

# Hydrodynamic Modeling of Tides Using Delft3D in the Coastal Area of Pangali–Ali, Majene Regency

Imam Rohani<sup>1</sup>, Apriansyah<sup>2</sup>, Raodhatul Jannah<sup>3\*</sup>

Author One<sup>1</sup>, Author Two<sup>2</sup>, Author Three<sup>3\*</sup>

<sup>1</sup>Civil Engineering Department, Faculty of Engineering, Universitas Sulawesi Barat, Majene, Indonesia.

<sup>2</sup>Civil Engineering Department, Faculty of Engineering, Universitas Sulawesi Barat, Majene, Indonesia

<sup>3</sup>Civil Engineering Department, Faculty of Engineering, Universitas Sulawesi Barat, Majene, Indonesia

\*[raodhatuljannah400@gmail.com](mailto:raodhatuljannah400@gmail.com)

## Abstract

*The waters surrounding Pangali–Ali Beach, located in Majene Regency, West Sulawesi Province, represent a coastal area that plays a strategic role in the local community's social, economic, and ecological aspects. The relatively high level of fishing activity in this region makes tidal information an essential dataset to support sustainable coastal management and planning. This study aims to identify the hydrodynamic characteristics, particularly tides, at Pangali–Ali Beach as a basis for designing coastal protection structures. The research was conducted using numerical modeling with Delft3D, incorporating tidal data and bathymetric maps as input. Delft3D was selected due to its strong numerical performance and comprehensive features for simulating coastal and marine water dynamics. The simulation results for December 2021 indicate that the maximum sea level (highest tide) reached approximately 0.956 m, while the minimum sea level (lowest tide) ranged from 0.05 to 0.1 m. Based on the sea-level elevation analysis, the tidal pattern at Pangali–Ali Beach is classified as semi-diurnal, characterized by two high tides and two low tides within a day.*

**Keywords**— Tidal dynamics, Delft3D modeling, Pangali–Ali coastal, Hydrodynamic characteristics

## I. INTRODUCTION

Indonesia's archipelagic regions have largely developed from coastal areas, making coastal protection an important aspect of regional development. One commonly applied method of shoreline protection is the construction of breakwaters, particularly in the waters of West Sulawesi (Rohani and others 2020; Saengsupavanich et al. 2022).

Tides are periodic fluctuations in sea level caused by the gravitational forces of the moon and the sun. Tidal observation is essential for establishing a vertical datum, as it enables alignment between marine and terrestrial measurement data so that they can be consistently used within an integrated mapping system (Fitriana and others 2019). Tides can also be defined as sea-level variations resulting from the gravitational attraction of celestial bodies, primarily the moon and the sun, acting on the Earth's ocean masses. Although the moon's mass is much smaller than that of the sun, its closer distance to the Earth results in a stronger gravitational influence. In general, the moon's tidal force is estimated to be about 2.2 times greater than that of the sun (Triatmodjo 1999).

At Pangali–Ali Beach, tides have a considerable impact on the adjacent land area. Changes in sea level affect the surrounding coastal environment. During high tide, seawater may overflow onto land, especially along gently sloping beaches, potentially causing inundation, temporarily shifting the shoreline position, triggering coastal erosion, and allowing saltwater intrusion into normally dry areas such as agricultural fields or fish ponds. Conversely, during low tide, the sea retreats away from the shore, exposing the seabed that is usually submerged (Asrofi and others 2024). Local communities often take advantage of low-tide conditions to collect marine resources in the intertidal zone; however, extremely low tides may hinder fishing activities by making it difficult for boats to dock (Maria Teresa Reis, João Alfredo Santos 2025).

In general, the coastal area of Majene experiences a semi-diurnal tidal pattern, characterized by two high tides and two low tides within 24 hours, with varying tidal ranges across different periods. Such tidal variability is a natural phenomenon influenced by astronomical cycles. Therefore, coastal protection structures are required to safeguard shorelines and settlements. Several types of coastal protection structures commonly used include seawalls to protect settlements from tidal flooding during extreme high tides, breakwaters to reduce wave energy, and revetments to stabilize coastal slopes. In planning these structures, tidal data serve as one of the key parameters required.

In addition to supporting coastal protection design, tidal data also play a crucial role in coastal disaster mitigation, particularly in relation to tidal flooding, storm surges, tsunamis, and coastal erosion. Majene Regency is considered a coastal region with topographic conditions that are vulnerable to disasters. Therefore, harmonic tidal analysis is necessary for the waters of Majene. This tidal modeling is expected not only to enhance understanding of marine dynamics but also to serve as a critical step in mitigating disaster risks such as tidal flooding and tsunamis.

