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Original Article

Hydrodynamic Modeling of Maximum Tidal Levels at the Tondano River Estuary

Ferry Wantouw[1,2*], Tiny Mananoma[2], Arthur Harris Thambas[2], Cindy Jeane Supit[2]

[1]*Department of Civil Engineering, De La Salle University, Manado, Indonesia.*
[2]*Doctoral Program in Civil Engineering, Postgraduate Program, Sam Ratulangi University, Manado, Indonesia.*

[*]*Corresponding Author : fwantouw@unikadelasalle.ac.id*

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Abstract *- The Tondano River Estuary is an area affected by the interaction of tides, currents, winds, and bathymetric conditions that affect sea level and hydrodynamic conditions of the coastal area. This study aims to analyze the maximum tidal height at the Tondano River Estuary using the MIKE 21 Flow Model (FM). The study was conducted using a quantitative approach, employing numerical hydrodynamic modeling that integrated bathymetry, coastline, tides, and wind data into a flexible mesh domain. Simulation results show that the maximum sea level height in the northern and northwestern open-sea areas of the model domain exceeds 1.392 m. The highest current velocity was identified in the open sea area, with a value exceeding 0.325 m/s, while the estuary area showed lower currents due to shallow water conditions. Overall, this model can represent hydrodynamic conditions in the Tondano River Estuary spatially and temporally.*

Keywords - *Maximum tidal elevation, MIKE 21 FM Flow Model, Tondano River Estuary.*

1. Introduction

A river estuary is a location that is influenced by the interaction between river discharge and tides. These interactions lead to sea-level changes that can affect coastal conditions and the potential for flooding from tidal inundation in estuarine areas [4, 6, 8]. One of the areas in North Sulawesi whose hydrodynamic characteristics align with this study is the mouth of the Tondano River in Manado City. This location serves as the main channel of the Tondano River to Manado Bay and is located in a coastal area that is directly affected by tidal changes [2].

Sea level changes due to tides in estuarine areas can increase the risk of flooding, especially when high river discharges coincide with high tides. This research is important to analyze considering the increasing urban development and community activities in Manado City [2]. Previous research in the Tondano region has analyzed flood discharge characteristics and water levels using hydrological modeling [1]. In addition, changes in hydrodynamic conditions in estuary areas can also affect flow patterns, sediment transport, and coastal morphological stability [7], [12]. Therefore, an approach capable of describing the maximum tidal characteristics at the mouth of the Tondano River is needed. Hydrodynamic modeling is a widely used numerical method for the study of currents, tides, sea level, and the interaction of changes between coastal waters and estuaries [4, 5]. One of the software used in modeling is DHI-MIKE 21 FM. The application can model two-dimensional currents, sea level, waves, and tidal interactions and can optimally adapt to the geometry of the research site [3, 13]. Previous research has applied hydrodynamic models to analyze current and tidal conditions in coastal areas. Martyr-Koller et al. [6] used a three-dimensional hydrodynamics model to analyze flow dynamics and salinity in the San Francisco-Delta Gulf estuary. Sandbach et al. [8] performed hydrodynamic modeling at the mouths of large rivers to understand the interaction between tidal flow and river discharge. Setiawan et al. [17] analyzed waves, tides, and currents in the Banyuasin River Estuary to evaluate their influence on sediment distribution. Research by Talitha et al. [14] showed that the DHI-MIKE 21 FM model is capable of producing accurate tidal current simulations based on low Root Mean Square Error (RMSE) values. More recently, Aurela and Hirmawan [16] compared tidal analysis using the Admiralty method and MIKE 21 modeling in Tanjung Uban waters. Nurlianti et al. [15] used a two-dimensional hydrodynamic model to analyze ocean waves. They show that seasonal wind conditions significantly affect wave changes and sea level elevation. Although hydrodynamic modeling has been widely applied in estuarine and coastal areas, studies that specifically analyze hydrodynamic conditions during high tides in the Tondano River Estuary are still limited, so this study aims to analyze hydrodynamic characteristics during high tides in the Tondano River Estuary using DHI-MIKE 21 FM software. The modeling process was carried out by combining bathymetric data, coastline, and tidal data into the model. The parameters analyzed include water surface elevation, bathymetry, U and V velocity components, total flow speed and direction, and U- and V wind speed components.

