JOURNAL OF APPLIED GEOSPATIAL INFORMATION

Vol 9 No 1 2025

http://jurnal.polibatam.ac.id/index.php/JAGI
ISSN Online: 2579-3608

Spatial Variability of Tidal Characteristics in Bintan Coastal Waters: A Case Study of Moco Port, Bakau Bay, and Tanjung Uban Port

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Received: January, 12 2025
Accepted: May 19, 2025
Published: June 26, 2025

Abstract

Tidal dynamics play a crucial role in coastal processes, port operations, and coastal management, particularly in regions characterized by complex oceanographic interactions such as Bintan Island, Riau Islands Province, Indonesia. This study analyzes the spatial variability of tidal characteristics in the coastal waters of Bintan Island at three observation sites, namely Bakau Bay, Tanjung Uban Port, and Moco Port, using global tidal prediction data generated by MIKE Powered by DHI and harmonic analysis based on the Admiralty method. Eight principal tidal constituents (M_2, S_2, K_1, O_1, N_2, P_1, K_2, and Q_1) were examined, and tidal types were classified using the Formzahl number. The results reveal clear spatial variability in tidal harmonic characteristics despite the close geographic proximity of the sites, with the M_2 constituent dominating tidal behavior at all locations, indicating strong lunar control. Significant contributions from diurnal constituents (K_1 and O_1) result in mixed tidal regimes, with Formzahl values of 1.10 at Bakau Bay, 0.66 at Tanjung Uban, and 1.29 at Moco, classifying all sites as mixed tides with a predominance of semidiurnal components. Variations in tidal amplitudes are closely related to local coastal morphology and exposure to open waters, with Tanjung Uban exhibiting the strongest tidal influence. This multi-location analysis provides a comprehensive understanding of spatial tidal variability in Bintan coastal waters and supports coastal planning, port management, and hydrodynamic modeling in the region.

Keywords: Tidal harmonic analysis, Spatial tidal variability, Mixed tide, Formzahl number, Bintan Island

1. Introduction

The coastal waters of Bintan Island are part of the coastal region of the Riau Islands Province and play a strategic role in ecological, social, and economic aspects. Geographically, Bintan Island is located along an international maritime corridor adjacent to the Singapore Strait and the South China Sea, causing its waters to be influenced by complex oceanographic dynamics. Human activities in this region have developed rapidly, including port operations, fisheries, marine tourism, maritime transportation, and coastal settlements (Anugrah et al., 2022; Jemi et al., 2022). These conditions highlight the importance of understanding oceanographic characteristics, particularly tidal processes, to support sustainable coastal management in the waters of Bintan Island.

Tides are a periodic phenomenon characterized by the rise and fall of sea level, primarily driven by the gravitational forces of celestial bodies, particularly the Moon and the Sun, and further modified by coastal morphology, water depth, and local hydrographic conditions (Alajuri et al., 2025; SETIAWAN et al., 2020). In coastal waters such as those surrounding Bintan Island, tides play a crucial role in controlling current dynamics, sediment transport processes, sea level fluctuations within ports, and the potential for coastal inundation. Spatial variations in tidal characteristics within a single coastal region may arise from differences in bay configuration, shoreline geometry, and exposure to the open sea, resulting in non-uniform tidal behavior across locations (Lestari et al., 2024).

Tidal studies provide broad benefits, particularly in supporting navigational safety and efficiency, port planning and operations, mitigation of tidal flooding, and the management of coastal ecosystems (Sagala et al., 2021; Sufyan et al., 2022). Accurate tidal information also serves as a fundamental basis for hydrodynamic modeling, the establishment of vertical datums, and the planning of coastal infrastructure. For regions such as Bintan Island, which host several active ports and coastal tourism areas, an understanding of tidal characteristics across multiple locations is crucial for informed, data-driven decision-making (Hermialingga, 2020; Rahawarin et al., 2025).

Nevertheless, a common challenge lies in the limited number of studies that explicitly address the spatial variability of tidal characteristics among observation sites within a single coastal region. Tidal data are often analyzed in a generalized manner or based on a single observation station, which may not adequately represent local-scale differences. This limitation can potentially lead to inaccuracies in port planning, estimations of safe navigation depths, and assessments of coastal inundation risk at different locations.

To address these limitations, tidal studies that explicitly incorporate spatial aspects are required by utilizing observational data from multiple locations with differing physical characteristics. This approach enables the identification of variations in tidal types, tidal ranges, and dominant harmonic constituents at each site, thereby providing a more comprehensive understanding of tidal dynamics in the coastal waters of Bintan Island.

