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Harmonic Analysis and Validation of Tidal Prediction Models Using Observational Data from the Sekupang and Kabil Tidal Stations in 2024

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Abstract: Tides are periodic variations in sea level caused by the gravitational forces of the Moon and the Sun, as well as the Earth's rotation. Accurate tidal information plays an important role in supporting maritime activities, including navigation, port operations, fisheries, coastal management, and disaster mitigation in coastal areas. Batam City, located along an international shipping route, has high maritime activity, making accurate tidal prediction essential for ensuring navigation safety and supporting sustainable coastal development. This study aims to analyze tidal characteristics and validate a tidal prediction model using harmonic analysis based on tidal observation data from Sekupang and Kabil stations in 2024. The tidal data from both stations were analyzed using the harmonic analysis method implemented in the T_TIDE toolbox in MATLAB to obtain the main tidal harmonic constituents, including their amplitudes and phases. The obtained harmonic constants were then used to develop a tidal prediction model. The accuracy of the prediction results was evaluated by comparing the predicted tidal elevations with observed data using statistical parameters, including Root Mean Square Error (RMSE) and correlation coefficient. The analysis provides information regarding the dominant tidal constituents, tidal types, and the performance of the prediction model at Sekupang and Kabil stations. The comparison between the two stations also illustrates the influence of local geographical and oceanographic conditions on tidal characteristics and prediction accuracy. The results of this study are expected to contribute valuable information for improving tidal prediction accuracy in Batam waters and supporting maritime activities, hydrographic surveys, and coastal zone management.

Keywords : tidal analysis; harmonic analysis; tidal prediction; T_TIDE; Batam waters

Introduction

Tides are periodic variations in sea level caused by the gravitational forces of the Moon and the Sun, as well as the rotation of the Earth (Triatmodjo, 1999). This phenomenon is not only an important subject in oceanographic studies but also plays a significant role in supporting human activities in coastal areas. Tidal conditions influence various aspects, including coastal ecosystems, marine navigation, port operations, fisheries activities, and coastal reclamation projects (Ongkosongo & Suyarso, 1989; Pugh & Woodworth, 2014). For instance, efficient maritime transportation relies on accurate tidal information to determine appropriate berthing and departure schedules, while the fisheries sector requires tidal data to optimize fishing operations and ensure vessel safety during anchoring. Therefore, a comprehensive understanding of tidal characteristics is essential for supporting maritime activities and sustainable coastal management. The availability of accurate tidal information is crucial for navigation safety and coastal planning. In terms of disaster mitigation, tidal data can be utilized to anticipate coastal flooding or tidal inundation, which occurs when high tides coincide with extreme meteorological conditions (Marfai et al., 2008; Rosyid, 2018). Such information is required not only by port authorities and maritime operators but also by coastal communities and policymakers for spatial planning, infrastructure development, and coastal protection strategies.

One of the widely applied methods for obtaining accurate tidal information is harmonic tidal analysis. This method decomposes tidal signals into several harmonic constituents influenced by the gravitational interactions between the Earth, Moon, and Sun. The resulting harmonic constants, consisting of amplitude and phase values for each tidal constituent, can be used to predict future sea level variations (Pawlowicz et al., 2002). However, the accuracy of tidal prediction models can be affected by local environmental conditions, such as bathymetry, coastal morphology, currents, and wind conditions (Setiawan et al., 2018). Therefore, prediction results need to be validated using observational data through statistical parameters, such as Root Mean Square Error

(RMSE) and correlation coefficient, to evaluate the agreement between the model and actual tidal conditions (Willmott, 1981; Supriyono et al., 2015). Batam City is a strategic region located along an international shipping route with intensive maritime activities (Bappenas, 2020). In addition to being an industrial center, Batam has several important ports that support logistics activities and international trade. The high intensity of maritime operations in this region requires accurate tidal predictions to support navigation safety, hydrographic surveys, and sustainable coastal development.