2. Research Methodology

2.1. Research Approach

This study uses a quantitative approach based on hydrodynamic modeling using DHI-MIKE 21 FM software, with the file type being MIKE 21 Flow Model FM (.m21fm). The purpose of this study is to analyze the maximum tidal elevation at the mouth of the Tondano River, Manado Bay, Manado City. The model uses bathymetry, coastline, tidal, and wind data to generate hydrodynamic conditions at the research site. The equipment and materials used in this study are laptops with Intel(R) Core(TM) i5-10300H CPU @ 2.50 GHz and 16 GB of RAM, as well as DHI-MIKE 2026 software as the main tool in modeling. In addition, the study used Google Earth Pro version 7.3.7.1155 (64-bit) for shoreline generation, ArcMap version 10.8 (10.7.0.10450) for spatial data generation, and secondary bathymetric data obtained from tanahair.indonesia.go.id. The modeling stage in this study is carried out through several main steps. First, secondary data is collected and processed, including shoreline creation and bathymetric data collection from tanahair.indonesia.go.id. Second, secondary coastline and bathymetric data were further processed using ArcMap 10.8 to create the model in .xyz format. Third, tidal and wind data were collected from the Bitung Maritime Meteorological Station of the Meteorological Agency (BMKG). Fourth, a mesh was created in the DHI-MIKE 21 FM application. Fifth, hydrodynamic modeling was conducted using DHI-MIKE 21 FM software to obtain maximum tidal elevation results and analyze hydrodynamic characteristics at the mouth of the Tondano River, Manado City. Through these measures, the resulting hydrodynamic model can describe water level conditions, current patterns, and the influence of tides and winds on water changes in the mouth of the Tondano River and surrounding coastal areas.

2.2. Study Area

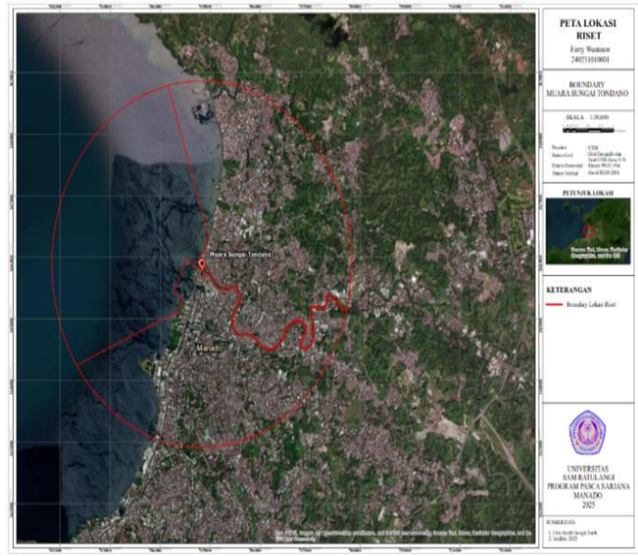

Fig. 1 Research location map

This research was conducted at the mouth of the Tondano River, Manado City, North Sulawesi Province. Geographically, the research location is at the coordinates of 1.499865° N, 124.840565° E, as shown in Figure 1.

The Tondano River is one of the main rivers in North Sulawesi Province, starting from Lake Tondano and flowing through several areas before entering Manado Bay, and has an important role in the hydrological system. In addition, the Tondano River Estuary is a meeting location between river flows and seawater, which provides hydrodynamic characteristics in this location that can pose a flood risk, especially due to the influence of river discharge, tides, currents, and the coastal conditions of Manado Bay.

2.3. Data Collection

The data used in this study are the main data that support the Highest Tide modeling process. The data used are shown in Table 1 below.

Table 1. Data collection

No	Data Required	Data Source	Data Function
1	Data Bathimetry	tanahair.indonesia.go.id	Determine the depth of the waters and underwater topographic conditions in the area to be modeled
2	Coastline Data / Boundary of Coast with Estuary	Processed results using Google Earth Pro software version 7.3.7.1155 (64-bit)	Forming the boundaries of the area to be studied
3	Tidal Data in 2025	Meteorology, Climatology, and Geophysics Agency – Bitung Maritime Meteorological Station	for sea level elevation simulation
4	Wind Data in 2025	Meteorology, Climatology, and Geophysics Agency – Bitung Maritime Meteorological Station	Describe the influence on sea level elevation

2.4. Data Analysis

Data analysis in this study was conducted to evaluate the hydrodynamic characteristics and highest tidal elevation in the Tondano River Estuary using DHI-MIKE 21 FM software. Here is the process of data analysis:

1. Download bathymetric data from tanahair.indonesia.go.id.
2. Create coastlines and estuary boundaries using Google Earth Pro.
3. Process bathymetric and coastline data using ArcMap to form research area boundaries.
4. Convert the created coast and river boundaries to *.xyz file type as input for the Mesh Generator process.
5. Create a Mesh Generator in MIKE 21 Flow Model FM with file type (*.xyz).
6. Prepare time series data consisting of :
   a. Tidal data
   b. Wind data
7. Enter all data into MIKE 21 FM with file type (*.xyz), including :
   a. Coastal and river boundaries
   b. Bathymetric data
   c. Mesh
   d. Tidal data
   e. Wind data
   f. Other model parameters
8. Perform modeling simulation using MIKE 21 Flow Model FM.
9. Analyze model output results, including:
   a. Sea level elevation
   b. Current speed
   c. Current direction

