(p-issn: 2089-8630) (e-issn: 2962 5696)
Jurnal Sains dan Teknologi Tadulako

DOI: https://doi.org/10.22487/jstt.v12i2.1071

DEVELOPMENT AND VALIDATION OF A DELFT3D TWO-DIMENSIONAL HYDRODYNAMIC MODEL FOR WIND-WAVE HINDCASTING AND TIDAL CHARACTERIZATION IN THE PANTOLOAN CUSTOMS PORT WATERS

Estiana[1], Andi Rusdin[2], and Setiyawan[3*]

[1,2,3]*Department of Civil Engineering, Faculty of Engineering, Tadulako University, Palu, Indonesia*
[1]estiana09102001@gmail.com, [2]andi.rusdin_sipil@untad.ac.id, [3]setiyawan_sipil@untad.ac.id
*Corresponding author: setiyawan_sipil@untad.ac.id

Abstract

The waters of Pantoloan Customs Port in Palu Bay feature a semi-closed, narrow, and elongated morphology with steep bathymetry, so that a validated numerical modeling procedure is required before the hydrodynamic behavior of the port basin can be interpreted with confidence. This study develops and validates a two-dimensional (2D) hydrodynamic model using Delft3D (FLOW and WAVE modules) for the Pantoloan port waters. The model domain was built as an 85.7 ha curvilinear/Cartesian grid of 117 x 288 cells with a 60-second time step. Model forcing was derived from 10 years of hourly wind data (2012-2021, 87,648 records) from BMKG Palu, 15 days of tidal field observation referenced to the BIG Pantoloan station, and bathymetry integrating direct echosounder survey with BATNAS data. Effective fetch was computed radially at 6-degree increments up to +-42 degrees from each cardinal direction, giving a maximum effective fetch of 106.430 km from the Northwest. Deep-water wave hindcasting with the Sverdrup-Munk-Bretschneider (SMB) method produced a significant wave height (Hs) of 1.43 m and significant period (Ts) of 5.50 s. The FLOW model was calibrated with a seafloor roughness of Chezy = 65 m^1/2/s and validated against 362 temporal water-level samples, yielding a Root Mean Square Error (RMSE) of 0.0230 m and a Mean Absolute Error (MAE) of 0.0190 m, both below the 5 cm accuracy threshold commonly used for port-scale tidal models. These results indicate that the constructed model reliably reproduces the observed tidal and wave-forcing conditions and is therefore suitable as a validated baseline for subsequent current-circulation and wave-deformation analyses in the port basin.

Keywords: Delft3D; hydrodynamic model; model validation; tidal simulation; wind-wave hindcasting.

1. Introduction

Indonesia's coastline of more than 95,000 km places sea transport and port infrastructure among the main pillars of national connectivity and economic distribution. Within Central Sulawesi Province, Pantoloan Customs Port carries out both commercial loading/unloading and customs-patrol functions in the narrow, semi-enclosed waters of Palu Bay. Because the bay geometry (about 30 km long, 3-7 km wide) is combined with a steep underwater bathymetric slope, the resulting current and wave circulation is considerably more complex than in an open coastal setting, which makes a properly validated numerical model a prerequisite for any operational or planning conclusion drawn from it.

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

Coastal and port hydrodynamic modeling has developed rapidly over the past decade, supported by process-based software such as Delft3D, MIKE 21, and SWAN, which numerically solve the shallow-water and spectral wave-action equations to reproduce tide, current, and wave behavior at engineering scale. Applications of Delft3D in Indonesian waters range from storm-surge and flood-inundation studies (Ke et al., 2019; Damayanto et al., 2024; Mardika et al., 2024) to sediment-transport and coastal-morphology analyses (Arizal, 2011; Prananda et al., 2024), demonstrating the flexibility of the platform but also showing that the accuracy of any such model depends heavily on how faithfully the input wind, tide, and bathymetry data are processed and how rigorously the resulting simulation is validated against field observation.