In this study, the Sekupang Tidal Station and Kabil Tidal Station were selected as research locations because both stations provide tidal observation data that can be used to analyze tidal characteristics in Batam waters. These two stations represent the western and eastern regions of Batam Island, which have different geographical and oceanographic conditions. The utilization of two tidal stations enables comparative analysis of harmonic constituents, tidal types, and the accuracy of prediction models, providing a more comprehensive understanding of tidal dynamics in the Batam coastal area. The comparison also enables the evaluation of spatial variations in tidal characteristics and prediction accuracy under different coastal and hydrodynamic conditions. This study utilizes tidal observation data from Sekupang and Kabil Stations in 2024 to represent the latest tidal conditions in Batam waters. Harmonic analysis was performed using the T_TIDE toolbox in MATLAB to determine the dominant harmonic constituents, identify tidal characteristics, and develop a tidal prediction model. Furthermore, the predicted tidal elevations were validated against observational data using RMSE and correlation coefficient parameters to assess model accuracy. The results of this study are expected to provide more accurate information regarding tidal characteristics in Batam waters and contribute to maritime navigation, hydrographic surveys, and coastal zone management.

Materials and Methods

Study Area and Data

This study was conducted in the coastal waters of Batam City, Indonesia, using tidal observation data collected from two permanent tidal stations: Kabil Tidal Station and Sekupang Tidal Station. Kabil Station is located in the eastern part of Batam Island (Nongsa District) at approximately 1°04′23.304″ N, 104°08′15.360″ E, while Sekupang Station is situated in the western part of Batam Island (Sekupang District) at approximately 1°07′26.400″ N, 103°55′39.000″ E. The two stations were selected because they represent the eastern and western coastal regions of Batam Island, allowing a comparative analysis of tidal characteristics under different geographical and oceanographic conditions. The study utilized hourly tidal observation data covering the period from January to December 2024, obtained from the Geospatial Information Agency (Badan Informasi Geospasial, BIG). The dataset provides continuous tidal observations suitable for harmonic analysis and tidal prediction.

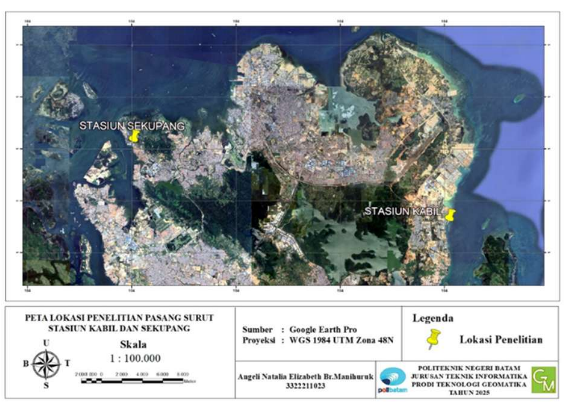

Figure 1. Study Area Showing the Locations of Sekupang and Kabil Tidal Stations.

Materials and Software

The primary dataset used in this study consisted of tidal observation records from the Kabil and Sekupang tidal stations for the year 2024. Harmonic analysis was performed using the T_TIDE toolbox implemented in MATLAB R2022a, which estimates harmonic constituents based on the least-squares method. Microsoft Excel

(Office 365) was used for data preprocessing and tabulation, Microsoft Word was employed for documentation and manuscript preparation, while ArcMap 10.8 and Google Earth Pro 7.3 were used to visualize the study area and verify the geographical locations of the observation stations.

Research Workflow

The research workflow consisted of several sequential stages. First, a literature review was conducted to establish the theoretical background of tidal harmonic analysis and prediction. Second, tidal observation data from the Kabil and Sekupang stations were collected and preprocessed to ensure data completeness and consistency. Third, harmonic analysis was carried out using the T_TIDE toolbox to estimate the amplitudes and phases of the major tidal constituents. The estimated harmonic constants were subsequently used to generate tidal predictions for each observation station. Finally, the predicted tidal elevations were validated against the observed tidal data using statistical performance indicators, including the Root Mean Square Error (RMSE) and the correlation coefficient (R). The validated results were then analyzed to compare the tidal characteristics and prediction accuracy between the two stations.

