully reproduce all sea level variations observed in the field, although the overall temporal pattern was simulated well.

The gray-shaded area in Figure 1 represents the tidal flooding event during 21–25 December 2024, which was the primary focus of the evaluation in this study. During this period, Delft3D-FLOW continued to reproduce the tidal patterns observed in the field, including the timing of high and low tides. Although some differences in amplitude remained between the simulation results and observations, the consistent representation of tidal phases indicates that the model performed well in representing sea level dynamics during the tidal flooding event.

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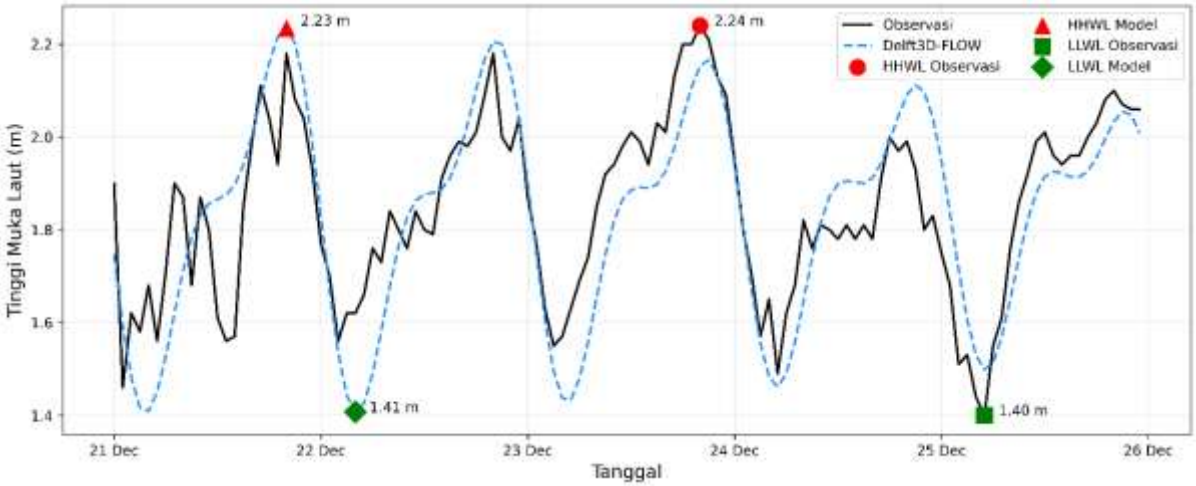


Figure 2. Time series of Delft3D simulation and observed sea level during the tidal flooding period, 21–26 December 2024

Based on Figure 2, the Delft3D-FLOW simulation results indicate that sea level dynamics during the period from 21 to 26 December 2024 followed the tidal patterns observed in the observational data. The sea level fluctuations exhibited a mixed, mainly semidiurnal tidal regime, characterized by two high tides and two low tides generally occurring within a day, with unequal water levels and time intervals between successive tidal phases (Wyrtki, 1961). This characteristic is evident from the occurrence of two tidal peaks and two tidal troughs per day, with varying amplitudes throughout the study period.

The Delft3D-FLOW model was able to represent the highest high water level (HHWL) and lowest low water level (LLWL) during the study period with good accuracy. The simulation produced an HHWL of 2.23 m, while the observational data recorded 2.24 m, resulting in a difference of only 0.01 m. Similarly, for the LLWL, the simulation produced an elevation of 1.41 m, whereas the observations recorded 1.40 m, also resulting in a difference of 0.01 m. Although the extreme sea level elevations simulated by the model were very close to the observations, the timing of the HHWL and LLWL did not fully coincide. This temporal discrepancy indicates that the model still has limitations in representing sea level dynamics under extreme conditions. These differences may be influenced by hydrodynamic and hydrometeorological processes that were not fully incorporated into the simulation, such as rainfall, river discharge, and other local conditions.

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Temporal Characteristics of Sea Level

The evaluation was conducted using density scatter plot and residual plot analyses, supported by statistical parameters including the correlation coefficient (r), coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). These approaches were employed to assess the model's ability to represent temporal variations and the degree of agreement between the simulation results and observational data.