Monthly tidal conditions can be classified into two main types: spring tides and neap tides (Dzul Qarnain and others 2014). Spring tides occur when the Earth, moon, and sun are aligned in a straight line, typically during the new moon and full moon phases (around the 1st and 15th days of the lunar month). In this configuration, the gravitational forces of the moon and sun reinforce each other, producing higher-than-average high tides and lower-than-average low tides. In contrast, neap tides occur when the moon and sun form a right angle relative to the Earth, typically during the first and third quarter moon phases (around the 7th and 21st days). In this situation, the gravitational forces partially counteract each other, resulting in smaller tidal ranges compared to other days.

Delft3D is a numerical simulation software developed by Deltares to model hydrodynamic processes, sediment transport, morphology, water quality, and ecosystems in various aquatic environments such as rivers, lakes, coastal zones, and marine waters. One of its key modules is Delft3D-FLOW, a hydrodynamic module capable of simulating unsteady flow and transport phenomena driven by tides or meteorological forcing (Ma 2019).

According to the Delft3D-FLOW Manual, this module enables multidimensional hydrodynamic simulations (in both 2D and 3D). The program is used to compute flow and current patterns generated by tides and meteorological conditions, using either rectangular or curvilinear grid systems adjusted to the modeling domain boundaries. In this study, a Cartesian square grid was applied, which was generated using the Delft3D-RGFGRID tool (Hardiansyah et al. 2021).

## **II. RESEARCH METHOD**

This study applies a numerical modeling approach using the Delft3D software to simulate tidal conditions in the waters of Pangali–Ali Beach, Majene Regency. The main data used in the modeling process consist of tidal data obtained from the Indonesian Geospatial Information Agency (BIG) and bathymetric maps as the primary model inputs. The modeling procedure includes the development of the computational domain and grid, the definition of model boundaries, data calibration, and validation of the simulation results against BIG observation data (Gerritsen and de Goede 2007).

### **A. Tidal Data**

The tidal data used in this study were obtained from the BIG website for a one-month period, from 1 December 2021 to 31 December 2021. The tidal analysis was performed using the Delft3D–FLOW module by importing the

observational tidal data file in (.obs) format and conducting the analysis through the TIDE Window. The results were then used to determine the amplitude and phase of tides in the Pangali–Ali coastal waters (Deltares 2010).

#### B. Bathymetry Data

The bathymetry data used in this research represent water depth information around the study area and were acquired from tanahair.indonesia.go.id. Bathymetric data processing was carried out using QGIS (Quantum Geographic Information System) by importing bathymetry raster datasets such as BATNAS (Geospatial Information Agency (BIG) 2019). Spatial analysis tools and available plugins in QGIS were subsequently utilized to visualize and analyze seabed depth and underwater morphology in the Pangali–Ali coastal area.

#### C. Model Validation

A model that has undergone validation and demonstrates a high level of agreement with real field conditions can be used to predict changes and dynamic processes occurring in coastal waters (Adibhusana and others 2016) . After running the simulation using BIG tidal observation data, the next step is validation to assess the quality and consistency of the simulation results compared to the BIG reference dataset.

In this study, statistical indicators such as the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) are employed to quantify the deviation between model outputs and observational data, allowing the evaluation of model performance and error magnitude. RMSE is considered advantageous because it accounts for error distribution without using absolute values in the computation, making it more sensitive to larger errors. The RMSE and MAE values can be calculated using the following equations (Deltares 2010):

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

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

Description:

n = Total number of observations

$y_i$  = Measured field data

$\hat{y}_i$  = Model output data

### III. RESULTS AND DISCUSSION

#### A. Domain Model

The development of the hydrodynamic model begins with defining the land boundary and generating the computational grid to represent the modeling area, as shown in Figure 1. This step is essential to establish the simulation extent and the physical limitations of the study area.