2.4.1. Tidal Data Validation

Tidal data validation is carried out to assess the suitability between water surface data and tidal predictions. The measured data was obtained from BMKG, while the prediction data was obtained from the results of the research. The two datasets were compared over the same period using a one-hour time interval. A total of 720 points in November 2025 were used in the validation process, and the Root Mean Square Error (RMSE) was used to measure the magnitude of the difference between the recorded and predicted water level values. The RMSE value is calculated using Equation (1).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_{obs,i} - H_{pred,i})^2} \quad (1)$$

Description :
$H_{obs,}$ i: water level elevation observed by BMKG at time i (m)
$H_{pred,}$ i: predicted water level elevation at time i (m)
n: number of data points compared

Lower RMSE values show a smaller difference between the data used and the results of the study. In addition to RMSE, the degree of relationship between the two datasets was analyzed using correlation coefficients (r) and determination coefficients (R^2). This analysis is used to evaluate the ability of the predicted data to represent patterns of water level change over the period analyzed.

2.4.2. Boundary Conditions

Model boundaries are set to show the modeling results of the tidal influence. The model domain consists of land boundaries and sea boundaries. Land boundaries are defined based on coastlines and river boundaries processed using Google Earth Pro and ArcMap 10.8. The open sea boundary is located on the outer edge of the domain, directly connected to the waters of Manado Bay.

Tidal time series data are used at sea boundaries to define water surface conditions. Tidal data obtained from BMKG represent water level fluctuations throughout the simulation period in November 2025. The data are fed into the Model as a time series to serve as hydrodynamic boundary conditions.

In addition to tides, wind data are also used, which consist of U and V velocity components for the November 2025 simulation period. The U component represents the wind speed in the east-west direction, while the V component represents the wind speed in the north-south direction.

The discharge of the Tondano River is not included as an upstream boundary condition in this model, as the study focuses on the analysis of hydrodynamic conditions driven by maximum tides.

2.4.3. Estuary

The river estuary is the meeting point between river discharge and seawater, with hydrodynamic characteristics that pose a high risk of flooding due to the interaction between river discharge and tides. [4, 6]. The changes that occur in the estuary area are greatly influenced by the tidal conditions and the large amount of river discharge that enters coastal waters.

According to Ji [4], estuarine areas show a pattern of change driven by the combined effects of tidal forces and river flows. These interactions result in variations in sea level elevation during high and low tides. Martir-Koller et al. [6] explain that changes in estuary flow are greatly influenced by the size of the estuary and the elevation conditions operating in the area.

Estuaries also play an important role in maintaining the stability of the coastal environment and coastline morphology. Sandbach et al. [8] state that the interaction between river flows and tidal changes affects flow patterns, sediment transport, and sedimentation processes in estuary systems. In addition, changes in hydrodynamic conditions in estuaries can contribute to tidal flooding, coastal erosion, and shoreline changes [11].

2.4.4. Tides

Tides are the periodic rise and fall of sea level caused by the gravitational forces of the moon and sun acting on Earth [9]. Tides are a key parameter in the study of coastal and estuarine hydrodynamics because they directly affect sea level elevation, current patterns, sediment transport, and coastal environmental dynamics [4, 6]. Ji [4] explained that tides are a key component in estuarine and coastal hydrodynamic simulations because they affect the distribution of water levels and current circulation patterns.

In numerical modeling, tidal data are typically used as boundary conditions to represent sea level fluctuations over the simulation period [3, 13].

The tidal conditions at the mouth of the Tondano River are directly influenced by the dynamics of the Sulawesi Sea and the coastal conditions of Manado Bay. Sea level fluctuations caused by tides can raise the water level in the estuary, especially at high tide. Therefore, tidal analysis is carried out to determine the maximum sea level characteristics.

2.4.5. Wind

Wind data was applied in a time series obtained from the BMKG Bitung Maritime Meteorological Station during the November 2025 simulation period. The wind parameters used in the model include wind speed U and wind speed V. Wind speed U represents the component of east-west wind speed, while wind speed V represents the component of wind speed north-south.

Stokes et al. [11] explain that wind conditions significantly affect wave changes and current flow patterns in coastal and estuarine areas. Research conducted by Nurlianti et al. [15] also showed that seasonal wind variations affect wave conditions and hydrodynamic energy distribution in coastal areas.

2.4.6. Numerical Modeling Methods

Numerical modeling was used in this study to characterize hydrodynamic conditions at the mouth of the Tondano River and Manado Bay. Modeling uses DHI-MIKE 21 FM, with a two-dimensional approach and flexible mesh. The model was used to analyze variations in water surface elevation, current velocity, and current direction, as well as the influence of tides and winds during the simulation period in November 2025.