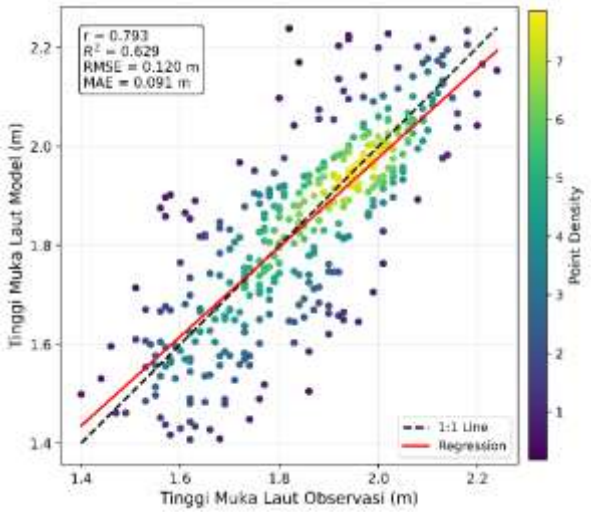


Figure 3. Density scatter plot

The relationship between the simulation results and observational data is presented in Figure 3 using a density scatter plot. Most of the data points are concentrated around the 1:1 line and follow the direction of the regression line, indicating good agreement between the simulation results and observations. The high concentration of points within the sea level elevation range of approximately 1.85–2.00 m indicates that the model performed well in representing the most frequently occurring sea level conditions during the simulation period.

Nevertheless, several data points at lower and higher elevations deviate from the 1:1 line, indicating model discrepancies under certain conditions. In addition, the slope of the regression line being slightly lower than that of the 1:1 line indicates a tendency for the model to slightly overestimate sea level at lower elevations and underestimate it at higher elevations. However, these deviations are relatively small and do not substantially affect the overall relationship between the simulation results and observational data.

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Table 2. Model Performances

Parameters	Value	Interpretation
Correlation Coefficient (r)	0.793	Strong relationship
Coefficient of Determination (R^2)	0.629	62.9% explained
RMSE (m)	0.120	Low deviation
MAE (m)	0.091	9.1 cm error

Statistically, the simulation results yielded a correlation coefficient (r) of 0.793, indicating a strong relationship between the simulation results and observational data. The coefficient of determination (R^2) of 0.629 indicates that approximately 62.9% of the variation in observed sea level can be explained by the Delft3D-FLOW model. In addition, the RMSE of 0.120 m and MAE of 0.091 m indicate relatively small deviations from the observations. These results demonstrate that Delft3D-FLOW performs well in simulating sea level in the Pekalongan coastal area during the study period.

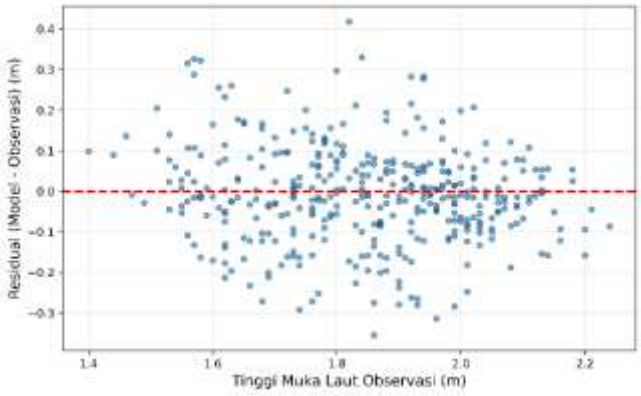


Figure 4. Residual plot

The model error pattern was further analyzed using the residual plot presented in Figure 4. The residuals were mostly distributed around the zero line without forming a distinct pattern with changes in the observed sea level. This indicates that the model errors are predominantly random and do not show a systematic tendency toward overestimation or underestimation. Although several relatively large residuals were observed, they were limited in number and distributed across various sea level elevation ranges, with no clear bias pattern. Therefore, the model errors are more likely influenced by local variations than by systematic errors in the model formulation.

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Spatial Distribution of Sea Level