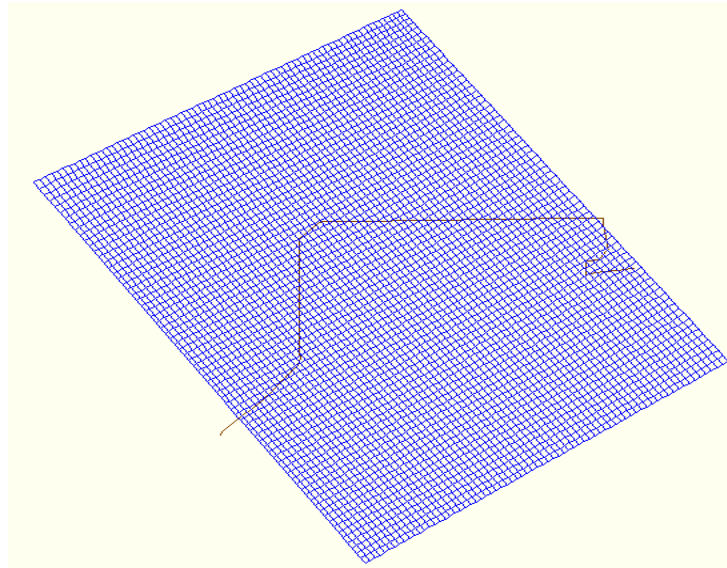


Figure 1. Grid and Landboundary

The figure shows the computational grid used in tidal hydrodynamic modeling with Delft3D-FLOW, which was generated using the Delft3D-RGFGRID module. This Cartesian (rectangular) grid consists of small cells that serve as numerical calculation elements, allowing Delft3D to compute parameters such as sea surface elevation and current patterns across the modeling domain. Grid resolution influences simulation accuracy, where a finer grid generally produces more detailed results but requires greater computational time. The grid was designed to match the study area in the waters of Pangali–Ali Beach, ensuring that the simulation can represent tidal conditions more accurately.

Furthermore, a meshing process is conducted to integrate bathymetric (depth) information into the model grid. Figure 2 illustrates the meshed grid with integrated bathymetry, which serves as a basis for further hydrodynamic analysis.

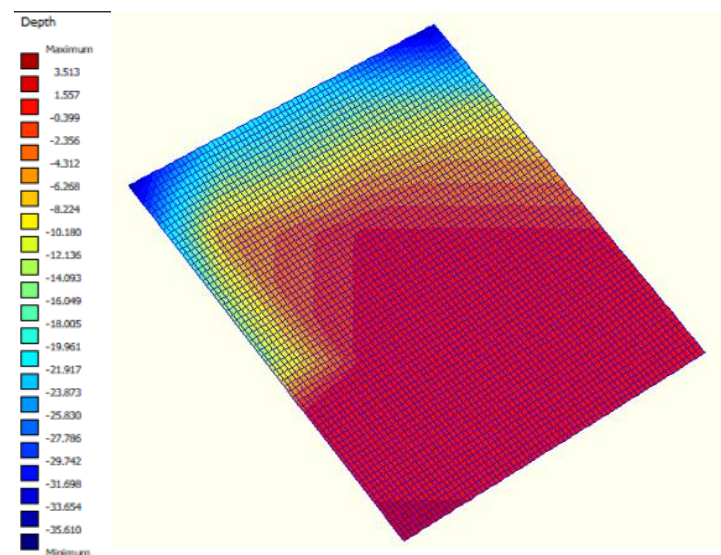


Figure 2. Meshing Grid and Depth

Figure 2 shows the meshing grid combined with water depth (bathymetry) information within the Delft3D modeling domain. The Cartesian grid consists of numerical computational cells, while the color variation represents the depth distribution, where red–yellow indicates relatively shallower waters and green–blue indicates deeper areas. The depth scale is displayed in the legend on the left side of the figure, illustrating gradual bathymetric changes across different parts of the domain. This visualization is important to ensure that the model accurately represents seabed morphology, since water depth strongly influences current patterns and tidal dynamics in the simulation process.

## B. Tidal Analysis

Based on the tidal data analysis from the Indonesian Geospatial Information Agency (BIG) over the last ten years (2014–2023), the highest tide at Pangali–Ali Beach occurred on 6 December 2021 at 11:00:00, with a maximum water level of approximately 0.965 m. Therefore, BIG tidal data for December 2021 were used as the main input for a one-month model simulation.

The results of the tidal analysis for Pangali–Ali Beach in 6 December 2021 are presented in Table 1. These results were subsequently used as input parameters in the Delft3D software.