The modeling was constructed using bathymetric and shoreline data, using triangular mesh elements. Open boundary conditions are set in the Manado area, with tidal data being the boundary conditions for water level elevation and wind data. Details about the parameters used in this modeling are presented in the following Table 2.

Table 2. Hydrodynamic modeling parameters at the Tondano River Estuary

No.	Parameter	Value/Description
1	Model Dimension	2D
2	Simulation Start Date	November 1 2025, 00:00
3	Simulation End Date	November 30 2025, 23:00
4	Time Step Interval	3600 s
5	Number of Time Steps	719
6	Mesh Type	Flexible Mesh, triangular elements
7	Number of Nodes	1218
8	Number of Elements	2042
9	Maximum Mesh Area	(2 \times 10^{-7})
10	Minimum Mesh Angle	26°
11	Hydrodynamic CFL	0.8
12	Minimum Internal Time Step	0.01 s
13	Maximum Internal Time Step	30 s
14	Maximum Number of Iterations	3000
15	Open Boundary	Manado Bay
16	Tidal Boundary Input	TS-Pasut.dfs0
17	Wind Input	TS-Angin.dfs0
18	Simulation Input	Bathymetry, coastline, Mesh, tides, and wind

2.4.7. Google Earth Pro Application

Google Earth Pro is a Geographic Information System (GIS)-based software developed by Google to display the Earth's surface in three-dimensional spatial visualization. The software is widely used in geospatial research, regional mapping, shoreline digitization, and geographic condition identification as it provides high-resolution and easy-to-use satellite imagery [4]. In hydrodynamics studies, Google Earth Pro is used to help identify study areas and generate shoreline data. The coastline was created using satellite imagery at the mouth of the Tondano River to generate land and sea boundaries for the model domain.

In this study, Google Earth Pro version 7.3.7.1155 (64-bit) was used to create the shoreline of the Tondano River Estuary. Shoreline data is used as one of the key parameters in building the model [3, 13].

2.4.8. ArcMap 10.8

ArcMap is a Geographic Information Systems (GIS)-based software developed by the Environmental Systems Research Institute (ESRI) to process, analyze, visualize, and manage spatial data. ArcMap is widely used in geospatial research, regional mapping, hydrological analysis, and environmental data processing due to its ability to effectively integrate different types of spatial data and attributes [4, 10]. In hydrodynamics studies, ArcMap 10.8 is used to process spatial data, including shoreline and bathymetric data, and model domain boundaries. Shoreline data generated in Google Earth Pro is fed into ArcMap for spatial data processing, including setting coordinate systems, editing data, converting formats, and adjusting study area boundaries.

2.4.9. MIKE 21 Flow Model FM

DHI-MIKE 21 FM is a two-dimensional hydrodynamic modeling software developed by DHI to simulate hydrodynamic processes in coastal, marine, river, and estuarine environments [3, 13]. This model is widely used in the study of hydrodynamics because it can represent patterns of currents, sea level, tides, waves, and other hydrodynamic interactions using numerical approaches [4]. According to DHI [3], the MIKE 21 FM Flow Model uses a Flexible Mesh (FM) system that allows the model domain to adapt more accurately to the size of the study area. The flexible mesh approach offers an advantage for complex modeling simulations, as the size of the mesh element can be adjusted to reflect bathymetric and shoreline conditions.

3. Results and Discussion

3.1. Hydrodynamic Modeling Results using MIKE 21 Flow Model FM Version 2026

Hydrodynamic modeling in this study was carried out using the MIKE 21 Flow Model FM software licensed from DHI for 1 year (May 2026 - May 2027) to simulate tidal conditions at the Tondano River estuary during November 2025. Modeling was carried out using bathymetry, shoreline, tidal, and wind data integrated into a flexible mesh model. The modeling results produced several output parameters, including bathymetry, surface elevation, U velocity, V velocity, current velocity, current direction, wind U velocity, and wind V velocity.

Area boundary conditions were first created using the Mesh Generator module in MIKE 21 FM, as shown in Figure 3. Area boundaries are used to determine which tidal model applies. Before the modeling process is carried out, tidal and wind data are first processed in the Time Series module in MIKE Zero to produce time-series data that serve as input to and parameters for the hydrodynamic model. Tidal time series data were used to represent sea level fluctuations during November 2025, while wind time series data were used to illustrate the influence on current circulation patterns and hydrodynamic energy distribution in the study area. Based on the tidal time series graph in Figure 4, the results of the time series data analysis indicate that the maximum sea level in Manado Bay occurred on November 6, 2025, at 10:00 WITA. This condition indicates the occurrence of maximum tidal elevation, which is used as the primary reference for hydrodynamic modeling in this study.