Previous hydrodynamic studies in Palu Bay - such as the COHERENS-based circulation study of Meidji et al. (2022), the Delft3D sediment-transport study of Prananda et al. (2024) near the Palu-3 power plant, and the post-earthquake bathymetric change analysis of Akifa et al. (2023) - have each examined particular aspects of the bay's hydrodynamics, but none has published a fully documented, validated model workflow specific to the Pantoloan port basin that integrates a decade of wind data, local tidal observation, and combined bathymetric sources into a single reproducible numerical procedure. Comparable port-scale modeling efforts elsewhere in Indonesia, such as the Belawan Port flood-zone mapping of Putra et al. (2023) and the pre-construction hydrodynamic study for Patimban Port by Isnaeni et al. (2024), similarly show that a transparent, statistically validated model is treated as a prerequisite deliverable before any operational or design conclusion is drawn, reinforcing the need for the same rigor at Pantoloan.

This study therefore focuses on the modeling methodology itself: how the Delft3D FLOW and WAVE model of the Pantoloan port basin was constructed, what input data and boundary conditions were used, and how the resulting model was statistically validated against field observation. The specific objectives are to: (1) build an integrated 2D Delft3D hydrodynamic model of the Pantoloan Customs Port basin; (2) derive the tidal open-boundary forcing from field and reference station data; (3) compute the effective fetch and hindcast the deep-water design wave (Hs, Ts) using the SMB method from 10 years of wind data; and (4) statistically validate the simulated water-level elevation against 15 days of field observation. A companion paper (submitted separately to SINERGI) applies this validated model to analyze the resulting current circulation and wave-deformation characteristics inside the port basin from an operational-safety perspective.

2. Literature Review

2.1 Currents and Waves

Sea currents in coastal waters form through the interaction of several primary forces: the gravitational pull of celestial bodies (tides), atmospheric pressure gradients, surface wind stress, and freshwater discharge from river mouths (Gross, 1990). Surface ocean waves are mostly generated by the transfer of wind kinetic energy to the water surface; the three main parameters governing wind-wave growth are wind speed (U), minimum wind duration (D), and the unobstructed distance over which the wind blows, or fetch (F) (CERC, 1984).

2.2 Classification of Waves by Relative Depth

Based on the ratio between water depth (d) and wavelength (L), wave behavior is classified into three regimes: shallow-water waves when $d/L <= 1/20$ (0.05); transitional waves when $1/20 < d/L < 1/2$; and deep-water waves when $d/L >= 1/2$ (0.5). The establishment of this spatial classification framework is paramount, as it precisely delineates the applicability boundaries for specific simplified

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

wave-theory assumptions—such as linear wave mechanics versus non-linear formulations—across varying bathymetric profiles. Consequently, this theoretical bounding serves as the foundational mechanism for the subsequent hydrodynamic analyses within this study. It is systematically utilized to evaluate the complex transformation processes—specifically shoaling, refraction, and energy dissipation—experienced by incident offshore swells as they propagate into the progressively shallower nearshore environment of the Pantoloan basin. By rigorously coupling wave theory to local bathymetry, the analysis ensures high-fidelity interpretation of wave kinematics critical for coastal engineering applications.

2.3 Delft3D Numerical Modeling Mechanism

The Delft3D-FLOW module solves the three-dimensional (here applied in depth-integrated, 2D form) Shallow Water Equations for incompressible fluid under the Boussinesq hydrostatic-pressure assumption. In curvilinear coordinates, the depth-integrated continuity equation relates the time-rate of change of free-surface elevation to the divergence of the depth-integrated velocity components U and V, driven by a source/sink term Q representing any additional discharge. The Delft3D-WAVE module is built on the SWAN (Simulating WAves Nearshore) spectral action-balance equation, in which the wave action density N(x, y, sigma, theta, t) evolves under geographic and spectral propagation together with a total source term Stot representing wind-energy input, whitecapping dissipation, bottom friction, and depth-induced breaking (Lesser et al., 2004; Deltares, 2024).