Table 1. Tidal Data of Pangali–Ali Beach

Time	Water Level (m)	Time	Water Level (m)
00:00:00	0.102	12:00:00	0.862
01:00:00	0.154	13:00:00	0.664
02:00:00	0.159	14:00:00	0.52
03:00:00	0.076	15:00:00	0.38
04:00:00	0.079	16:00:00	0.21
05:00:00	0.168	17:00:00	0.228
06:00:00	0.165	18:00:00	0.17
07:00:00	0.384	19:00:00	0.258
08:00:00	0.52	20:00:00	0.226
09:00:00	0.788	21:00:00	0.213
10:00:00	0.943	22:00:00	0.25
11:00:00	0.965	23:00:00	0.149

*Source: Indonesian Geospatial Information Agency (BIG)*

Table 1 presents the hourly tidal water level data at Pangali–Ali Beach obtained from the Indonesian Geospatial Information Agency (BIG). The table shows sea level fluctuations over a 24-hour period, indicating the rise and fall of water levels throughout the day. The water level gradually increases from 0.102 m at 00:00 to its peak value of 0.965 m at 11:00, representing the highest tide during the observation period. After reaching the maximum level, the sea surface elevation decreases steadily and reaches lower values in the afternoon and evening, with water levels ranging between 0.210 m and 0.258 m from 16:00 to 22:00. This dataset is essential as input for tidal analysis

and numerical modeling, as it provides baseline information for determining tidal amplitude, phase, and daily tidal characteristics in the Pangali–Ali coastal waters.

### C. Tidal Modeling Results

#### 1. Peak High Tide

The simulation output can be visualized using the QUICKPLOT feature, which is available to generate basic graphical representations of data or create rapid animations. The simulation results of tidal modeling at Pangali–Ali Beach are shown in Figure 3.

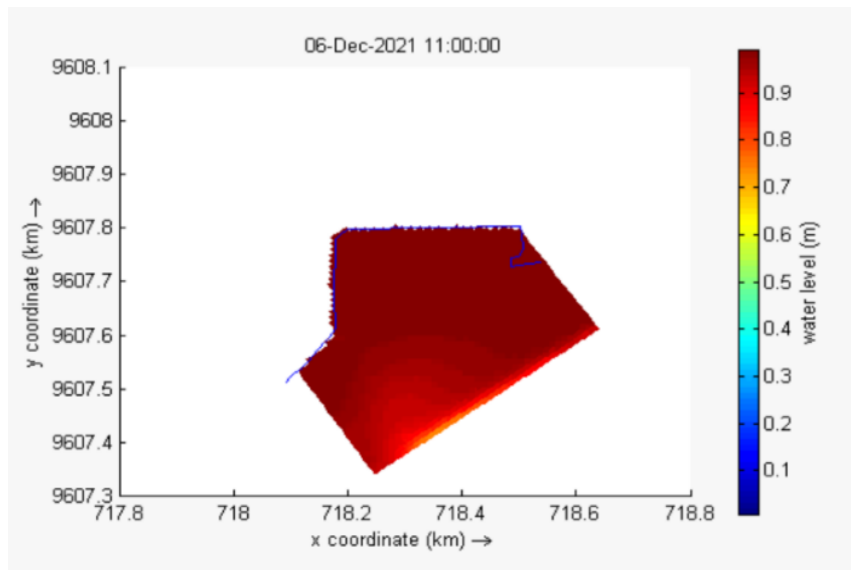


Figure 3. Peak High Tide Condition

The simulation indicates that the maximum water level at Pangali–Ali Beach reaches approximately 0.95 m. This value is consistent with local tidal forecasts for Majene Harbor, where extreme conditions may reach 0.8–1.4 m; therefore, the modeled value of 0.95 m falls within a realistic range (Tide-Forecast; Tide.Today).

In addition, the spatial distribution in Figure 3 shows relatively elevated water levels across the modeling domain at the time of peak high tide (06-Dec-2021 11:00:00), which is consistent with the expected response of coastal waters to astronomical tidal forcing. Delft3D-FLOW is specifically designed to simulate multi-dimensional hydrodynamic flows driven by boundary conditions such as tides, allowing water-level gradients and their propagation within a coastal domain to be represented numerically (Idier et al. 2019). Moreover, peak coastal water levels can be further influenced by non-tidal processes such as wind-driven setup and wave setup, which may locally increase sea level—particularly in shallow nearshore settings—making the modeled peak conditions physically plausible when interpreted together with local forecasting ranges.