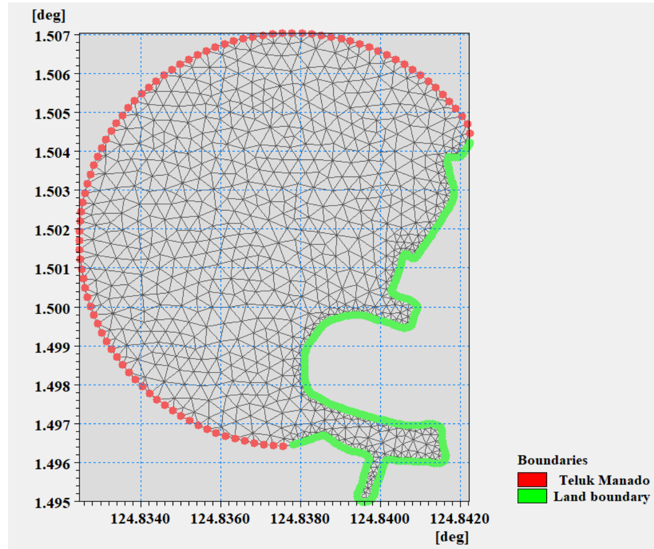

Fig. 3 Boundary condition in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026
Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

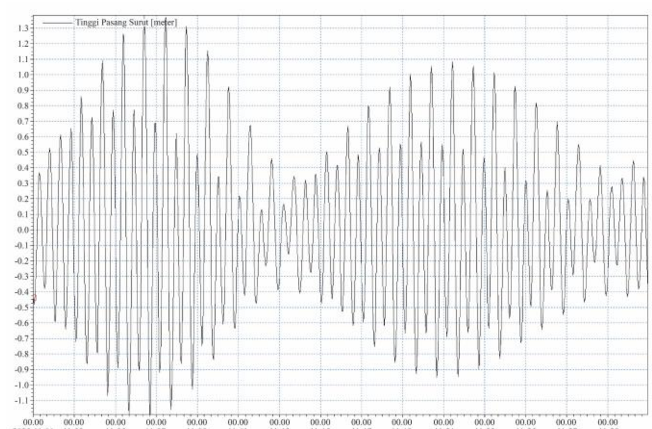

Fig. 4 Tidal time series data in MIKE zero time series November 2025
Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

3.1.1. Tidal Data Validation Results

Tidal data validation was carried out by comparing observed tidal data from BMKG with predicted tidal data used in the modeling for November 2025.

The comparison uses 720 data points recorded every one hour. The results showed that the predicted change in water level elevation was in line with the tidal pattern recorded by BMKG during the period analyzed.

Analysis using Root Mean Square Error (RMSE) yielded a value of 0.0927 m, or about 9.27 cm. This value shows a relatively small difference. In addition, a correlation coefficient (r) of 0.9888 and a determination coefficient (R^2) of 0.9777 were obtained. A correlation value close to 1 indicates a very strong relationship.

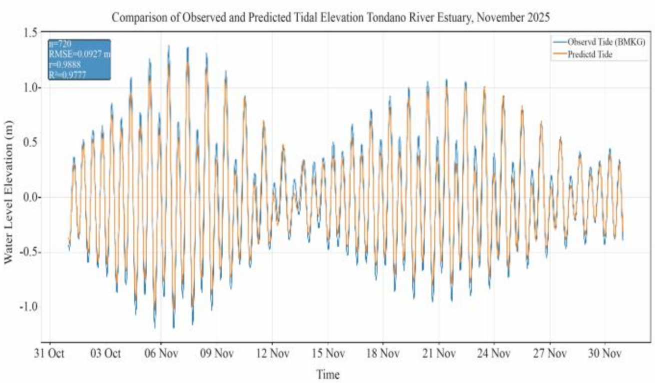

Fig. 5 Comparison of observed and predicted tidal elevation at the Tondano River Estuary, November 2025

3.1.2. Bathymetry Modeling Results

The results of bathymetric modeling using DHI-MIKE 21 FM software in the Tondano River Estuary showed variations in water depth, which became the basis for the modeling. The bathymetric distribution shows significant changes in depth from coastal areas to the open sea around Manado Bay. Coastal and estuarine waters have relatively shallow depths between 0 m to -45 m. Meanwhile, the open sea area has greater depths, reaching more than -140 m in the northwest. These variations in depth affect the current distribution and sea level elevation during the simulation.