Several previous studies have examined tidal characteristics in Indonesian waters and the Riau Islands, including the determination of tidal types, harmonic constituent analysis, and their relationships with current dynamics and sediment transport. according to (Umam et al., 2022), the tidal types produced by the TPXO 7.1 model are consistent with observations at Sebatik but differ at Marina Ancol, indicating that the model does not always accurately represent tidal types across all coastal locations. The study explains that the tidal type in Sorong waters was determined using harmonic analysis based on the Admiralty method, with nine tidal constituents identified. A Formzahl value of 0.614 indicates a mixed, mainly semidiurnal tidal regime (Setyowati & Zahrina W., 2024). The study identified a diurnal tidal type at Pondok Dayung using the ErgTide software with high accuracy (Adriansyah et al., 2024).

Based on this background, this study aims to analyze and compare tidal characteristics in the coastal waters of Bintan Island at three observation sites, namely Moco Port, Teluk Bakau Bay, and Tanjung Uban Port. Specifically, this study seeks to identify tidal types, tidal ranges, and the spatial variability of tidal characteristics among the observation sites.

The novelty of this study lies in its spatially explicit, multi-location tidal analysis within a single coastal region, focusing on sites with different functions and physical coastal characteristics. The results are expected to contribute to the scientific understanding of coastal physical oceanography and provide practical references for port management, coastal planning, and the reduction of coastal hazard risks in the waters of Bintan Island.

2. Method

This study uses global tidal prediction data from MIKE Powered by DHI. The predictions are produced using a global hydrodynamic model that incorporates the main astronomical tidal constituents and is calibrated with observational data and satellite altimetry. Data were extracted at Moco Port, Bakau Bay, and Tanjung Uban Port (**Fig. 1**) with a uniform temporal resolution.

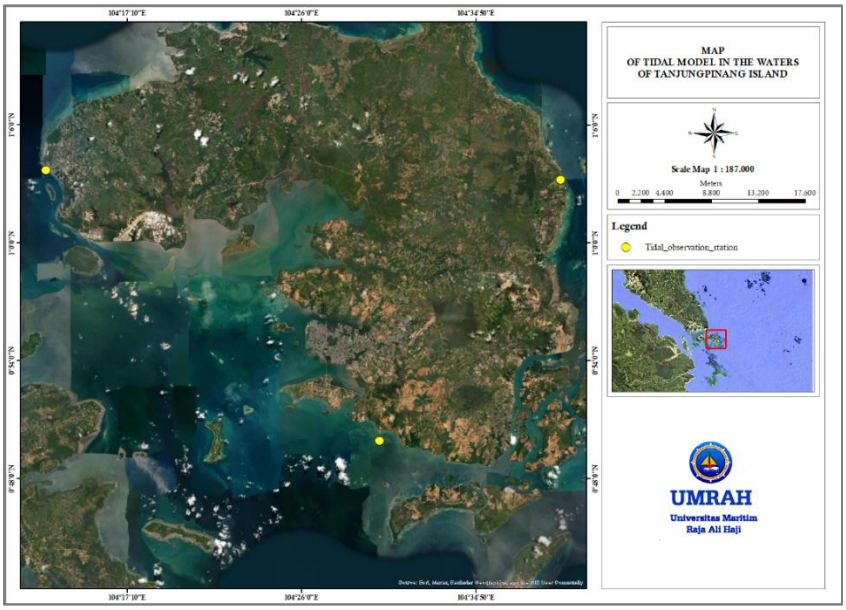


Figure 1. Research Location

Tidal characteristics were analyzed using harmonic analysis based on the Admiralty method, which decomposes tidal signals into harmonic constituents driven by the astronomical influences of the Moon and the Sun. This method is widely applied in coastal and port tidal studies due to its ability to represent tidal characteristics in a simple yet effective manner.

Sea level elevation can be expressed as :

$$\eta(t) = Z_0 + \sum_{i=1}^{n} A_i \cos(\omega_i + \phi_i) \quad (1)$$

Where :

$\eta(t)$: Sea level elevation at time (t)
Z_0 : mean sea level
A_i : Amplitude
ω_i : Angular frequency
ϕ_i : Phase
n : Number of harmonic constituents

The principal harmonic constituents analyzed include M_2, S_2, K_1, and O_1, along with additional secondary constituents depending on the resolution of the MIKE DHI tidal prediction data.