3. Method

3.1 Study Location and Model Domain

The study is centered on the mooring-pond waters of Pantoloan Customs Port (0 deg 42'03" S, 119 deg 51'03" E), Palu City, Central Sulawesi. The spatial domain was constructed as a square (Cartesian) grid measuring 1,210 m by 713.65 m, covering a total area of 85.7 ha, with a grid resolution of 117 x 288 cells oriented Southwest-Northeast. The time step of numerical integration was set at 60 seconds to keep the Courant number within a stable range.

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

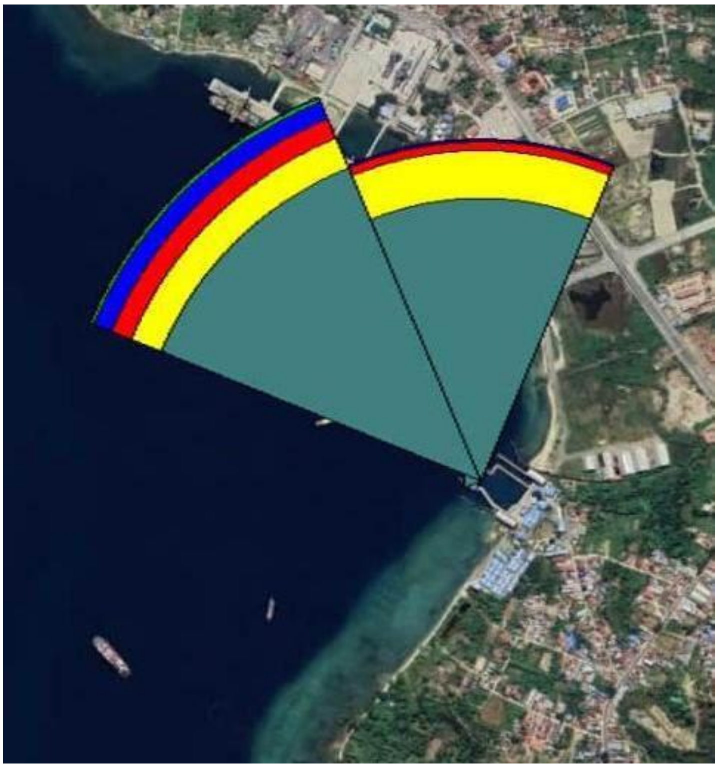

Figure 1. Model grid and land boundary of the Pantoloan port basin.

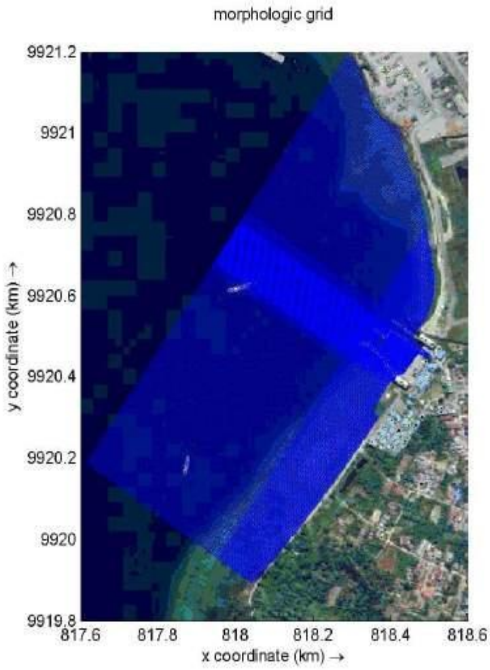

Figure 2. Meshing grid and bathymetric depth of the model domain.

3.2 Input Data

Three categories of input data were used to force the model: (1) wind data - 10 years of hourly time series (January 2012-December 2021) from the BMKG Palu (Mutiara Sis Al-Jufri) station, totaling 87,648 spatial-temporal records, processed following the long-term data-length recommendation of the Shore Protection Manual (CERC, 1984) to minimize seasonal bias; (2) tidal

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

data - reference series from the BIG Pantoloan station combined with 15 days of direct field observation (18 October-2 November 2021); and (3) bathymetry data - a combination of a direct echosounder survey of the port pond and the national BATNAS bathymetry grid, merged to represent both the shallow basin and the surrounding steeper slopes.