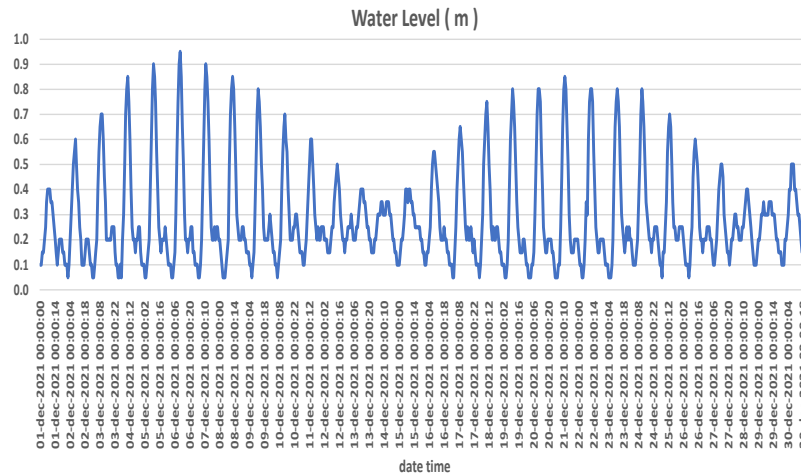


Figure 4. Tidal Water Level

Based on the modeling results and the water level condition graph (Figure 4), sea-level variations exhibit a regular and repetitive pattern, with peak tides around 0.95 m and low tides approximately 0.1 m. This pattern reflects a semi-diurnal tidal regime, characterized by two high tides and two low tides within one day. Overall, the modeled sea level appears relatively stable without extreme spikes, indicating that the water level simulation adequately represents actual tidal conditions.

## 2. Spring High Tide

The simulation results show that during the spring tide period (Figure 5), the peak sea level at Pangali–Ali Beach reaches approximately 0.9–1.0 m. This condition consistently occurs in the early month (5–7 December) and mid-month (20–22 December). This is physically consistent since spring tides, from an astronomical perspective, produce larger tidal amplitudes. In addition, the Banggae area (Pangali–Ali) is located within a bay-like coastal setting that is susceptible to local sea-level amplification due to wind setup and bathymetric effects.

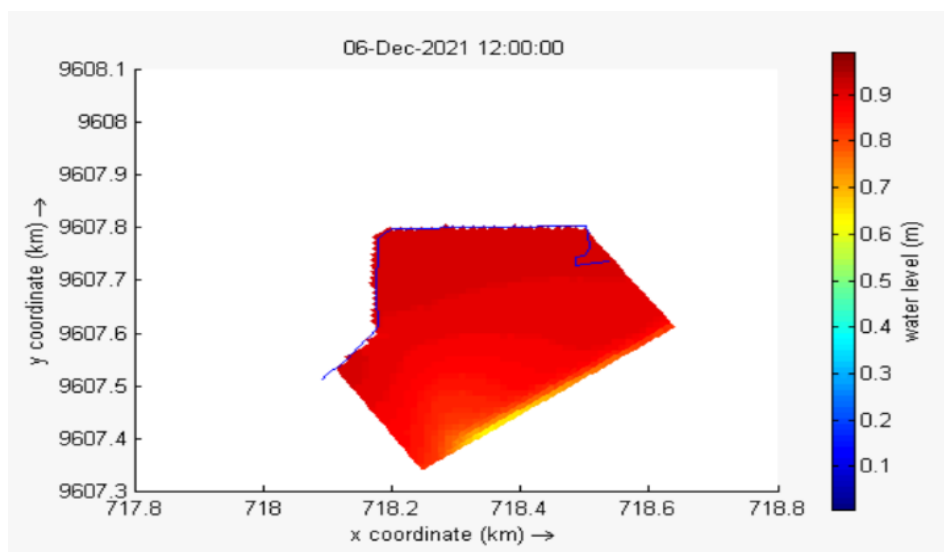


Figure 5. Spring High Tide Condition

According to (STMKG, 2015), the simulation has been calibrated against the nearest tidal observations/forecasts and analyzed through sensitivity testing regarding wind and wave contributions as well as bathymetric variations. The combined effects of astronomical tides and wind/wave setup demonstrate an increase in sea level that corresponds to the modeled peak values. Hence, the range of 0.9–1.0 m can be considered realistic for spring high tide conditions in the study area and relevant for coastal flood mitigation assessments.

Furthermore, local studies on prevailing wind patterns and wave characteristics at Pangali–Ali Beach indicate the occurrence of localized sea-surface setup. This increase results from the combined influence of astronomical tides and wind and wave forcing, which were also incorporated into the model (Yusman, Rohani, and Apriansyah 2025).

### 3. Spring Low Tide

Based on the Delft3D simulation (Figure 6), the spring low tide condition at Pangali–Ali Beach occurred on 21 December 2021, with minimum sea levels ranging from 0.05 to 0.1 m. This value is considered realistic because the spring tide period produces the largest tidal range due to the combined gravitational influence of the moon and the sun.

