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# Tidal Circulation Modeling in Prigi Bay, Indonesia: Hydrodynamic Patterns and Implications for Fisheries-Port Management

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**ABSTRACT**

Prigi Bay is a semi-enclosed coastal system where tidal hydrodynamics govern circulation patterns and constitute the dominant hydrodynamic forcing within the bay. The purpose of this study is to model tidal circulation characteristics and evaluate their implications for fisheries-port management in Prigi Bay, Trenggalek Regency, East Java, Indonesia. Tidal currents were simulated using the Advanced Circulation (ADCIRC) model and supported by *in situ* current measurements conducted through purposive sampling and Eulerian observations using current meters, while tidal characteristics were derived using harmonic analysis based on the Admiralty method and model outputs. The results indicate that Prigi Bay has a mixed predominantly semidiurnal tide. Station-representative observed current velocities ranged from 0.10 to 0.34 m $s^{-1}$, while individual field measurements reached up to 0.50 m $s^{-1}$. ADCIRC simulations produced current velocities of up to 0.63 m $s^{-1}$ during the simulated tidal cycle. The Admiralty analysis yielded HHWL at +1.32 m and LLWL at −1.32 m relative to MSL, whereas the ADCIRC simulation produced a maximum water level of +1.15 m and a minimum of approximately −1.09 m during the simulation period. The model showed a mean relative error of 7.18% for tidal elevation, indicating good agreement with field observations. The simulated circulation patterns suggest that the narrow bay entrance and gently sloping bathymetry influence the spatial distribution of tidal currents within the bay. These findings provide a hydrodynamic baseline that can support coastal zoning, navigation planning, and fisheries-port management in Prigi Bay.

## INTRODUCTION

Semi-enclosed bays are dynamic coastal environments where tidal forcing interacts with geomorphology to control circulation patterns, sediment transport, shoreline stability, and water exchange efficiency (Passeri et al., 2016; Li et al., 2025). Bay geometry, inlet configuration, and bathymetry regulate the spatial distribution of tidal energy (Woodroffe, 2002; Pugh & Woodworth, 2014), creating zones of current acceleration and sediment transport that directly affect navigation safety, port operability, and ecosystem health. These issues are increasingly critical under rising anthropogenic pressure, sediment input, and climate-driven sea-level rise (Pugh & Woodworth, 2014; Masselink et al., 2020).

Coastal and bay-scale hydrodynamic studies play a fundamental role in understanding and managing the complex interactions between physical forcing and coastal system responses. Tidal hydrodynamics, in particular, control water circulation, mixing processes, and sediment transport pathways, which directly influence water quality, nutrient distribution, and ecological productivity in semi-enclosed environments (Pugh & Woodworth, 2014; Masselink et al., 2020). Moreover, hydrodynamic studies provide critical baseline information for evaluating coastal vulnerability to sea-level rise, storm surges, and changing boundary conditions under climate variability (Passeri et al., 2016; Li et al., 2025). In data-limited tropical regions, such as many parts of Indonesia, process-based hydrodynamic analysis is particularly important for supporting evidence-based coastal planning, optimizing infrastructure placement, and enhancing the resilience of fisheries-dependent communities.

Coastal hydrodynamic research has advanced substantially through numerical models such as ADCIRC, Delft3D, and ROMS, which are widely used to simulate tidal elevations and current dynamics in complex coastal domains (Luettich & Westerink, 2004; Dietrich et al., 2011). Recent developments have extended these modeling approaches to incorporate three-dimensional flow structures, wave–current interactions, and data-driven improvements, including metocean clustering and remote sensing-based bathymetry estimation (Tan et al., 2024; Andriolo et al., 2025; Gic-Grusza, 2025). In parallel, studies have increasingly focused on hydrodynamic responses to sea-level rise, extreme climate forcing, and long-term environmental variability (Passeri et al., 2016; Arafat et al., 2025; Li et al., 2025; Huang et al., 2026), as well as on coupled wave-tide processes along open and deltaic coastlines (Sultana et al., 2025). Process-based investigations in estuaries and tidal inlets have also revealed complex circulation features such as ebb jets, eddies, and flow asymmetries driven by inlet configuration and basin geometry (Pratama & Venugopal, 2024; Adithya et al., 2025; Torres-Córdoba et al., 2025). Furthermore, hydrodynamic analyses have been increasingly linked to fisheries distribution and oceanographic connectivity in Indonesian waters (Sartimbul et al., 2023; Wicaksono et al., 2025).