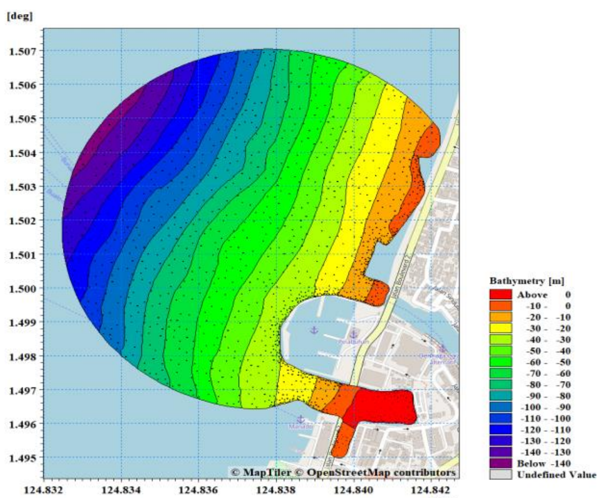

Fig. 6 Bathymetry distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026

Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

3.1.3. Surface Elevation Modeling Results

The results of the surface elevation simulation show the distribution of sea level in the Tondano River Estuary during November 2025. Most of the modeled areas have sea level levels ranging from 1.367 m to 1.397 m. The maximum sea level is concentrated in the open sea areas to the north and northwest, with values exceeding 1.392 m. This condition shows that the tides of the Sulawesi Sea significantly affect sea level changes at the mouth of the Tondano River.

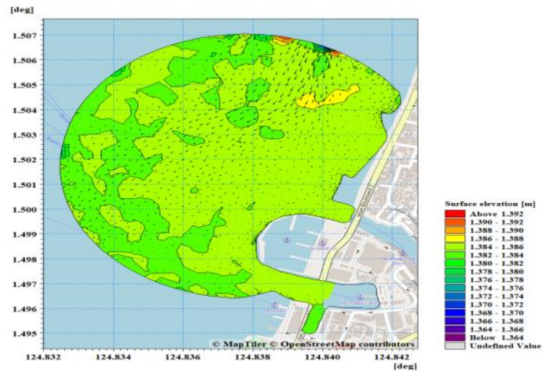

Fig. 7 Surface elevation distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026

Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

3.1.4. U-Velocity Modeling Results

The results of the U velocity simulation show the distribution of horizontal current velocity components (east-west direction) within the study area. The highest U-speed values were identified in open sea areas, with values exceeding 0.075 m/s. Most estuarine and coastal areas have relatively low U-speed values due to the influence of shallow water depth and estuary geometry.

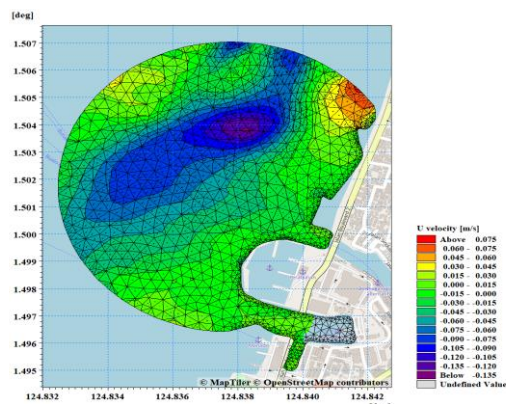

Fig. 8 U-Velocity distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026

Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

3.1.5. V-Velocity Modeling Results

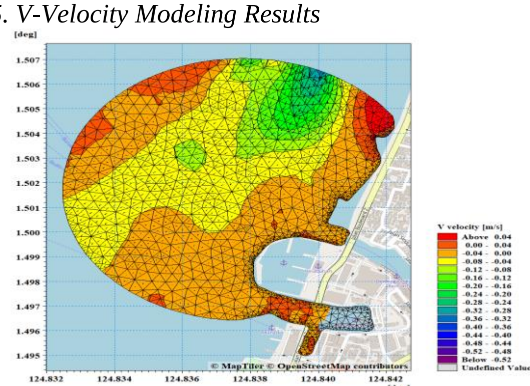

Fig. 9 V-Velocity distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026

Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

The results of the V velocity simulation show the distribution of horizontal current velocity components (north-south direction) during the November 2025 simulation period. The V velocity distribution indicates that the north-south current pattern is influenced by the interaction among tides, bathymetric conditions, and wind during modeling.

3.1.6. Current Speed Modeling Results

The results of the current velocity simulation show the distribution of total current velocity at the mouth of the Tondano River. The highest current velocity was identified in open sea areas, exceeding 0.325 m/s. Most of the inner estuary region has a relatively low current speed due to the shallow water depth and the slowdown of the flow.