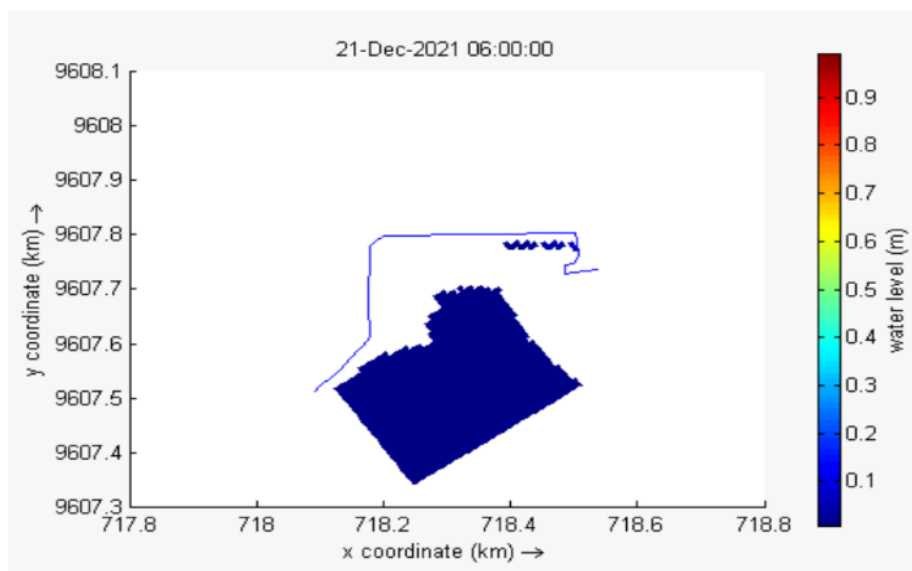


Figure 6. Spring Low Tide Condition

A similar phenomenon was reported by (Nurhayati 2018) in a study conducted at Nusa Dua Beach, Bali, which documented minimum sea levels of approximately 0.05–0.1 m during spring low tide. Morphologically, Pangali–Ali Beach, located on the western coast of Majene, is characterized by relatively shallow and semi-enclosed waters, making it more susceptible to extreme sea-level variations. Therefore, the modeled spring low tide range of 0.05–0.1 m can be considered valid and consistent with tidal characteristics in West Sulawesi.

Moreover, Figure 6 (21-Dec-2021 06:00:00) shows a pronounced drawdown of water levels across the domain, which is consistent with the larger tidal range typically associated with spring-tide conditions in semi-enclosed, shallow coastal settings. In such basins, geometry and bathymetry strongly control tide propagation, and local topographic effects can enhance sea-level extremes through co-oscillation and amplification processes, making

unusually low water levels physically plausible during spring low tide (Roos and Schuttelaars 2011). In addition, nearshore hydrodynamics can further modulate the mean water level through wave–current interactions (e.g., radiation-stress gradients linked to wave set-up/set-down), which can contribute to spatial variability in coastal water levels even when the primary forcing is astronomical tides.

#### 4. Neap High Tide

During the period 11–13 December 2021 (Figure 7), the Delft3D simulation results show that the maximum sea level ranges between 0.4 and 0.5 m. This condition corresponds to the neap tide phase, which astronomically occurs during the first and third quarter moon phases. In this phase, the gravitational forces of the Sun and the Moon partially cancel each other, resulting in lower maximum sea levels compared to spring tides.