Despite these advances, most investigations continue to focus on large estuaries, open coasts, or basin-scale systems, while medium-scale fisheries ports in semi-enclosed tropical bays remain underrepresented. At the same time, growing evidence highlights the critical role of geomorphological controls in shaping hydrodynamic behavior. Recent studies demonstrate that feedback mechanisms between hydrodynamics and sediment dynamics can drive morphological evolution and even regime shifts in tidal environments (Zhu et al., 2025), while anthropogenic alterations in bathymetry and coastal geometry can significantly modify tidal propagation, salinity structure, and circulation thresholds (Zhong et al., 2024).

Furthermore, coastal management frameworks, including Integrated Coastal Zone Management, emphasize process-based, interdisciplinary approaches that explicitly integrate hydrodynamic and geomorphological perspectives to support sustainable and resilient coastal development (Windayati et al., 2020; Windayati et al., 2022; Gunawan et al., 2025).

This study aims to characterize Prigi Bay's tidal circulation using two-dimensional hydrodynamic modeling with ADCIRC, validate the model against field observations, and assess its potential to support fisheries port management. This study applies and validates a two-dimensional ADCIRC model to characterize tidal circulation in Prigi Bay, with particular attention to spatial variation in current velocity relative to the bay configuration and bathymetry. By combining numerical simulation with field observations at ten stations, the study provides a bay-scale hydrodynamic baseline for a tropical fisheries-port environment where spatially distributed tidal-current information remains limited. The analysis is intended to improve understanding of tidal circulation patterns relevant to navigation and subsequent fisheries-port management assessments.

## RESEARCH METHODS

This study was conducted in Prigi Bay, which is administratively located in Trenggalek Regency, East Java Province, Indonesia. Geographically, Prigi Bay lies between approximately 8°17′–8°22′ South latitude and 111°42′–111°46′ East longitude, covering about 82.94 km² (8,294 ha) **(Figure 1)**. The bay is bordered by Tasikmadu Village to the north, Popoh Beach (Tulungagung Regency) to the east, the Indian Ocean to the south, and Damas Village (Trenggalek Regency) to the west. This location places Prigi Bay along Java's highly energetic southern coast, directly facing the Indian Ocean.