3.3 Effective Fetch and Wave Hindcasting

Because Palu Bay is narrow and V-shaped, the fetch that generates wind-waves cannot be treated as a single straight line. Effective fetch (Feff) was instead computed as a radial average using a deviation increment of 6 degrees up to a maximum of +-42 degrees on either side of each cardinal direction, implemented through GIS radial measurement. The resulting fetch lengths were combined with the wind-stress-corrected design wind speed in the Sverdrup-Munk-Bretschneider (SMB) empirical wave-growth method (Setiawan et al., 2016) to hindcast the deep-water significant wave height (Hs) and significant period (Ts) for the governing (Northwest) direction.

3.4 Model Calibration and Validation

The FLOW model was calibrated using a seafloor-roughness coefficient of Chezy = 65 m^1/2/s and forced at the open boundary with the astronomical tidal constituents derived from the BIG/field observation. Model performance was evaluated by comparing simulated versus observed water-surface elevation at 362 temporal sample points spanning the 15-day observation window, using the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) as the accuracy indicators. Table 1 summarizes the complete set of model parameters used in the simulation.

Table 1. Summary of Delft3D FLOW-WAVE model parameters.

Parameter	Value
Grid type	Cartesian (curvilinear-compatible), 117 x 288 cells
Domain size	1,210 m x 713.65 m (85.7 ha)
Orientation	Southwest - Northeast
Time step	60 seconds
Seafloor roughness (Chezy)	65 m^1/2/s
Open boundary forcing	Astronomical tidal constituents (BIG Pantoloan + 15-day field observation)
Wave boundary input	Hs = 1.43 m, Ts = 5.50 s (SMB hindcast, Northwest)
Simulation window	18 October - 2 November 2021 (15 days)

4. Results and Discussion

4.1 Wind Climatology (2012-2021)

Statistical processing of the 87,648-record wind dataset shows that wind speeds in the 0.50-2.10 m/s class dominate, occurring 48.2% of the time, followed by the 2.10-3.60 m/s (20.3%) and 3.60-5.70 m/s (16.1%) classes, as summarized in Table 2 and Figure 3.

Table 2. Wind speed class frequency distribution, Palu Bay (2012-2021).

Wind Speed Class (m/s)	Frequency (%)	Category
Calm	0.3	Calm

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

0.50 - 2.10	48.2	Light air
2.10 - 3.60	20.3	Light breeze
3.60 - 5.70	16.1	Gentle breeze
5.70 - 8.80	14.5	Moderate breeze
8.80 - 11.10	0.6	Fresh breeze
>= 11.10	0.0	Strong breeze

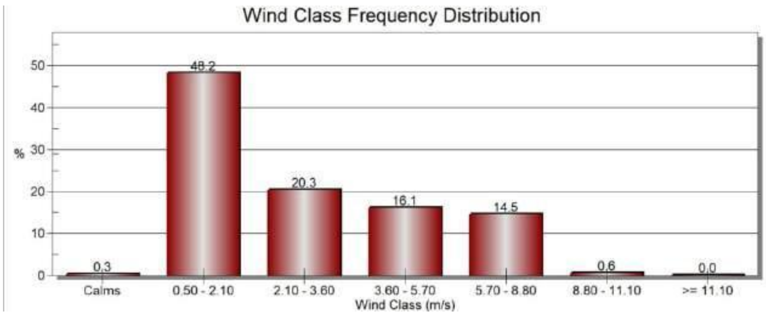

Figure 3. Wind speed distribution graph.

Windrose analysis (WRPlot) shows the prevailing direction is Northwest (22.7% of occurrences), followed by North (14.3%), while wind from the landward sectors (East, Southeast, South) contributes less than 3%, consistent with the funneling effect of the Palu Bay corridor on air masses entering from the Makassar Strait (Figure 4).