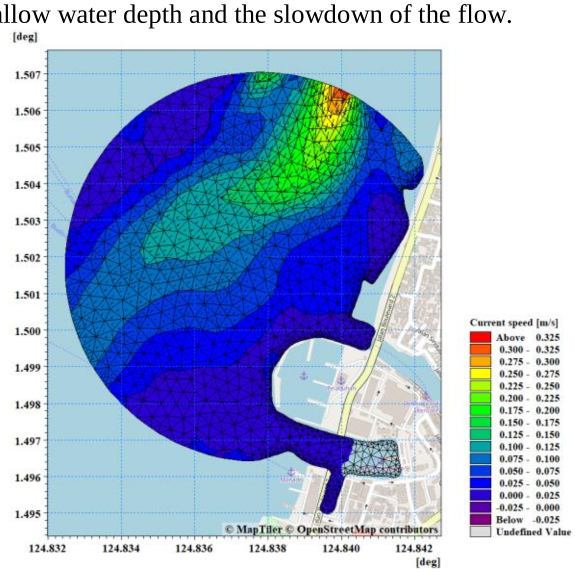

Fig. 10 Current speed distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026
Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

3.1.7. Current Direction Modeling Results

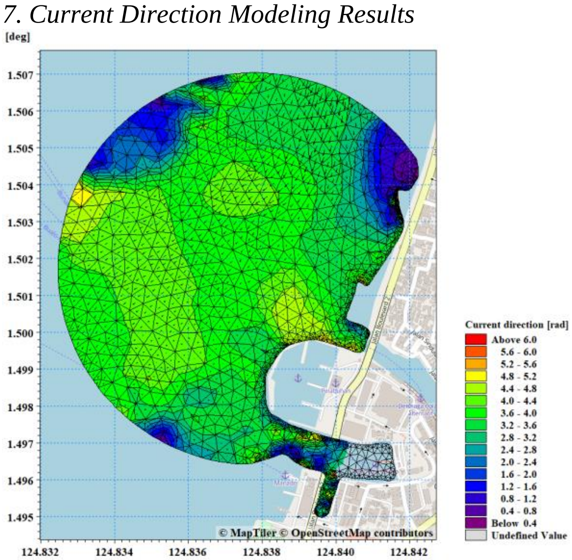

Fig. 11 Current direction distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026
Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

The results of the current directional simulation show the distribution of the direction of the flow during the simulation period of November 2025. The pattern of current movement tends to follow the tidal movement from the open sea to the estuary area. The distribution of the current direction shows a circulation pattern influenced by the interaction between tides, winds, and coastal morphology in the Tondano River Estuary.

3.1.8. Wind U-Velocity Modeling Results

The results of the U wind speed simulation show the distribution of horizontal wind speed components (east-west direction) during the November 2025 simulation period. The U-wind speed value ranges from -0.640 m/s to -0.632 m/s, indicating that the dominant wind direction is moving westward.

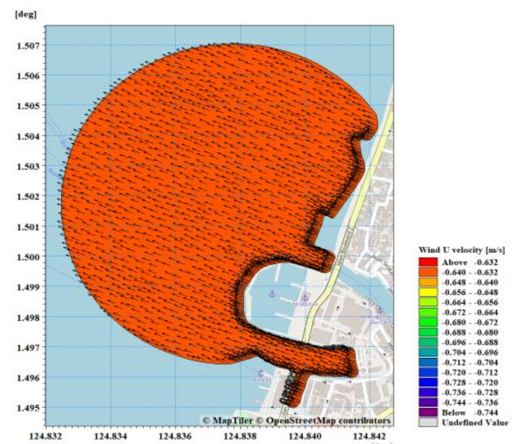

Fig. 12 Wind U-velocity distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026
Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

3.1.9. Wind V-Velocity Modeling Results

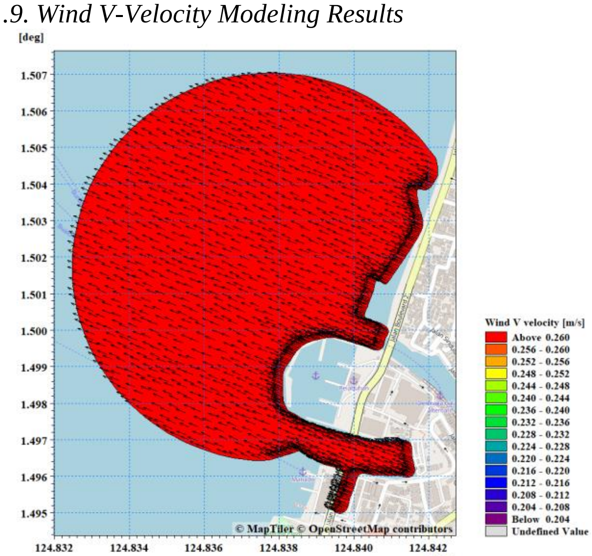

Fig. 13 Wind V-velocity distribution in the Tondano River Estuary model domain using MIKE 21 Flow Model FM version 2026
Source: MIKE 21 Flow Model FM modeling results, May 10, 2026

The results of wind speed modeling V at the Tondano River Estuary show the distribution of horizontal wind speed components in the north-south direction during the November 2025 simulation period. The wind speed value V exceeds 0.260 m/s. This positive value indicates that the dominant wind component is moving north.