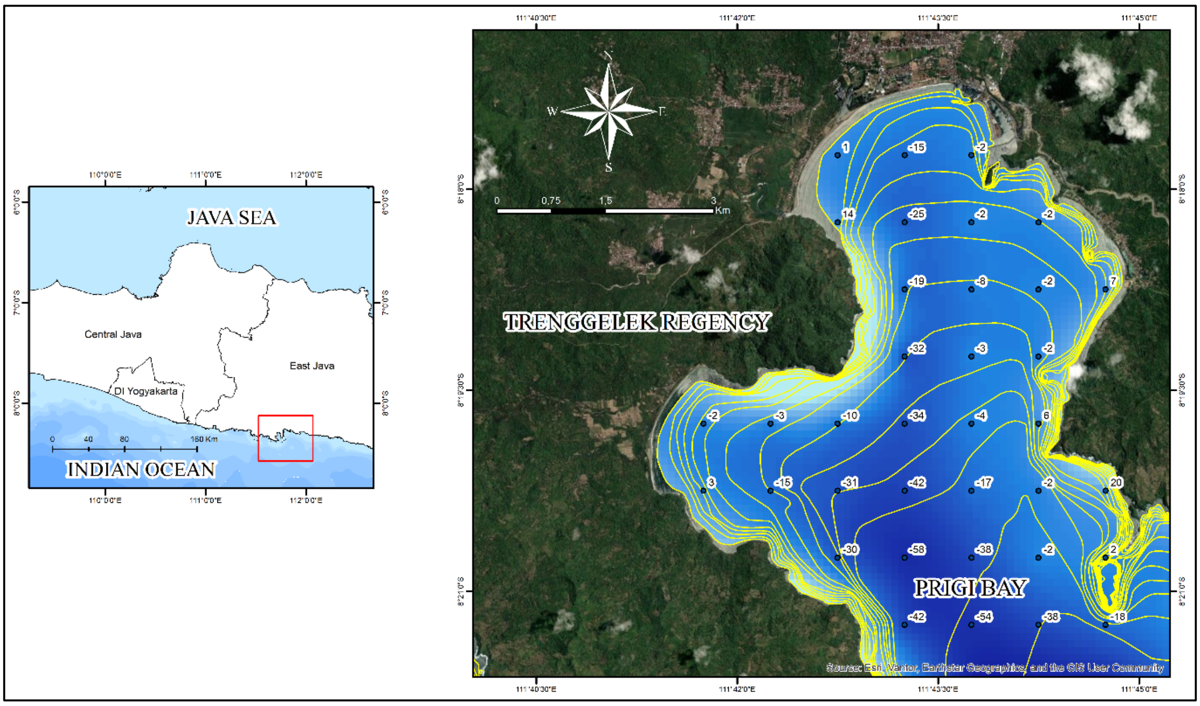


**Figure 1**. Location of Prigi Bay, Trenggalek Regency – Indonesia (Source: Sentinel-2, 2026)

Prigi Bay has a narrow southern opening that limits direct water exchange with the open ocean. The surrounding coastal landscape spans from low-lying shorelines at sea level to steep terrain reaching 200 m elevation in the hinterland, illustrating the shift from coastal plains to uplifted volcanic and structural features typical of southern Java (Heliani et al., 2013). Prigi Bay is also an important fisheries hub in Fisheries Management Area (WPP) 573, namely Prigi Archipelago Fishery Port (Pelabuhan Perikanan Nusantara Prigi, known as PPN Prigi), located in Tasikmadu Village, Watulimo District. PPN Prigi has grown from a small fishing village into an important fisheries hub in southern East Java, supporting offshore fishing, vessel services, fish landing, and post-harvest activities (Directorate General of Capture Fisheries, 2026). Set within a semi-enclosed bay with complex coastal landforms and intense port operations, Prigi Bay offers an ideal setting to study how tidal currents interact with coastal geomorphology, making it highly relevant for evaluating water circulation and its implications for sustainable coastal and fisheries-port management.

We conducted field measurements at ten purposively selected stations across the Prigi Bay system. The stations were selected to represent different hydrodynamic settings, including the fisheries port area, river-mouth and nearshore areas, the central bay, and the eastern and western sections of the bay mouth. The ten stations comprised the area in front of the PPN Prigi, the Prigi Beach river mouth, Kumbokarno Cave, Karanggongso Beach, Pasir Putih Beach, Damas Beach, the central bay, the area near Mutiara Island, the eastern bay mouth, and the western bay mouth. **Table 1** shows the spatial distribution of the ten observation stations.

**Table 1**. The Spatial Distribution of Observation Stations

| Poin | Latitude (X) | Longitude (Y) | Description |
|---|---|---|---|
| 1 | 8°17'29.19"S | 111°43'45.77"E | In front of the PPN Prigi anchorage area |
| 2 | 8°18'70.40"S | 111°42'34.83"E | Near the river mouth at Prigi Beach |
| 3 | 8°18'39.07"S | 111°42'55.22"E | Near Kumbokarno Cave |
| 4 | 8°17'55.28"S | 111°44'10.86"E | Karanggongso Beach area |
| 5 | 8°18'42.14"S | 111°44'35.16"E | Pasir Putih Beach area |
| 6 | 8°19'35.05"S | 111°42'24.17"E | Near Damas Beach |
| 7 | 8°20'21.59"S | 111°42'39.39"E | In the middle of Prigi Bay |
| 8 | 8°19'52.58"S | 111°44'14.24"E | Near Mutiara Island |
| 9 | 8°20'38.68"S | 111°44'39.91"E | At the eastern mouth of the bay |
| 10 | 8°21'29.68"S | 111°43'2.08"E | At the western mouth of the bay |

(Source: Field-based Observation, 2026)

Current velocity and direction were measured using a Flowatch FL-03 Portable Flow Meter. We operated the instrument using a fixed-point Eulerian approach. We deployed the current meter at approximately 0.6 m below the water surface, following the field measurement procedure used in the original survey. Geographic coordinates of each station were recorded using a Garmin GPSmap 60CSx. For model validation, we collected field observations and compared them with ADCIRC outputs extracted at the corresponding model locations and times. This comparison was intended to evaluate whether the model reproduced the magnitude of observed current velocity across the bay.