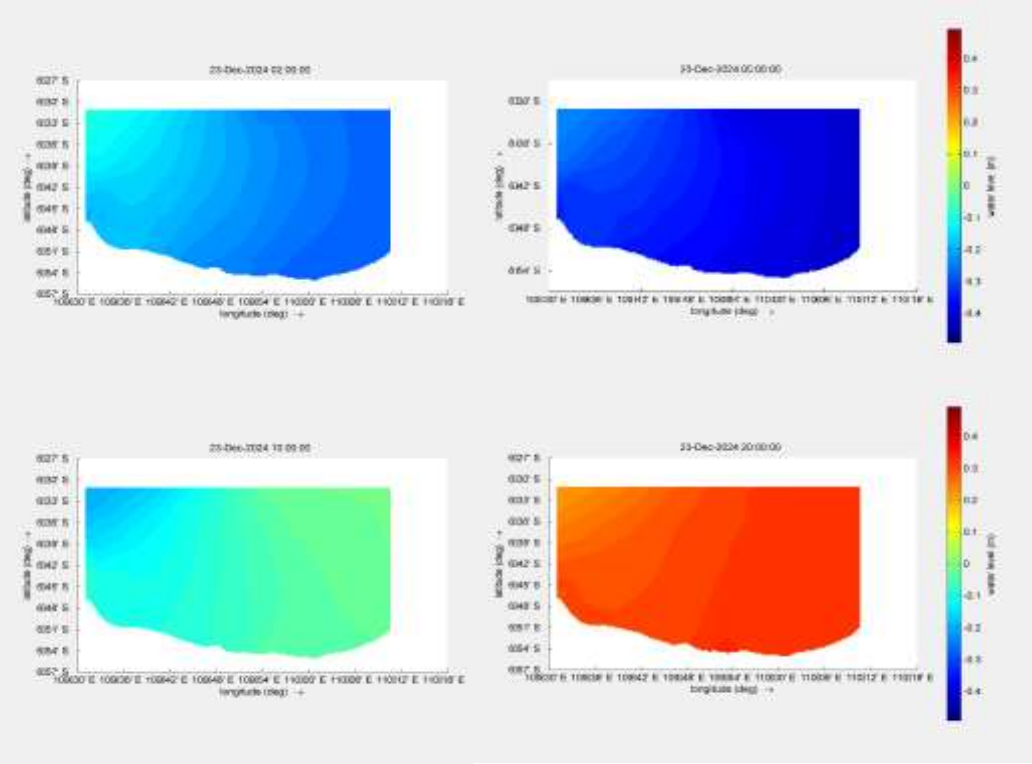


Figure 5. Spatial Distribution of Sea Level

The spatial distribution of sea level simulated by Delft3D-FLOW during four tidal phases is presented in Figure 5. The analysis was conducted for the ebbing phase (02:00 UTC), lowest low water level (LLWL) (05:00 UTC), flooding phase (10:00 UTC), and highest high water level (HHWL) (20:00 UTC) to illustrate changes in sea level elevation throughout a single tidal cycle during the tidal flooding period on 23 December 2024.

During the ebbing phase (02:00 UTC), sea level elevation began to gradually decrease from the eastern toward the western part of the study area. This condition is indicated by the color gradient, which changes from light blue in the west to darker blue in the east, suggesting that the ebbing process occurred earlier in the eastern part of the Pekalongan coast. At the BIG observation point, the model produced a sea level elevation of 1.60 m, while the observed value was 1.63 m, resulting in a difference of approximately 0.03 m.

The lowest low water level (LLWL) occurred at 05:00 UTC, with the sea level distribution across the modeling domain predominantly represented by blue shades. The eastern region

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continued to exhibit lower elevations than the western region, indicating that the maximum ebbing condition developed first in the east before propagating to other areas. At this stage, the model produced a minimum elevation of 1.43 m, while the observation recorded 1.55 m. Although the model underestimated the elevation by approximately 0.12 m, the simulated spatial pattern remained consistent with the maximum ebbing phase.

During the flooding phase (10:00 UTC), sea level elevation gradually increased again. The increase initially occurred in the eastern region, indicated by a transition toward green shades, before propagating westward. At the BIG observation point, the model produced an elevation of 1.82 m, while the observed value was 1.94 m, resulting in a difference of approximately 0.12 m. These results indicate that the model was able to represent the transition from ebbing to flooding conditions, although a slight underestimation relative to the observations remained.

The highest high water level (HHWL) occurred at 20:00 UTC, with the sea level distribution relatively homogeneous and predominantly represented by orange to red shades across the modeling domain. Nevertheless, the elevation gradient still indicated slightly higher sea levels in the eastern region than in the western region. At the BIG observation point, the model produced a maximum elevation of 2.15 m, while the observed value was 2.24 m, resulting in a difference of approximately 0.09 m. This difference indicates a slight underestimation of the actual sea level; however, the model was still able to adequately represent the characteristics of the maximum tidal phase.

CONCLUSION

Based on the results, the Delft3D-FLOW hydrodynamic model performed well in representing tidal dynamics and sea level variations in the Pekalongan coastal area during December 2024. Validation against observational data yielded a correlation coefficient of 0.793, an RMSE of 0.120 m, and an MAE of 0.091 m, indicating good agreement between the simulation results and observations. Temporally, the simulation successfully reproduced the tidal fluctuation patterns, characterized by a mixed, mainly semidiurnal tidal regime, and represented the highest high water level (HHWL) and lowest low water level (LLWL) with relatively small elevation differences compared with observations, although discrepancies remained in the timing of extreme conditions. Spatially, the simulation showed that tidal propagation occurred gradually from the eastern toward the western part of the Pekalongan coast, with the flooding phase lasting longer than the ebbing phase. The remaining discrepancies between the simulation and observations, particularly during maximum tidal conditions, indicate that some local hydrodynamic processes were not fully represented in the model. Nevertheless, the results

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demonstrate that Delft3D-FLOW can serve as a reliable tool for analyzing sea level dynamics in the Pekalongan coastal area and supporting future coastal hydrodynamic studies.

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