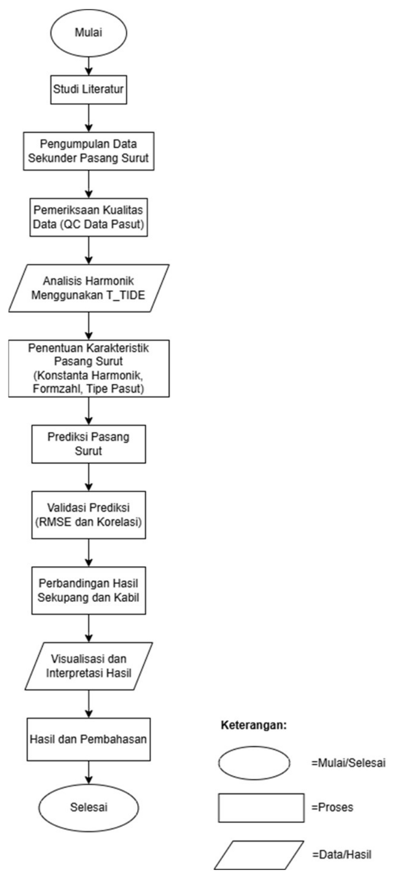

Figure 2. Research Workflow

Data Processing Methods

Data Collection and Preparation

The tidal data used in this study were obtained from observations at the Kabil and Sekupang Tidal Stations during 2024, with an hourly sampling interval. The dataset consists of sea level elevation records referenced to observation time and served as the primary input for harmonic analysis and tidal prediction. Prior to processing, the dataset was examined to identify missing values, recording errors, and inconsistencies.

According to Triatmodjo (1999), the reliability of tidal analysis depends on the consistency of observations and the duration of the measurement period. Therefore, data cleaning was performed to ensure that only valid observations were included in the analysis.

```
Nama Stasiun     :        Kabil
Data      :       Data Pasang Surut
Referensi        :        Palem
Koordinat        :        1.073137        104.1376
Lokasi    :       Badan Pengusahaan Batam
===============================================
Tanggal    Waktu_UTC Ketinggian Air
DD/MM/YYYY hh:mm:ss  (cm)
===============================================
01/01/2024 00:00:00 162
01/01/2024 01:00:00 164
01/01/2024 02:00:00 179
01/01/2024 03:00:00 199
01/01/2024 04:00:00 220
01/01/2024 05:00:00 238
01/01/2024 06:00:00 241
01/01/2024 07:00:00 225
01/01/2024 08:00:00 198
01/01/2024 09:00:00 161
01/01/2024 10:00:00 114
01/01/2024 11:00:00 75
01/01/2024 12:00:00 55
01/01/2024 13:00:00 54
01/01/2024 14:00:00 69
01/01/2024 15:00:00 97
02/01/2024 00:00:00 156
02/01/2024 01:00:00 148
02/01/2024 02:00:00 156
02/01/2024 03:00:00 174
02/01/2024 04:00:00 199
02/01/2024 05:00:00 220
```

Figure 3. Tidal Observation Data from Kabil Station in 2024.

Data Quality Control

A quality control (QC) procedure was conducted to ensure the reliability of the tidal observations before harmonic analysis. The QC process included checking data completeness, identifying missing records, verifying the uniformity of the observation interval, and applying linear interpolation to fill missing values. This procedure produced a continuous tidal time series suitable for harmonic analysis (Pawlowicz et al., 2002; Pugh & Woodworth, 2014). The preprocessing procedure follows the approach proposed by Khansah and Heliani (2014), who emphasized the importance of transforming observational data before harmonic modeling to minimize computational errors.

```matlab
% ==============================
% 2. PRA-PENGOLAHAN DATA
% ==============================

clc; clear; close all;

% Membaca data pasut dari file txt
data = readtable('0034SKPG01_2024.txt', 'Delimiter', '\t', 'ReadVariableNames', false);

% Kolom 1: waktu (dd-mm-yyyy HH:MM), Kolom 2: tinggi muka air (meter)
time = datenum(data.Var1, 'dd-mm-yyyy HH:MM');
eta  = data.Var2;

% Menghapus data kosong
valid = ~isnan(eta);
time = time(valid);
eta  = eta(valid);

% Menghilangkan tren atau offset
eta = detrend(eta);

% Menampilkan grafik data hasil pra-pengolahan
figure;
plot(time, eta, 'b');
datetick('x', 'dd-mmm', 'keeplimits');
xlabel('Waktu');
ylabel('Tinggi Muka Air Laut (m)');
title('Data Pasang Surut Setelah Pra-Pengolahan');
grid on;
```

Figure 4. Data Preprocessing Script.