3.2. Discussion

Based on the modeling results using DHI-MIKE 21 FM presented in Table 3, several parameters describing the hydrodynamic conditions at the Tondano River Estuary, Manado Bay, Manado City, were obtained. The modeling results indicate that bathymetry, tides, and wind influence the distribution of water surface elevation and current patterns during the November 2025 simulation period. The bathymetric distribution reveals that the estuary and coastal areas are shallower than the open sea. Depths in the open sea exceed -140 m, whereas the estuary area is relatively shallow. This depth variation influences the current movement patterns in the model. The highest current velocities were observed in the open sea, exceeding 0.325 m/s, while velocities in the estuary were comparatively lower. These conditions demonstrate that changes in depth and the geometric shape of the estuary play a role in governing current velocity distribution at the Tondano River Estuary. The modeling results also indicate that current direction tends to follow tidal movements from the open sea toward the estuary. This pattern suggests that tides are a primary factor influencing current circulation at the Tondano River Estuary. These findings align with the study by Lumbanraja et al. [13], who used MIKE 21 to analyze current patterns driven by tidal movement in the Kapuas River Estuary. Similarly, Wicaksono et al. [14] demonstrated that two-dimensional modeling can effectively characterize tidal current patterns in coastal areas. Furthermore, Setiawan et al. [17] employed a modeling approach to analyze waves, tides, and currents at the Banyuasin River Estuary. The primary distinction between the present study and those mentioned lies in the location and analytical focus-specifically, the hydrodynamic conditions of the Tondano River Estuary during maximum high tide. The reliability of the tidal data used in the modeling was evaluated by comparing BMKG data with predicted data-comprising 720 hourly data points-for November 2025. The analysis yielded a Root Mean Square Error (RMSE) of 0.0927 m, a correlation coefficient (r) of 0.9888, and a Coefficient of Determination (R^2) of 0.9777. These values indicate a very strong correlation between the predicted water level elevation patterns and the BMKG tidal data. This study did not conduct a sensitivity analysis regarding changes in mesh size, numerical parameters, or boundary conditions; therefore, the modeling results must be interpreted within the context of the specific model configuration employed. Nevertheless, the numerical settings have been detailed-including 1218 nodes, 2042 elements, a 3600-second time interval, a Hydrodynamic CFL value of 0.8, a minimum internal time step of 0.01 seconds, and a maximum internal time step of 30 seconds-enabling the replication of the modeling process using identical parameters.

The modeling results can serve as preliminary information for understanding locations experiencing increased water level elevations and current patterns during peak high tide. This information can support further studies regarding inundation risks in the Tondano River Estuary area and the coastal regions of Manado City. The modeling in this study has several limitations. The model employs a two-dimensional approach; consequently, vertical variations in hydrodynamic conditions are not represented. Modeling results may also be influenced by the resolution of bathymetric data, mesh configuration, boundary conditions, as well as tidal and wind input data. Furthermore, the Tondano River discharge was not included as an upstream boundary condition, as the study focuses on maximum tidal conditions. Future research could be expanded by incorporating the Tondano River discharge as an upstream boundary condition and considering sediment transport, estuarine morphological changes, and sea-level rise scenarios.

Table 3. Tidal modeling at the Tondano River Estuary in 2025

No	Research Results	Remarks
1	Surface Elevation	Maximum sea surface elevations are concentrated in the open ocean areas in the northern and northwestern parts of the model domain.
2	Bathymetry	The estuary area is relatively shallow, while the open sea has a depth exceeding -140 m
3	Current Speed	The highest current speed is in the open sea with a value of > 0.325 m/s
4	U Velocity dan V Velocity	Influenced by tidal interactions, bathymetry, and estuary geometry
5	Current Direction	The current pattern follows the tidal movement towards estuaries and coastal areas.
6	Wind U Velocity	Dominantly moving west with a value of -0.640 m/s to -0.632 m/s
7	Wind V Velocity	Dominantly moving north with a value > 0.260 m/s

4. Conclusion

Based on the results of hydrodynamic modeling using the MIKE 21 Flow Model FM at the Tondano River Estuary during the November 2025 simulation period, it can be concluded that :

1. The open-sea area has a depth greater than -140 m. This depth variation affects the current distribution and sea level during the simulation. The highest current velocities were identified in the open sea area, with values exceeding 0.325 m/s. In contrast, the estuary area showed lower current velocities due to the influence of shallow depths and flow deceleration.
2. The current patterns are influenced by the interaction among tides, bathymetric conditions, and estuary geometry, with the current direction generally following tidal dynamics towards the estuary and coastal areas.
3. The results of wind parameter modeling show that the dominant wind speed U moves westward with values ranging from -0.640 m/s to -0.632 m/s, while the dominant wind speed V moves northward with values exceeding 0.260 m/s. This condition indicates that wind influence during the simulation period is relatively stable and contributes to the surface current circulation pattern in the study area.

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