Complementary secondary data included tidal elevation records from the Geospatial Information Agency of Indonesia (BIG), which were used for harmonic analysis, tidal classification, and water-level validation. Bathymetric data required for hydrodynamic modeling were obtained from the Indonesia Army Map Service dataset and processed to represent the bathymetric configuration of Prigi Bay and the adjacent offshore waters.

Tidal hydrodynamics in Prigi Bay were simulated using the Advanced Circulation (ADCIRC) model, which solves depth-averaged shallow water equations based on mass and momentum conservation (Luettich & Westerink, 2004). ADCIRC is a geometry-based numerical model in which bathymetric configuration and coastal geometry strongly control hydrodynamic behavior. The model domain encompassed the entire Prigi Bay and adjacent offshore waters to accurately represent tidal propagation from the Indian Ocean into the bay. We defined bathymetric geometry using scattered depth points and closed boundary polygons formed by feature arcs, and determined mesh quality based on bathymetric point density and vertex distribution along boundaries. We simulated tidal circulation in Prigi Bay using the two-dimensional depth-integrated ADCIRC model (ADCIRC-2DTR). The computational domain covered Prigi Bay and adjacent offshore waters, with bathymetry represented by digitized depth points and a finite-element mesh constructed from feature arcs, vertices, and nodes. The model was forced at the ocean boundary using harmonic tidal constituents derived from the observed tidal record and represented through the Le Provost tidal formulation. The mainland boundary was treated as a closed boundary.

The simulation started at 00:00 on 1 March 2026 and ended at 00:00 on 16 March 2026, covering 15 days. A computational time step of 60 s was used. We extracted global elevation and velocity outputs from ADCIRC Fort.63 and Fort.64, respectively. We then used the model outputs to examine the spatial distribution of water-level elevation and depth-integrated current velocity across different tidal stages.

In this study, we applied the two-dimensional depth-integrated model (ADCIRC-2DTR) to compute water levels and horizontal current components (U and

V) in the longitudinal (x) and lateral (y) directions. The governing depth-averaged momentum equation solved in ADCIRC can be expressed as:

$$\frac{\partial v}{\partial t} + v\nabla.(v) + f.v + \nabla\left[\frac{\rho a}{\rho 0} + g(\zeta - \alpha\eta)\right] - \frac{\tau s + \tau b}{\rho 0} - \frac{\varepsilon}{H}\nabla^2(Hv) = 0$$

which includes local acceleration ($\partial v/\partial t$), momentum advection ($v\nabla.(v)$), the Coriolis force ($f\times v$), atmospheric pressure gradients ($\nabla(\rho a/\rho 0)$), and gravitational forcing associated with sea surface elevation and tides ($g(\zeta-\alpha\eta)$). Additional forcing terms include surface stress from wind and waves ($\tau s$) and bottom friction ($\tau b$), whose combined effect per unit mass ($(\tau s+\tau b)/\rho 0$) represents momentum exchange between the water column, the atmosphere, and the seabed. Horizontal momentum dispersion is parameterized through an eddy viscosity term ($(\varepsilon/H)\nabla^2(Hv)$), which accounts for turbulent mixing and smooths velocity gradients. We adopted several simplifying assumptions, including using depth-averaged values to represent vertical variability, neglecting vertical velocity and acceleration, assuming a hydrostatic pressure distribution, and assuming gently varying bottom slopes in the horizontal directions. This modeling framework was validated using field observations.

We analyzed tidal elevation data from the Geospatial Information Agency of Indonesia (BIG) using the Admiralty method to derive the principal harmonic constituents and classify the tidal regime. The Formzahl number was calculated from the amplitudes of the principal diurnal and semidiurnal constituents. We then derived the highest high water level (HHWL) and Lowest Low Water Level (LLWL) from the harmonic constituents and expressed them relative to mean sea level (MSL). To compare with ADCIRC, we referenced observed and simulated water levels to the same local datum used in the analysis. The comparison used corresponding time steps during the selected validation period. The analysis distinguished between harmonic tidal levels derived from the Admiralty analysis and the extreme water levels represented by the model output.