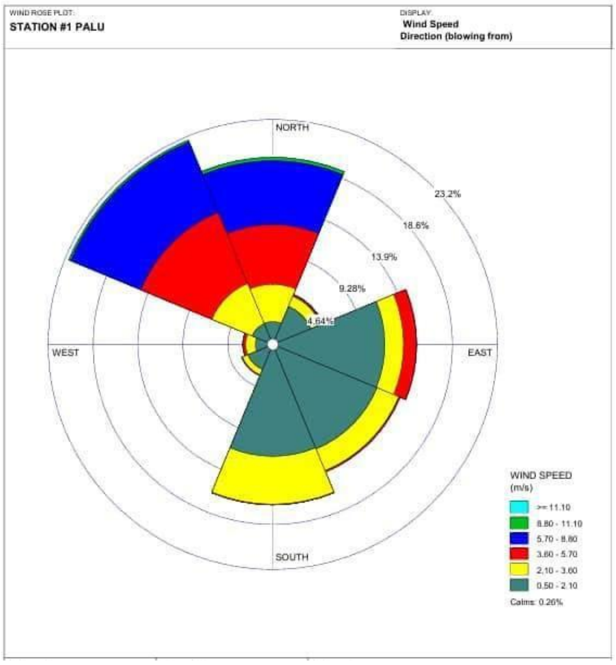

Figure 4. Windrose distribution of wind intensity and direction around Palu Bay, 2012-2021.

4.2 Effective Fetch

Because the East, Southeast, South, and Northeast sectors are directly blocked by the Pantoloan mountain slopes, their effective fetch is 0 km, while the Northwest sector - open directly to the Makassar Strait - yields the governing fetch length. From 15 radial lines computed at 6-degree

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

increments, the maximum effective fetch (Feff) reaches 106.430 km from the Northwest, as summarized in Table 3.

Table 3. Effective fetch length (Feff) by cardinal direction.

No.	Cardinal Direction	Fetch Length (km)	Note
1	North	39.40	-
2	Southwest	69.02	-
3	West	66.30	-
4	Northwest (dominant)	106.430	Governing direction
5	E, SE, S, NE	0	Topographically blocked

4.3 Wave Hindcasting

Using the design wind speed of 14.12 m/s (wind-stress corrected from the observed 11.2 m/s ground-station speed) for the Northwest sector together with the maximum effective fetch of 106.430 km, the SMB hindcasting procedure yields a deep-water significant wave height (Hs) of 1.43 m with a significant period (Ts) of 5.50 s from the Northwest - the sector with the least topographic obstruction and the most direct exposure to the Makassar Strait (Figure 5).

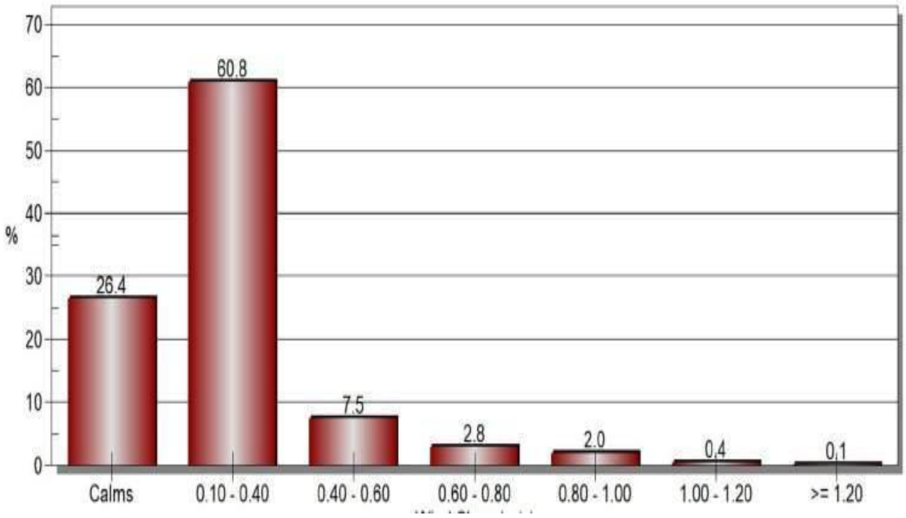

Figure 5. Wave height distribution graph derived from SMB hindcasting.