Harmonic Tidal Analysis

Harmonic analysis was performed to decompose the observed tidal signal into periodic harmonic constituents associated with astronomical forcing from the Moon and the Sun. Each constituent is characterized by its amplitude and phase, representing its contribution to sea level variation (Pugh & Woodworth, 2014). The analysis was conducted using the T_TIDE toolbox implemented in MATLAB R2022a, developed by Pawlowicz et al. (2002). The toolbox applies the Least Squares Harmonic Analysis method to estimate the amplitudes and phases of the principal tidal constituents, including M2, S2, K1, and O1. The estimated harmonic constants were subsequently used to determine tidal characteristics, calculate the Formzahl number, and construct tidal prediction models for each observation station. According to Setiawan et al. (2018), this method is effective for identifying tidal types (diurnal, semidiurnal, or mixed tides) and generating long-term tidal predictions.

```
% =============================
% 3. ANALISIS HARMONIK
% =============================

% Menjalankan analisis harmonik pasang surut
[tidecon, xout] = t_tide(eta, ...
    'interval', 1, ...              % interval data (1 jam)
    'start time', time(1), ...
    'latitude', -1.1, ...           % lintang lokasi Batam
    'output', 'hasil_t_tide.txt'); % hasil analisis disimpan ke file

% Menampilkan hasil komponen utama
disp('Hasil Komponen Harmonik Utama:');
disp(tidecon(1:10,:));  % tampilkan 10 komponen utama
```

Figure 5. Harmonic Analysis Script.

Determination of Tidal Characteristics

The tidal characteristics were determined based on the harmonic constants obtained from the harmonic analysis. The tidal type was classified using the Formzahl number (F), calculated as the ratio of the amplitudes of the diurnal constituents (K1 and O1) to the semidiurnal constituents (M2 and S2). In addition, several tidal datums, including Mean Sea Level (MSL), Highest Astronomical Tide (HAT), and Lowest Astronomical Tide (LAT), were computed to describe the tidal characteristics at each observation station (Ongkosongo & Suyarso, 1989; Djaja, 1987).

Tidal Prediction

After the harmonic constants were estimated, tidal predictions were generated using the t_predic function available in the T_TIDE toolbox. The prediction model reconstructs sea level variations by superimposing the harmonic constituents derived from the harmonic analysis. This approach follows the harmonic prediction theory developed by Boon (1978), in which sea level is represented as the sum of individual harmonic components.

```
% =============================
% 4. PREDIKSI PASANG SURUT
% =============================

% Membuat vektor waktu prediksi dengan interval 1 jam
t_pred = time(1):1/24:time(end);

% Menggunakan konstanta harmonik hasil analisis untuk prediksi
eta_pred = t_predic(t_pred, tidecon, 'latitude', -1.1);

% Plot hasil prediksi
figure;
plot(time, eta, 'b', 'DisplayName', 'Data Observasi');
hold on;
plot(t_pred, eta_pred, 'r', 'DisplayName', 'Hasil Prediksi');
datetick('x', 'dd-mmm', 'keeplimits');
xlabel('Waktu');
ylabel('Tinggi Muka Air Laut (m)');
legend('show');
title('Perbandingan Data Observasi dan Prediksi Pasang Surut');
grid on;
```

Figure 6. Tidal Prediction Script.

Model Validation

The predicted tidal elevations were validated against the observed tidal data to evaluate model performance. Prediction accuracy was assessed using the Root Mean Square Error (RMSE) and the Pearson correlation coefficient (r). RMSE quantifies the magnitude of prediction errors, whereas the correlation coefficient measures the agreement between predicted and observed sea levels (Willmott, 1981; Supriyono et al., 2015).

A prediction model is considered to perform well when it produces low RMSE values and correlation coefficients close to 1.0 (Rahmawati, 2020).

```
% ==============================
% 5. VALIDASI MODEL
% ==============================

% Menyamakan panjang data observasi dan hasil prediksi
n = min(length(eta), length(eta_pred));
eta = eta(1:n);
eta_pred = eta_pred(1:n);

% Menghitung indikator statistik
MSE  = mean((eta - eta_pred).^2);
MAE  = mean(abs(eta - eta_pred));
RMSE = sqrt(MSE);
r    = corrcoef(eta, eta_pred);S

% Menampilkan hasil validasi
fprintf('\nHASIL VALIDASI MODEL PASANG SURUT:\n');
fprintf('MSE   = %.6f\n', MSE);
fprintf('MAE   = %.6f\n', MAE);
fprintf('RMSE  = %.6f\n', RMSE);
fprintf('r     = %.4f\n', r(1,2));
```

Figure 7. Model Validation Script.