We validated the model by comparing ADCIRC outputs with field observations of tidal elevation and current velocity. We quantified simulation accuracy using Relative Error (RE) and Mean Relative Error (MRE) metrics following Donnel et al. (2003). The Relative Error is defined as:

$$RE = \frac{Xs - Xa}{Xs}$$

where $Xs$ represents the observed value, and $Xa$ represents the model value. The Mean Relative Error was calculated as the average of relative errors across all observations and expressed as a percentage:

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{Xs - Xa}{Xs} \times 100\%$$

where $n$ denotes the number of observations. The resulting MRE values indicate model reliability in representing tidal dynamics in Prigi Bay. Low MRE values indicate good agreement between the model and observed data, confirming that the ADCIRC model accurately represents tidal elevation and current patterns and is suitable for hydrodynamic analysis and coastal management applications in the study area.

## RESULTS AND DISCUSSION

### Tidal and Current Conditions

In situ observed current velocities ranged from 0.10 to 0.34 m s$^{-1}$, while individual field measurements reached up to 0.50 m s⁻¹, and ADCIRC-simulated current velocities reached a maximum of 0.63 m s⁻¹. These values reflect the bay's semi-enclosed nature, where tidal energy is partially dissipated due to geometric confinement and bathymetric restrictions. Similar current-velocity ranges in semi-enclosed and estuarine systems have been reported, indicating reduced hydrodynamic flushing and localized energy dissipation (Adithya et al., 2025; Torres-Córdoba et al., 2025).

Tidal characteristics derived from harmonic analysis using the Admiralty method reveal that the bay experiences a mixed, predominantly semidiurnal tide. The calculated Formzahl (F) value of 0.45, obtained from the ratio of diurnal (K1 + O1) to semidiurnal (M2 + S2) constituents, falls within the 0.25–1.50 range, confirming this classification. The harmonic analysis identified M2 and S2 as the dominant semidiurnal tidal constituents. The S0 component represents the mean water-level component and is therefore considered separately from the oscillatory astronomical tidal constituents. The dominance of the M2 and S2 constituents is consistent with classifying Prigi Bay as a mixed, predominantly semidiurnal tidal system. This tidal regime plays a key role in controlling current periodicity, as widely observed in coastal systems subjected to mixed tidal forcing (Sultana et al., 2025).

### Tidal Currents Model during High Highest Water Level (HHWL)

The ADCIRC hydrodynamic model captures tidal current behavior during the High Highest Water Level (HHWL) condition **(Figure 2)**. The model results indicate that during HHWL conditions, tidal currents mainly move landward, with stronger flows directed toward the eastern part of Prigi Bay, particularly around Pasir Putih Beach. At the same time, part of the circulation is deflected southward, flowing back toward the Indian Ocean. This pattern reflects how basin geometry and inlet configuration redistribute tidal energy and generate localized circulation cells, as commonly observed in semi-enclosed basins with geometric constraints (Torres-Córdoba et al., 2025).