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

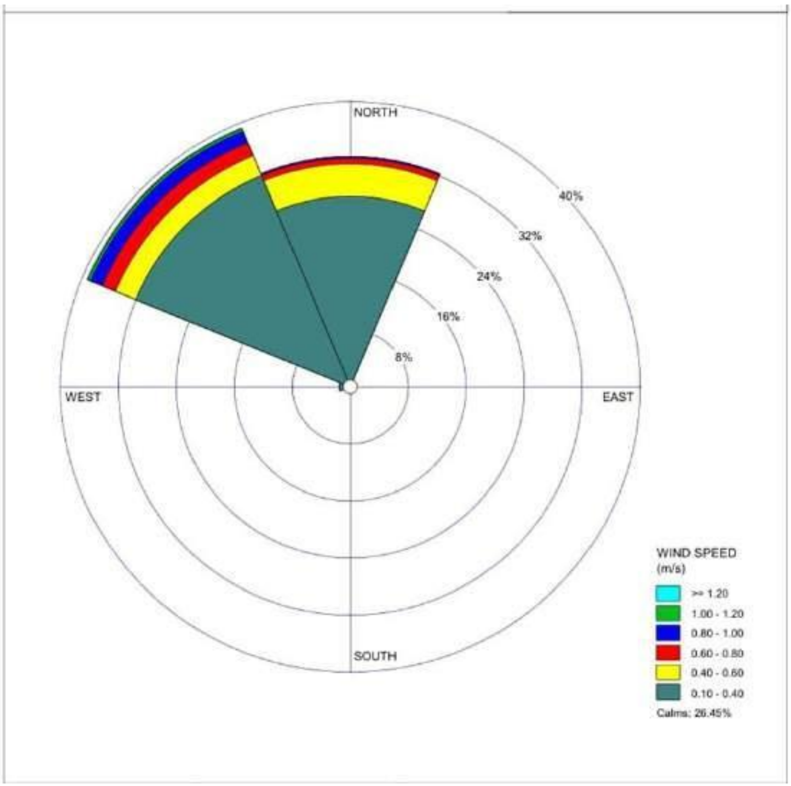

Figure 6. Waverose distribution of wave height and direction around Palu Bay, 2012-2021.

4.4 Model Validation

Comparison of the simulated water-surface elevation with the 15-day field observation and BIG reference series at 362 temporal sample points gives an RMSE of 0.0230 m and an MAE of 0.0190 m (Figure 7). Both indicators fall well below the 5 cm error threshold typically used to judge the acceptability of tidal models at port scale, confirming that the chosen seafloor-roughness coefficient (Chezy = 65 m^1/2/s) and the astronomical open-boundary forcing adequately represent the real tidal behavior of the basin.

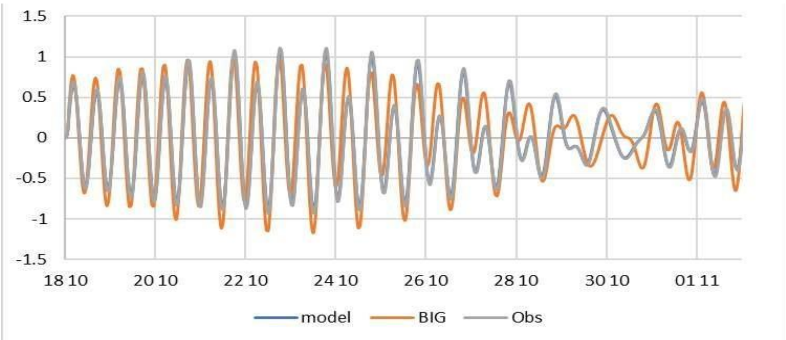

Figure 7. Comparison of simulated (model), BIG reference, and observed sea-level fluctuations.

4.5 Comparison with Related Modeling Studies

The validation accuracy obtained here (RMSE = 0.0230 m) is comparable to or better than tidal-elevation errors reported in other Indonesian Delft3D and MIKE-based port studies, such as the sub-5-cm range typically sought in the Belawan Port flood-mapping study of Putra et al. (2023) and the pre-construction Patimban Port model of Isnaeni et al. (2024), and is consistent with the general accuracy range reported for altimetry-assisted tide models in more data-rich settings (Hart-Davis et

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

al., 2023). This supports the conclusion that, despite Palu Bay's complex steep-sided geometry, a properly forced 2D Delft3D model with locally calibrated roughness can achieve engineering-grade tidal accuracy without requiring a full 3D formulation.