The tidal type at each location was determined using the Formzahl number (F), which is calculated based on the ratio of the amplitudes of diurnal and semidiurnal tidal constituents, expressed as:

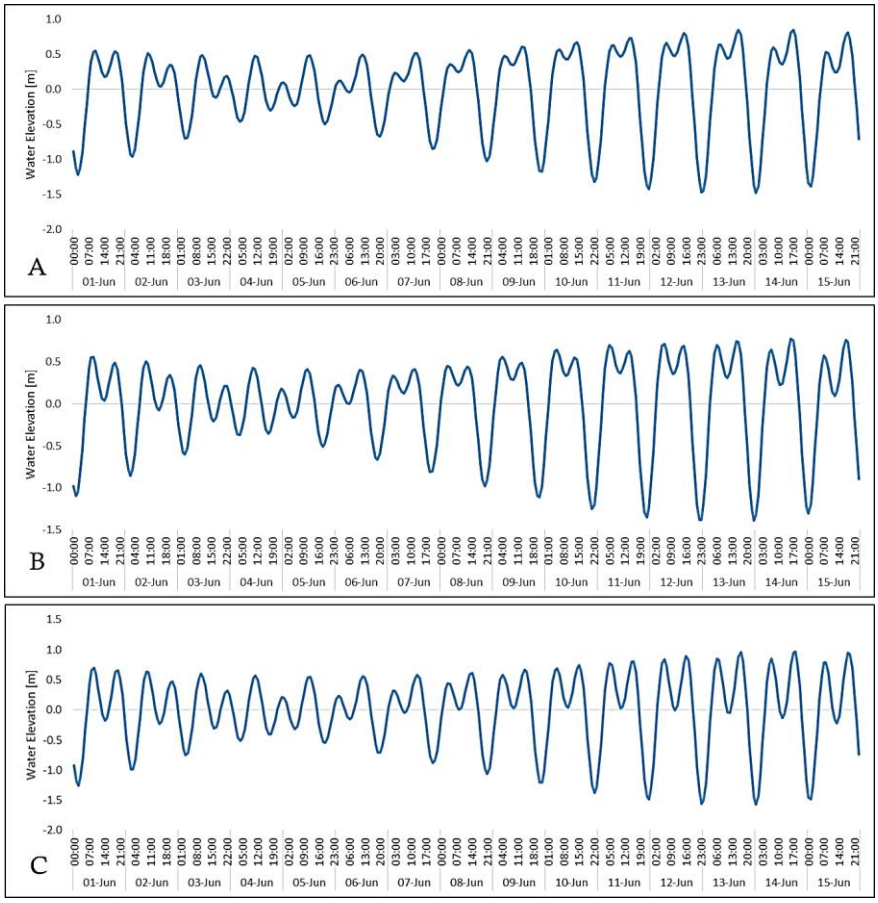
$$F = \frac{AK_1 + AO_1}{AM_2 + AS_2} \quad (2)$$

The tidal type classification based on the Formzahl number (F) is defined as follows:

- $F < 0.25$ Semidiurnal Tide
- $0.25 \leq F \leq 1.25$ mixed tide, mainly semidiurnal.
- $1.25 \leq F \leq 3.0$ mixed tide, mainly semidiurnal.
- $F < 3.0$ DiurnalTide

3. Result and Discussion

The results of the tidal harmonic analysis at three observation sites in the coastal waters of Bintan Island namely Bakau Bay, Tanjung Uban, and Moco reveal clear spatial variability in tidal characteristics, despite their relatively close proximity within the same coastal region (**Fig. 2**). The analysis was conducted using eight principal harmonic constituents, namely M_2, S_2, K_1, O_1, N_2, P_1, K_2, and Q_1 (**Table 1**), which collectively represent the dominant influence of lunar and solar gravitational forces on regional tidal dynamics (Triatmojo et al., 2024; Yuliardi et al., 2023).



(A) Moco Port; (B) Bakau Bay; (C) Tanjung Uban Port
Figure 2. Tidal Chart in Bintan Waters

Table 1. Tidal Harmonic Constants

Constituent	Bakau Bay Amp (m)	Phase (°)	Tanjung Uban Amp (m)	Phase (°)	Moco Amp (m)	Phase (°)
M_2	0.4897	87.19	0.6824	106.85	0.4705	108.36
S_2	0.1393	124.78	0.2369	149.49	0.1305	146.21
N_2	0.1220	46.75	0.1387	71.16	0.1096	63.80
K_2	0.0346	119.69	0.0628	145.27	0.0332	142.10
K_1	0.3295	342.02	0.3123	358.47	0.3896	2.98
O_1	0.3614	277.77	0.2961	289.91	0.3831	290.11
P_1	0.1137	338.79	0.1087	354.97	0.1332	358.09
Q_1	0.0905	252.78	0.0785	259.47	0.0939	260.35