Comparative Analysis of Sekupang and Kabil Stations

Finally, the harmonic constituents, tidal types, tidal datums, and prediction validation results obtained from the Sekupang and Kabil stations were compared to identify similarities and differences in tidal characteristics between the two locations. This comparative analysis provides a more comprehensive understanding of tidal dynamics in the coastal waters of Batam and highlights the influence of local geographical and oceanographic conditions on tidal behavior (Setiawan et al., 2018).

```
% ==============================
% 6. VISUALISASI HASIL
% ==============================

% Plot perbandingan observasi vs model
figure;
plot(time, eta, 'b', 'DisplayName', 'Observasi');
hold on;
plot(t_pred, eta_pred, 'r', 'DisplayName', 'Prediksi');
xlabel('Waktu');
ylabel('Elevasi (m)');
datetick('x', 'dd-mmm', 'keeplimits');
legend('show');
title('Hasil Pemodelan Pasang Surut');
grid on;

% Scatter plot untuk validasi korelasi
figure;
scatter(eta, eta_pred, 10, 'filled');
xlabel('Observasi (m)');
ylabel('Prediksi (m)');
title('Scatter Plot Observasi vs Prediksi');
grid on;
refline(1,0); % garis y=x
```

Figure 8. Visualization of Analysis Results.

Results and Discussion

Harmonic Tidal Analysis

Harmonic analysis was performed using the T_TIDE toolbox on the 2024 tidal observations collected from the Sekupang and Kabil tidal stations. The results indicate that the harmonic model explained 98.8% of the sea level variability at Sekupang Station and 96.1% at Kabil Station. The dominant harmonic constituents at both stations were M2, S2, K1, and O1, with M2 exhibiting the largest amplitude. These findings indicate that semidiurnal tidal forcing is the dominant characteristic of the study area, which is consistent with the general tidal regime in the Singapore Strait and surrounding waters.

Tidal Characteristics

The tidal type was determined using the Formzahl number (F). The calculated Formzahl values were 0.5792 for Sekupang Station and 0.8430 for Kabil Station. According to the Formzahl classification, both stations are classified as mixed tides with a predominant semidiurnal characteristic (mixed predominantly semidiurnal tide). Although both stations belong to the same tidal category, the higher Formzahl value at Kabil indicates a relatively stronger contribution of diurnal constituents compared with Sekupang. This difference suggests that local geographical and oceanographic conditions influence the relative contribution of tidal constituents.

Tidal Datum

The calculated tidal datums differed between the two observation stations. At Sekupang Station, the Mean Sea Level (MSL), Highest Astronomical Tide (HAT), and Lowest Astronomical Tide (LAT) were 132.75 cm, 426.17 cm, and −160.66 cm, respectively. In contrast, Kabil Station exhibited an MSL of 155.17 cm, HAT of 412.98 cm, and LAT of −102.63 cm. These differences indicate spatial variations in sea level characteristics within Batam waters. The observed variations are likely influenced by differences in coastal morphology, bathymetry, and local hydrodynamic conditions between the western and eastern parts of Batam Island.

Validation of the Tidal Prediction Model

The prediction model was validated by comparing the predicted tidal elevations with the observed data using the Root Mean Square Error (RMSE) and the Pearson correlation coefficient (r). The validation results showed that the prediction model achieved an RMSE of 7.28 cm and a correlation coefficient of 0.9945 at Sekupang Station. At Kabil Station, the model produced an RMSE of 11.03 cm with a correlation coefficient of 0.9829. The high correlation coefficients obtained at both stations indicate excellent agreement between predicted and observed sea levels, while the relatively low RMSE values demonstrate that the harmonic prediction model accurately represents the observed tidal variations. These results confirm the effectiveness of the T_TIDE harmonic analysis approach for tidal prediction in Batam waters.