This validated configuration provides the basis on which subsequent current-circulation and wave-deformation results (reported separately) can be interpreted with confidence, and it also establishes a reusable baseline that future studies of sediment transport, shoreline change, or climate-adaptive port design in Palu Bay can build upon without repeating the full model-construction and validation process.

5. Conclusion

(a) The wind characteristics in the waters of the Pantoloan Customs Port are dominated by gusts from the Northwest direction (22.7%) with a maximum effective fetch length of 106.430 km. (b) Empirical wave forecasting using the SMB method shows a deep-water significant wave height (Hs) of 1.43 m with a significant period (Ts) of 5.50 s. (c) The FLOW model, calibrated with Chezy = 65 m^1/2/s and forced by the observed tidal boundary, reproduces the 15-day field water-level record with an RMSE of 0.0230 m and MAE of 0.0190 m, both within acceptable engineering tolerance. (d) The Delft3D model configuration developed in this study is therefore judged valid and reliable, and constitutes a reusable baseline for further analysis of current circulation and wave deformation within the port pond.

6. Acknowledgement

The authors thank the Department of Civil Engineering, Faculty of Engineering, Tadulako University, and BMKG and BIG Palu for providing the wind and tidal reference data used in this study.

7. References

Ahmadi, M. M., Liviawaty, E., Faizal, I., & Purba, N. P. (2022). The vulnerability of small islands from coastlines change in Indonesia. IOP Conference Series: Earth and Environmental Science, 1095(1), 012026.

Akifa, S., Setiyawan, S., Sutapa, S., & Krestiadi, A. (2023). Modeling of sedimentation patterns in Palu Bay, Indonesia after the tsunami and earthquake disaster using MIKE 21. Journal of Ecological Engineering, 24(5), 1186-1192.

Arafat, Y., Tunas, I. G., & Hidaya, N. (2025). Modelling the impact of sea level rise on ocean hydrodynamics: A case study of Tambu Bay. Mathematical Modelling of Engineering Problems, 12(2), 367-377.

Arizal. (2011). Pemodelan numerik perubahan morfologi dasar Pantai Singkil dengan menggunakan Delft3D (Tugas akhir, Fakultas Teknik, Universitas Syiah Kuala). Universitas Syiah Kuala, Banda Aceh.

Bentivoglio, R., Isufi, E., Jonkman, S. N., & Taormina, R. (2023). Rapid spatio-temporal flood modelling via hydraulics-based graph neural networks. Hydrology and Earth System Sciences, 27, 4227-4246.

Coastal Engineering Research Center. (1984). Shore protection manual (4th ed.). U.S. Army Corps of Engineers.

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

Damayanto, M., Tubalawony, S., & Noya, Y. (2024). Kajian banjir pesisir menggunakan model Delft3D: Studi kasus wilayah Seram Bagian Timur. TRITON: Jurnal Manajemen Sumberdaya Perairan, 20(1), 28-35.

Deltares. (2024). Delft3D Flexible Mesh Suite: Technical reference manual. Deltares.

Fatimah, E., & Fauzi, A. (2021). Analisis pergerakan arus pasang surut terhadap perubahan perletakan pemecah ombak di Pelabuhan Ulee Lheue. Jurnal Teknik Sipil, 10(1), 1-8.

Gross, M. G. (1990). Oceanography: A view of Earth (6th ed.). Prentice Hall.

Hart-Davis, M. G., Laan, S., Schwatke, C., Passaro, M., Pons, F., & Seitz, F. (2023). Altimetry-derived tide model for improved tide and water level forecasting along the European continental shelf. Ocean Dynamics, 73, 475-491.