The M_2 component (principal lunar semidiurnal) exhibits the highest amplitude among all tidal constituents at the three observation sites, indicating that lunar gravitational forcing is the primary driver of tidal dynamics in the waters of Bintan Island. The M_2 amplitudes were recorded as 0.4897 m at Teluk Bakau, 0.6824 m at Tanjung Uban, and 0.4705 m at Moco. The highest amplitude observed at Tanjung Uban reflects its more open exposure to the Singapore Strait, allowing stronger regional tidal forcing compared to locations that are more morphologically sheltered. This pattern is consistent with the findings of (Lubis et al., 2020; Wisha et al., 2023), who reported that open coastal waters tend to amplify semidiurnal tidal components due to reduced tidal energy dissipation.

The S_2 component (principal solar semidiurnal) shows lower amplitudes than M_2 at all sites, with values of 0.1393 m at Teluk Bakau, 0.2369 m at Tanjung Uban, and 0.1305 m at Moco. The relatively high M_2/S_2 amplitude ratios indicate a dominance of lunar tides over solar tides, which is a common characteristic of tidal regimes in western Indonesian waters (Putra et al., 2021; Solom et al., 2020). The relatively consistent phase of the S_2 component across the study sites suggests that solar tidal forcing is predominantly regional in nature and is less influenced by local coastal conditions.

The diurnal tidal constituents K_1 and O_1 exhibit relatively significant amplitudes at all three observation sites, indicating that tidal conditions in the waters of Bintan Island are not purely semidiurnal. The amplitudes of the K_1 constituent range from 0.3123 to 0.3896 m, while those of O_1 range from 0.2961 to 0.3831 m. The highest amplitudes of both K_1 and O_1 are observed at Moco, suggesting a strong influence of Earth's rotation and lunar declination on tidal dynamics in this area. This finding is consistent with the results reported by (Alajuri et al., 2025), who documented significant contributions of diurnal tidal constituents in the waters of Tanjungpinang and its surrounding regions.

The relatively large contribution of diurnal constituents compared to semidiurnal components results in a mixed tidal regime. This characteristic is also in agreement with previous studies by (Rudiastuti et al., 2019; Siagian et al., 2019), which demonstrated that most Indonesian coastal waters exhibit mixed tidal behavior due to complex interactions between astronomical forcing and local hydrodynamic conditions.

The N_2 constituent, which represents a variation of the principal lunar semidiurnal component (M_2), exhibits relatively small but consistent amplitudes across the three study sites, ranging from 0.1096 to 0.1387 m. The presence of the N_2 component reflects the modulation of the lunar orbital cycle, which influences short-term tidal fluctuations. The P_1 and Q_1 constituents, which are the respective companions of K_1 and O_1, display smaller amplitudes but still contribute to the overall shaping of the tidal waveform. The relatively uniform amplitudes of the Q_1 constituent across all locations suggest that its astronomical forcing is predominantly regional and only weakly affected by local coastal morphology.

The K_2 constituent exhibits the smallest amplitude among the semidiurnal components, with a maximum value of 0.0628 m observed at Tanjung Uban. Despite its relatively small magnitude, the K_2 component plays an important role in harmonic tidal analysis, as it contributes to the formation of extreme tidal variations, particularly when superimposed with the M_2 and S_2 constituents (Fabus et al., 2022).

Differences in harmonic amplitudes among the study sites indicate that spatial variability in tidal characteristics within the waters of Bintan Island is governed by a combination of astronomical forcing and local physical conditions, including bay configuration, water depth, and exposure to open-sea environments. Tanjung Uban, which is more directly exposed to open waters, exhibits larger tidal amplitudes, whereas Bakau Bay and Moco, which are relatively more sheltered, experience greater tidal energy attenuation. This pattern is consistent with the concepts of tidal resonance and bottom friction as described by (Willemsen et al., 2020). Consequently, the Formzahl values obtained at Teluk Bakau (F = 1.10), Tanjung Uban (F = 0.66), and Moco (F = 1.29) indicate that tidal conditions at all observation sites are classified as mixed tides with a predominance of semidiurnal components, reinforcing previous findings that tidal regimes in the Riau Islands region are generally mixed in nature while still being significantly influenced by diurnal constituents (Suhana et al., 2018).

Acknowledgements

The authors would like to express their sincere gratitude to the research team for their valuable contributions in data processing, analysis, and manuscript preparation, which have made this study possible. Appreciation is also extended to all parties who provided technical support and constructive input during the completion of this article.

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