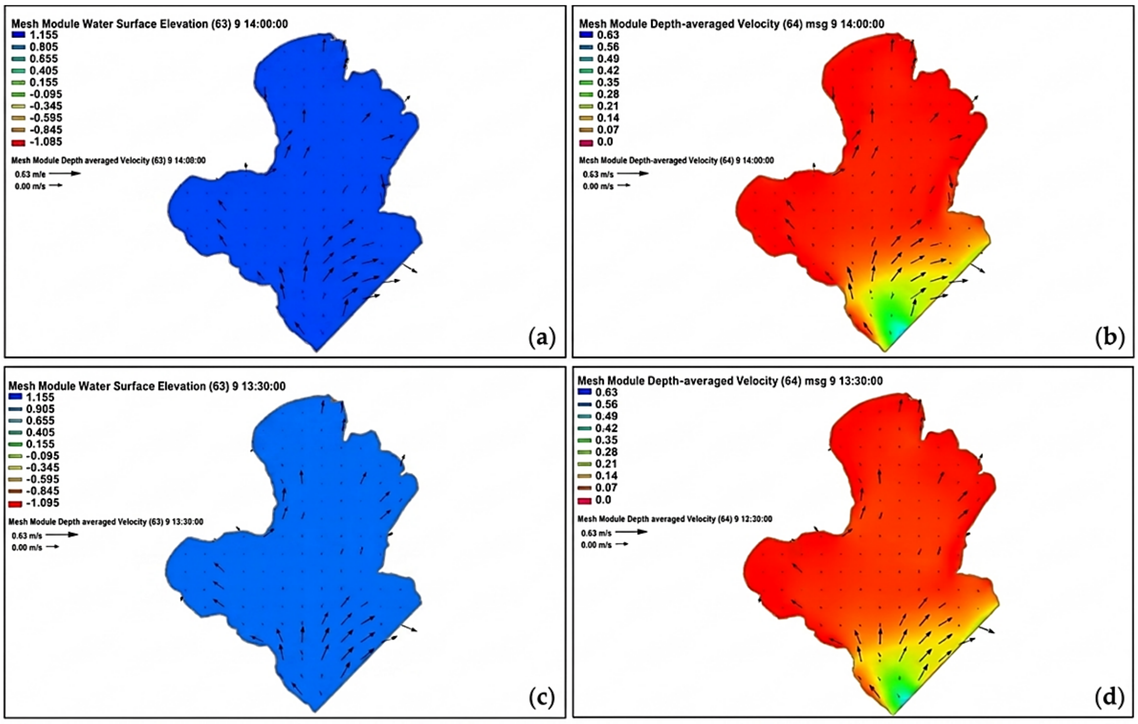


**Figure 2**. (a) Tidal current pattern during HHWL; (b) Tidal current patterns and velocities during HHWL; (c) Tidal current pattern approaching HHWL; (d) Tidal current patterns and velocities approaching HHWL

The tidal elevation reaches 1.15 m, closely matching observed real-time tidal data. The slight 30-minute temporal difference and negligible elevation discrepancy demonstrate strong model reliability. Current velocities during HHWL range from 0.07 to 0.49 m $s^{-1}$, with maximum velocities reaching 0.63 m $s^{-1}$ during spring tide conditions. Velocities are lower along the shoreline and inner bay, while higher velocities concentrate near the western bay entrance, where bathymetric narrowing accelerates tidal flow. This acceleration effect is consistent with previous findings that constricted inlets and abrupt bathymetric gradients can intensify current velocities and generate flow asymmetry (Pratama & Venugopal, 2024; Zhong et al., 2024).

**Tidal Currents Model during Low Lowest Water Level (LLWL)**

During the Low Lowest Water Level (LLWL) condition, the circulation pattern clearly reverses **(Figure 3)**. The model indicates that tidal currents predominantly flow seaward toward the Indian Ocean, accompanying a minimum water level of approximately –1.095 m. The negative elevation represents the lowest tidal stage during the simulation period. This ebb-dominated flow reflects the typical bidirectional nature of tidal systems, where flood and ebb phases control sediment transport pathways and water exchange processes (Adithya et al., 2025).