Isnaeni, K. Y., Putri, M. R., & Windupranata, W. (2024). Pemodelan hidrodinamika perairan Subang: Analisis awal sebelum pembangunan Pelabuhan Patimban. Journal of Marine Research, 13(2), 265-282.

Ke, Q., Bricker, J., & Ye, T. (2019). Storm surge modelling by Delft3D FM: A case study in Shanghai area. In Proceedings of the EGU General Assembly 2019. Vienna, Austria.

Lesser, G. R., Roelvink, J. A., Van Kester, J. A. T. M., & Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. Coastal Engineering, 51(8-9), 883-915.

Makris, C., Baltikas, V., Kontos, Y., Androulidakis, Y., Nagkoulis, N., Kazakis, I., Karambas, T., Papadimitriou, A., Metallinos, A., Chondros, M., Emmanouilidou, M.-E., Malliouri, D., Klonaris, G., Tsoukala, V., Memos, C., Spiliopoulos, G., & Zissis, D. (2021). Integrated modeling of sea-state forecasts for safe navigation near and inside ports: The Accu-Waves platform. In Proceedings of the 31st International Ocean and Polar Engineering Conference (ISOPE 2021) (pp. 2307-2314). International Society of Offshore and Polar Engineers.

Mardika, M. G. I., Mashuri, & Hakim, D. R. (2024). Studi modeling dan mapping inundasi tsunami menggunakan software Delft3D: Studi kasus Pantai Labuan Jukung, Lampung. PADURAKSA: Jurnal Teknik Sipil.

Meidji, R., et al. (2022). Surface current circulation modeling in Palu Bay using COHERENS.

Mora-Uribe, N., Caamano Avendano, D., Villagran-Valenzuela, M., Roco-Videla, A., & Alcayaga, H. (2025). Trends and applications of hydro-morphological modeling in estuarine systems: A systematic review of the past 15 years. Journal of Marine Science and Engineering, 13(6), 1056.

Putra, R. F. P., Nasution, T. I., Humaidi, S., & Darmawan, Y. (2023). Analysis of interaction between atmosphere and sea using the Delft3D hydrodynamics model for mapping coastal flood zone at Belawan Port and coastal area. Prisma Sains: Jurnal Pengkajian Ilmu dan Pembelajaran Matematika dan IPA IKIP Mataram, 11(2), 450-462.

Prananda, B. R., Sisinggih, D., & Sajali, M. A. (2024). Analisa hidrodinamika di perairan PLTU Palu-3 dengan menggunakan aplikasi numerik Delft3D. Jurnal Teknologi dan Rekayasa Sumber Daya Air, 4(2), 1327-1340.

Pratama, A. D., Suparta, I. W., & Syahputra, H. N. (2019). Konektivitas transportasi laut terhadap pertumbuhan ekonomi di negara maritim Asia Tenggara. Jurnal Ekonomi Pembangunan, 8(2), 1-13.

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026

Pratama, M. B., Venugopal, V., Ajiwibowo, H., Ginting, J. W., & Novico, F. (2020). Modelling tidal flow hydrodynamics of Sunda Strait, Indonesia. ILMU KELAUTAN: Indonesian Journal of Marine Sciences, 25(4), 165-172.

Setiawan, E., et al. (2016). Pengolahan gelombang permukaan laut menggunakan metode Sverdrup Munk Bretschneider (SMB) di perairan Pulau Pabelokan. Hidropilar, 2(2), 133-146.

Sofiana, R., Wiyono, R. U. A., & Nurtjahjaningtyas, I. (2022). Tsunami mitigation strategy at Watu Ulo Beach based on numerical modeling using Delft3D-Flow. U Karst, 6(1), 158-173.

Triana, Y. (2008). Longshore current yang ditimbulkan oleh transformasi gelombang di Eretan Kulon, Indramayu. Institut Pertanian Bogor.

Triatmodjo, B. (1999). Teknik pantai. Beta Offset.

Harianto, T. (2025). Laporan analisa hidrodinamika arus dan gelombang laut tahun 2025. Pusat Teknologi (COT).

Received August 6, 2026; August 20, 2026; Accepted for publication August 22, 2026