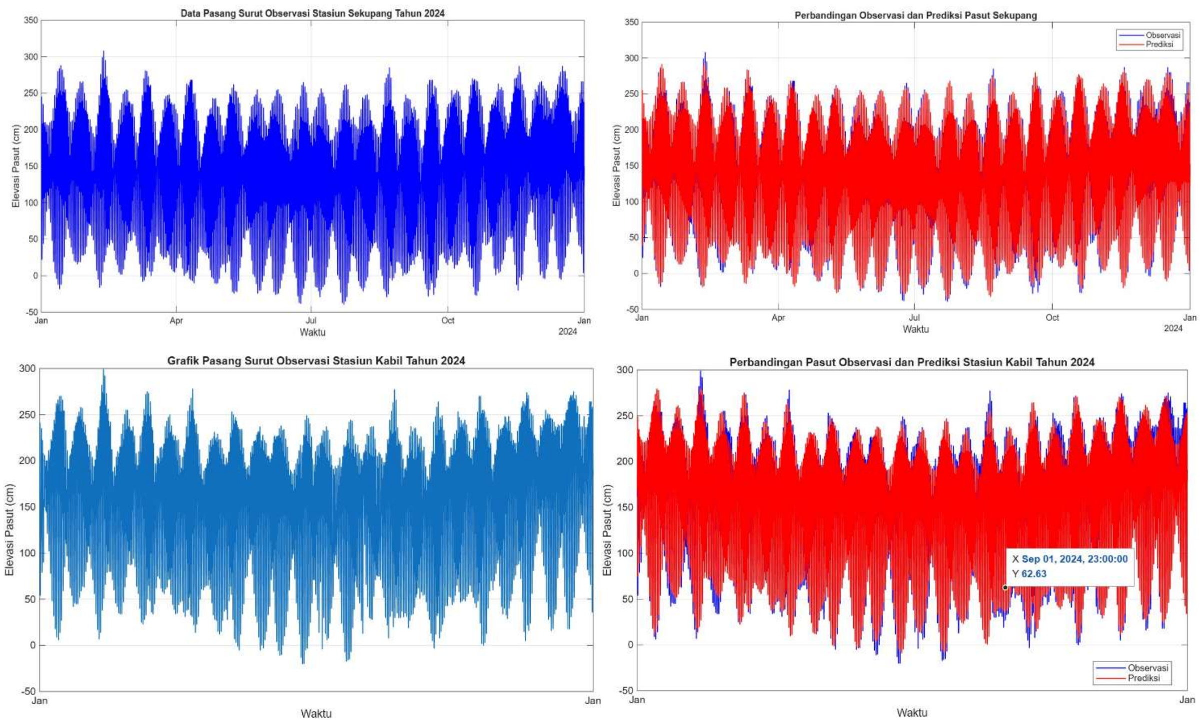

Figure 9. Comparison between observed and predicted tidal elevations at Sekupang and Kabil Stations.

Comparison Between Sekupang and Kabil Stations

Both observation stations exhibited the same tidal classification, namely mixed predominantly semidiurnal tides. However, differences were observed in the Formzahl values, tidal datums, and prediction accuracy. Overall, the harmonic prediction model performed slightly better at Sekupang Station, as indicated by its lower RMSE and higher correlation coefficient. This suggests that tidal dynamics at Sekupang are represented more accurately by the harmonic constituents estimated using the T_TIDE toolbox. The better performance at Sekupang Station may be related to differences in local hydrodynamic conditions, coastal morphology, bathymetry, and the influence of non-astronomical factors such as wind and currents. These factors may contribute to the slightly higher prediction error observed at Kabil Station. The differences between the two stations are likely associated with variations in local bathymetry, coastline geometry, and hydrodynamic processes. The results demonstrate that harmonic analysis using T_TIDE provides reliable tidal predictions and effectively characterizes tidal conditions in the coastal waters of Batam.