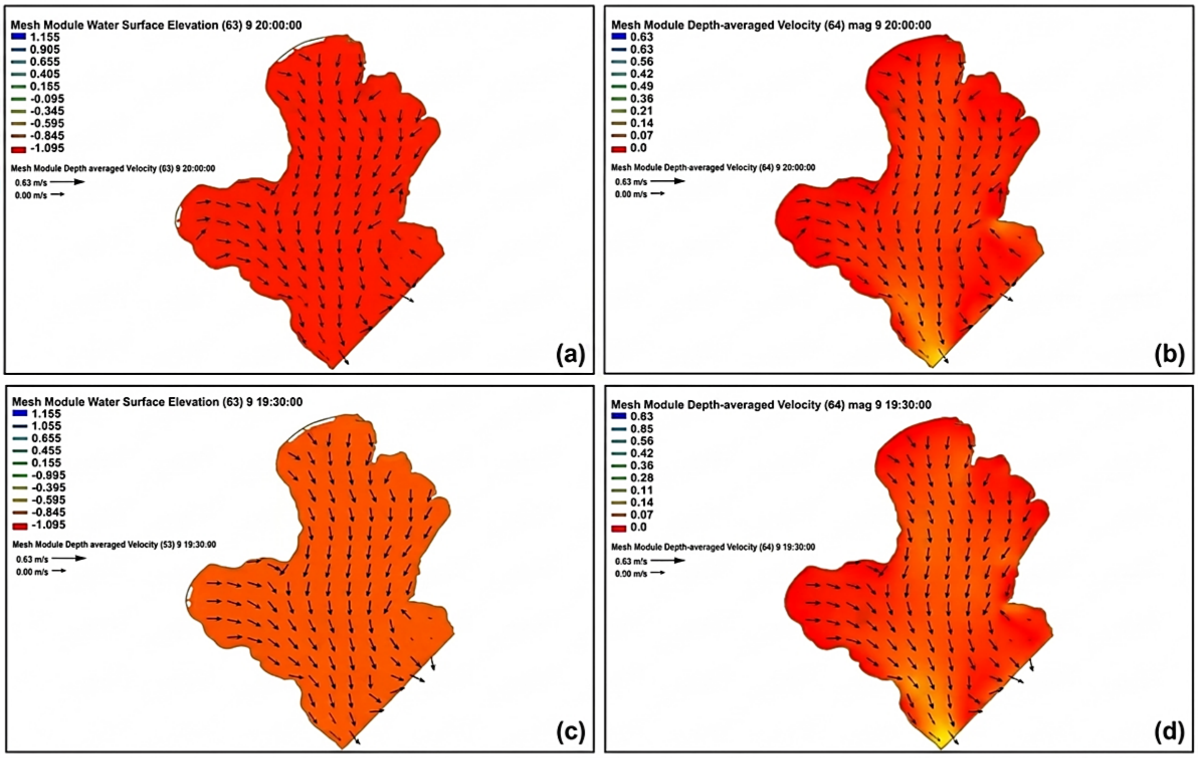


**Figure 3**. (a) Tidal current pattern during LLWL; (b) Tidal current patterns and velocities during LLWL; (c) Tidal current pattern approaching LLWL; (d) Tidal current patterns and velocities approaching LLWL

During LLWL, the simulated circulation reversed relative to the flood phase, with the dominant flow directed seaward toward the Indian Ocean. Maximum current velocity was approximately 0.14 m $s^{-1}$ and was concentrated near the bay mouth, whereas velocities within the inner bay were generally lower. This reversal represents the ebb phase of the tidal circulation. The model results show horizontal exchange between the bay and the adjacent Indian Ocean but do not provide direct evidence of upwelling, downwelling, or vertical nutrient transport because the two-dimensional model does not resolve vertical velocity.

Current velocities during LLWL are generally lower than during HHWL, with maximum values of approximately 0.14 m $s^{-1}$, particularly concentrated near the bay mouth. The spatial variation in tidal current velocity suggests differences in hydrodynamic energy within the bay. Relatively higher velocities near the bay mouth indicate stronger tidal forcing, whereas lower velocities in parts of the inner bay indicate weaker horizontal flow (Zhu et al., 2025). These patterns may be relevant to the potential distribution of suspended material; however, the present study did not directly simulate sediment transport, erosion, deposition, or shoaling.

## Model Validation

Comparison of ADCIRC outputs with field observations resulted in a mean relative error (MRE) of 6.82% for current velocity based on the ten validation stations. For tidal elevation, comparison of ten hourly observations with the corresponding model outputs resulted in an MRE of 7.18%. These values indicate relatively small differences between the model and the available observations during the validation period. This agreement supports using the model to describe the spatial pattern and temporal behavior of tidal circulation in Prigi Bay, while validation remains limited by the short duration and spatial coverage of the field observations. Beyond validation, this level of agreement is critical because it supports using the model as a tool for process interpretation rather than merely descriptive simulation. Comparable accuracy in recent studies shows that calibrated hydrodynamic models can reliably resolve spatial variability in tidal currents and circulation structures (Adithya et al., 2025; Sultana et al., 2025).