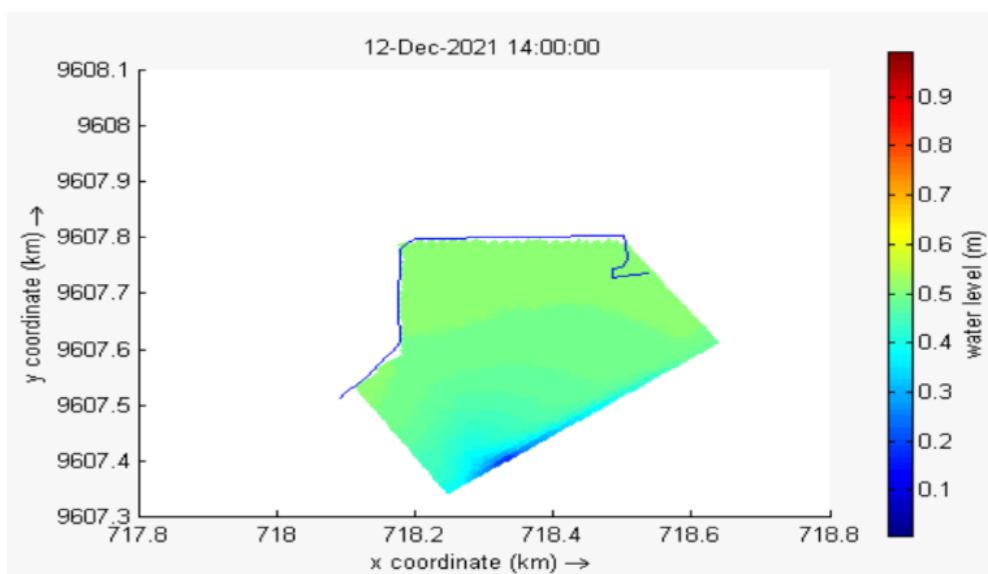


Figure 7. Neap High Tide Condition

These findings are consistent with (Numeris and others 2018), which reported that maximum sea levels during neap tides range from approximately 0.4 to 0.6 m. Therefore, the simulation results can be considered hydrodynamically valid and realistic.

In addition, the spatial pattern in Figure 7 (12-Dec-2021 14:00:00) illustrates a more moderate and relatively uniform water-level distribution compared to spring-tide conditions, which is expected during a neap tide when tidal forcing is weaker. From a physical perspective, nearshore sea levels can also be modulated by wave setup, defined as an increase in mean water level caused by breaking waves and associated radiation-stress gradients. This process may contribute to localized sea-level enhancement in shallow coastal waters, making the modeled neap high-tide condition physically reasonable when interpreted together with local hydrodynamic processes (Mark L. Buckley 2015).

#### 5. Neap Low Tide

During the neap tide period (Figure 8), neap low tide conditions were also observed, with minimum sea levels around 0.2–0.3 m. This indicates that tidal fluctuations during neap tides are relatively moderate, with a smaller tidal range compared to spring tide conditions.

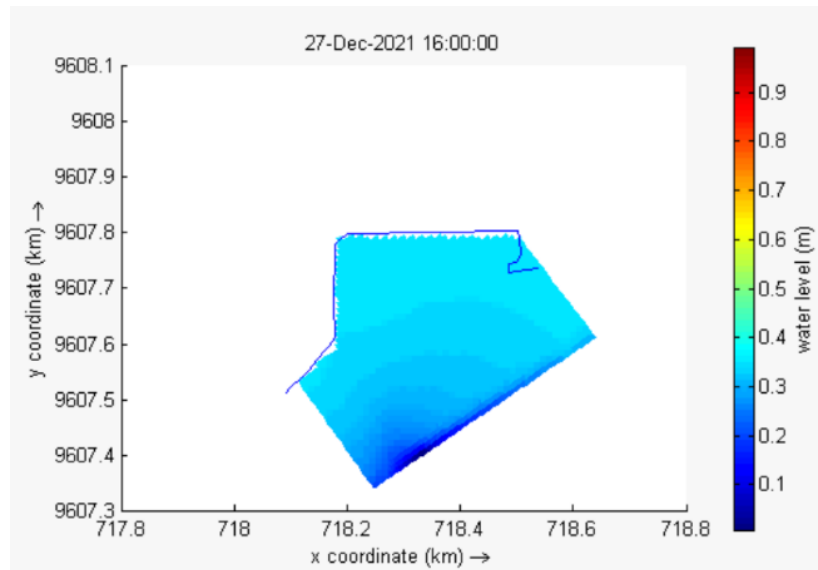


Figure 8. Neap Low Tide Condition

The Delft3D model results suggest that neap low tide at Pangali–Ali Beach produces minimum sea levels ranging from 0.2 to 0.3 m. Physically, this phenomenon is caused by the astronomical configuration of the Sun and Moon during quarter phases, where their gravitational forces form a perpendicular alignment relative to the Earth, leading to a reduced tidal amplitude. In addition, the relatively gentle coastal slope and shallow waters near the estuary contribute to damping sea-level fluctuations during the neap phase.

In Figure 8 (27-Dec-2021 16:00:00), the spatial field shows a relatively modest and smoother drawdown compared with spring-tide minima, which is consistent with neap-phase conditions where tidal forcing (and thus the tidal range) is reduced and the resulting water-level gradients inside a coastal domain are generally weaker. Recent estuarine studies emphasize that the expression of spring–neap variability and low-water conditions is strongly controlled by local geometry and bathymetry, because changes in depth and planform shape affect tidal propagation, attenuation/amplification, and the resulting asymmetry and extremes (Wünsche et al. 2024). Additionally, even during neap conditions, nearshore mean water level can be locally modified by processes such as wave setup, which can partially offset low-water levels in shallow coastal zones and contribute to the spatial variability seen in the model output.

#### D. Model Validation

Model validation was conducted to evaluate the agreement between the tidal input dataset and the simulation outputs, as well as to quantify the error between the modeled results and actual observations. The validation compared secondary BIG tidal data with the Delft3D simulation output.