Table 1. Comparison of Harmonic Analysis Results

Parameter	Sekupang Station	Kabil Station
Harmonic Model Variance Explained	98.8%	96.1%
Formzahl Number	0.5792	0.8430
Tidal Type	Mixed Predominantly Semidiurnal	Mixed Predominantly Semidiurnal
Mean Sea Level (MSL)	132.75 cm	155.17 cm
Highest Astronomical Tide (HAT)	426.17 cm	412.98 cm
Lowest Astronomical Tide (LAT)	−160.66 cm	−102.63 cm
RMSE	7.28 cm	11.03 cm
Correlation Coefficient (r)	0.9945	0.9829

Conclusions

Based on the harmonic analysis using the T_TIDE method, both the Sekupang and Kabil tide stations were classified as mixed mainly semidiurnal tides, with Formzahl values of 0.5792 and 0.8430, respectively. The tidal datum analysis produced MSL, HAT, and LAT values of 132.75 cm, 426.17 cm, and -160.66 cm for Sekupang, and 155.17 cm, 412.98 cm, and -102.63 cm for Kabil. Model validation demonstrated high prediction accuracy, with an RMSE of 7.28 cm and a correlation coefficient of 0.9945 for Sekupang, and an RMSE of 11.03 cm and a correlation coefficient of 0.9829 for Kabil. Overall, the T_TIDE method proved to be effective in determining tidal characteristics, tidal datums, and generating reliable tidal predictions to support hydrographic surveys, navigation, and coastal zone management.

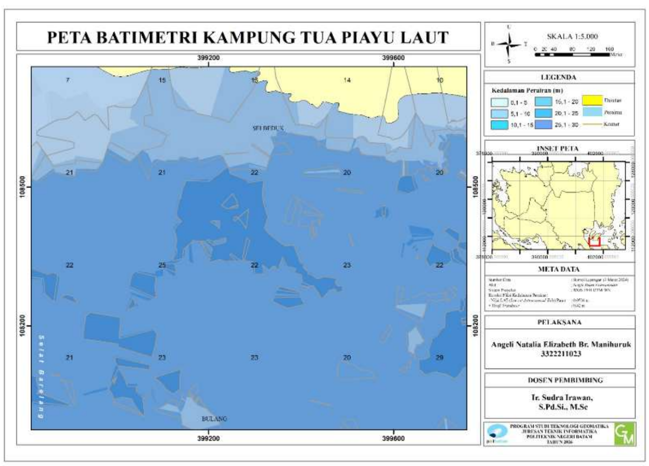

Figure 10. Bathymetric Map of Kampung Tua Piayu Laut

The bathymetric mapping results indicate that the water depths in Kampung Tua Piayu Laut generally meet the requirements for navigation and pier development. Most of the study area has depths greater than 20 m, providing sufficient clearance for vessel maneuvering and berthing, while the relatively gentle seabed morphology supports safe navigation channel planning. A Lowest Astronomical Tide (LAT) value of 0.0534 m was used as the vertical reference datum for depth correction, ensuring consistent bathymetric data for navigation analysis and pier site evaluation. Overall, the bathymetric characteristics, including adequate water depth, gentle seabed morphology, and access to deeper waters, indicate that Kampung Tua Piayu Laut is a suitable location for future pier development in accordance with the objectives of this study. These findings also demonstrate the importance of bathymetric correction using a consistent vertical datum to ensure reliable depth information for hydrographic surveys and navigation planning.

Author Contributions

Conceptualization, Angeli Natalia Elizabeth Br. Manihuruk and Sudra Irawan; methodology, Angeli Natalia Elizabeth Br. Manihuruk and Sudra Irawan; software, Angeli Natalia Elizabeth Br. Manihuruk; validation, Angeli Natalia Elizabeth Br. Manihuruk and Sudra Irawan; formal analysis, Angeli Natalia Elizabeth Br. Manihuruk; investigation, Angeli Natalia Elizabeth Br. Manihuruk; resources, Sudra Irawan; data curation, Angeli Natalia Elizabeth Br. Manihuruk; writing—original draft preparation, Angeli Natalia Elizabeth Br. Manihuruk; writing—review and editing, Sudra Irawan; visualization, Angeli Natalia Elizabeth Br. Manihuruk; supervision, Sudra Irawan; project administration, Sudra Irawan; funding acquisition, Not applicable. All authors have read and agreed to the published version of the manuscript.

Declaration of Generative AI Usage

Artificial intelligence (AI) tools, including ChatGPT (OpenAI), were used to assist in the preparation of this manuscript for language translation, grammatical improvement, and manuscript editing. All AI-assisted outputs were carefully reviewed, revised, and verified by the author(s). AI tools were not used for data collection, data processing, harmonic analysis, statistical analysis, result interpretation, or scientific decision-making. The author(s) take full responsibility for the accuracy, originality, and integrity of the content presented in this manuscript.

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