Robust model performance also enables further interpretation of hydrodynamic-geomorphological interactions. As previous studies highlight, accurately representing tidal dynamics is essential for assessing long-term coastal evolution, particularly in systems where morphology and hydrodynamics are strongly coupled (Passeri et al., 2016; Zhong et al., 2024). In this context, the validated model provides a basis for examining spatial variations in tidal circulation in relation to the bay configuration and bathymetric setting.

Prigi Bay displays geomorphological features along the southern coast of Java, formed through the combined influence of tectonic uplift, marine dynamics, and riverine inputs. In this coastal setting, coastline shape plays a key role in regulating how hydrodynamic energy is distributed and how water circulates (Woodroffe, 2002). The rocky headlands and semi-enclosed bay configuration contribute to spatial variation in the modeled tidal-current field. The relatively shallow and gently sloping inner-bay bathymetry is associated with lower modeled current velocities than those observed near the bay mouth.

The narrow entrance and uneven bathymetry are associated with spatial differences in tidal-current velocity and exchange between the bay and the Indian Ocean. Model results show that current speeds increase near the bay mouth, especially in the deeper western sector, reflecting the tendency of tidal flows to accelerate as they pass through constricted openings under pressure gradients (Torres-Córdoba et al., 2025).

During HHWL, the simulated flow was predominantly directed landward, with stronger currents concentrated toward the eastern part of the bay and around the bay mouth. The model also showed spatial differences in current velocity, with relatively higher velocities near the western entrance and lower velocities along the inner-bay margins. These patterns indicate that the distribution of depth-integrated tidal currents varies with the bay's configuration and bathymetric characteristics (Dzwonkowski et al., 2023). Because the present model is depth-integrated, the results describe horizontal circulation and do not resolve vertical velocity or vertical exchange processes.

The mixed, predominantly semidiurnal tide, together with the bay's semi-enclosed shape, produces uneven current patterns: stronger, high-energy flows concentrate near the bay entrance, while calmer, low-energy conditions dominate the inner bay and nearshore areas (Woodroffe, 2002; Winterwerp & Wang, 2013).

From a fisheries-port management perspective, the spatial distribution of tidal current velocity provides baseline hydrodynamic information for subsequent assessments of navigation, channel maintenance, and port development. Areas with relatively stronger currents near the bay mouth and weaker currents within the inner bay can be considered in future site-specific assessments. However, decisions concerning breakwater configuration, navigation-channel dimensions, dredging requirements, and port infrastructure should incorporate additional information on waves, sediment transport, bathymetric change, and navigation conditions, which were beyond the scope of this study. Finally, understanding the coupling between tidal dynamics and coastal morphology is becoming increasingly important under future sea-level rise and climate variability (Li et al., 2025), which may alter tidal propagation and current strength in the bay. Therefore, the validated hydrodynamic model provides a baseline for subsequent coastal and fisheries-port management assessments in Prigi Bay.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTION

**RW**. Conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing, visualization. **AS**. Investigation and visualization. All authors have read and agreed to the published version of the manuscript.

## CONCLUSION

Prigi Bay exhibits a mixed predominantly semi-diurnal tidal regime, with a Formzahl number of 0.45 based on harmonic analysis of the observed tidal record. The ADCIRC-2D simulation reproduced the principal horizontal tidal circulation pattern, characterized by predominantly landward flow during the flood phase and seaward flow during the ebb phase. Higher current velocities were generally concentrated near the bay mouth, while lower velocities occurred within parts of the inner bay, indicating spatial variation in tidal-current energy associated with the bay configuration and bathymetric setting.

Comparison with field observations at ten stations produced a mean relative error of 6.82% for the selected current-velocity validation data, while the selected tidal-elevation comparison yielded a mean relative difference of 7.18%. These results indicate reasonable agreement between the model and the available observations during the validation period. The resulting hydrodynamic information provides a baseline for subsequent fisheries-port and coastal-management assessments in Prigi Bay. However, the two-dimensional, depth-integrated model does not resolve vertical circulation and sediment transport; it did not directly simulate deposition and ecological processes. Therefore, further assessment incorporating longer field observations, improved bathymetric data, wave conditions, and sediment-related measurements is required for detailed port planning and coastal-process evaluation.

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