Tidal data collected over 31 days, from 1 December 2019 to 31 December 2019, were input into Delft3D to generate a simulated tide graph based on the provided observations. In this validation process, the RMSE value was calculated using 721 data samples. The results yielded an RMSE of 0.048 m and an MAE of 0.039 m. These error values are considered small, as they remain below 0.1 m, indicating that the simulated sea-level results show good agreement with BIG data.

Based on the calculation, the RMSE value of 0.049 m corresponds to a relative error of approximately 5.8%, while the MAE value of 0.039 m corresponds to an error of approximately 4.6%. Since these errors are below 10%, the tidal model can be classified as accurate in representing observed sea-level conditions.

Therefore, the Delft3D model used in this study is capable of representing tidal dynamics at the study location with sufficient accuracy. The comparison between BIG tidal observations and Delft3D simulation results is presented in Figure 9.

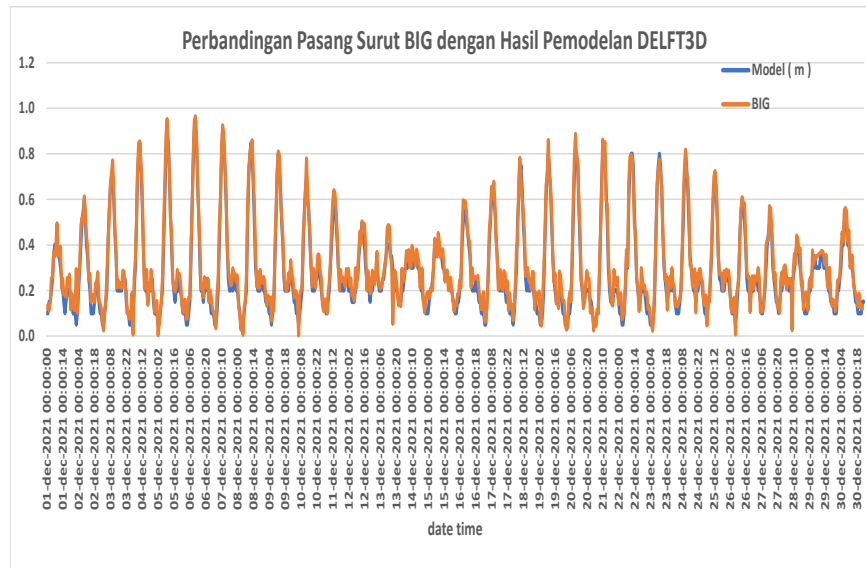


Figure 9. Observed vs. Simulated Tidal Water Levels (BIG and Delft3D)

Based on the comparison graph, both the BIG observational data and Delft3D simulation output show sea-level elevations that tend to remain positive. This is because both datasets use Lowest Astronomical Tide (LAT) as the zero reference datum. Under this reference, sea-level values are expressed relative to the lowest tidal level, resulting in no negative values. However, slight differences between the simulation and observational results are observed, which may be caused by discrepancies in boundary parameters or bathymetry representation within the model.

#### IV CONCLUSION

This study successfully modeled the hydrodynamic conditions at Pangali–Ali Beach, Majene Regency, using a numerical approach through the Delft3D software. Based on the tidal simulation results for December 2021, the highest tide occurred on 6 December 2021 at 11:00:00, with a water level elevation of approximately 0.95 m, while the lowest tide occurred on 26 December 2021 at 06:00:00, with a minimum sea level ranging from 0.05 to 0.1 m.

The tidal characteristics at Pangali–Ali Beach indicate that the maximum sea level reaches about 0.95 m, while the Delft3D model results show values within the range of approximately 0.9 m. Based on the sea-level elevation graph, the tidal regime in the study area is classified as semi-diurnal, characterized by two high tides and two low tides within a day. During maximum high tide, the sea level reaches approximately 0.9–1.0 m, whereas during minimum low tide it decreases to around 0.05–0.1 m.

During the spring high tide phase, the highest sea level ranges from 0.9 to 1.0 m, while during the spring low tide phase, the lowest sea level decreases to 0.05–0.1 m. In contrast, during the neap high tide phase, the maximum sea level is lower, ranging from 0.4 to 0.5 m, and during the neap low tide phase, the minimum sea level ranges between 0.2 and 0.3 m.

Therefore, it can be concluded that the spring tide period produces the most extreme tidal conditions (the highest high tide and the lowest low tide), whereas the neap tide period results in smaller and more moderate sea-level fluctuations.

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