Analysis of Wind Characteristics and Sea Surface Elevation Dynamics in Coastal Waters of Mantang Island, Bintan Regency, Indonesia

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Abstract

Geographically, Mantang Island is situated between the Malacca Strait, Natuna Sea, and Karimata Strait, and is exposed to the open sea, which influences the oceanographic dynamics of the region. The island's residents are heavily dependent on the sea for their livelihoods, making wind and sea tides crucial for meeting their daily needs. Consequently, this study aimed to measure wind data and sea surface elevation over a 30-day period, with the results visualized using a wind rose diagram. The specific objectives were: 1) to calculate harmonic constants using both the Least Squares and Admiralty methods to obtain FormZahl numbers, 2) to determine the characteristics of sea surface elevation based on each method, and 3) to analyze the relationship between sea surface elevation and wind speed. The findings revealed that the wind in the waters surrounding Mantang Island was primarily influenced by the monsoon, blowing from the west with maximum speeds ranging from 5.70 to 8.80 m/s. Each calculation method produced varying values for sea surface elevation, including Zo, HHWL, LLWL, MHWL, and MLWL, with respective values of 11.99 m, 15.9 m, 8 m, 17.9 m, and 6 m. FormZahl number calculations yielded values of 1.25 and 1.03 using the Least Squares and Admiralty methods, respectively. Despite the differences in the results, both methods indicated a mixed semi-diurnal tidal pattern. To examine the relationship between wind and sea surface elevation, a 6th-order polynomial regression analysis was performed. The analysis revealed a weak correlation, with a coefficient of determination (R^2) of 0.21 and a Root Mean Square Error (RMSE) of 0.30. These values suggest that the model's predictions were relatively close to actual field conditions.

Keywords: Admiralty, Wind, Least Square, Tides, Bintan Island

INTRODUCTION

Weather dynamics play a critical role in influencing hydrodynamic phenomena in the ocean. Similarly, physical processes such as currents, ocean waves, tides, and wind significantly contribute to the complex hydrodynamic characteristics of the sea (Molle *et al.*, 2022). The wind characteristics across different regions in Indonesia exhibits considerable variability. The average wind speed over land in Indonesia is approximately 30-40 km/h on a global scale. However, this average can vary significantly depending on both the time and location of measurement. These variations are influenced by periodic wind circulation patterns, which can lead to fluctuations in wind speed measurements from year to year (Sudarto, 2011).

A significant weather pattern that influences these dynamics is the monsoon, or seasonal winds. According to Fadholi (2013), periodic winds blow across the Earth's surface, reversing direction every six months. This reversal causes winds to flow towards the continent during the summer and away from it during the winter. This phenomenon is primarily driven by the apparent longitudinal movement of the Sun in the tropics, which creates a pressure differential between the continent and the ocean. Indonesia, a maritime nation comprising numerous islands and coastal regions, exemplifies this pattern. Specifically, the Riau Islands Province, and more precisely Bintan Regency,

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spans an area of 59,852.01 km², of which 57,906.00 km² (96.75%) is ocean and 1,946.01 km² (3.25%) islands.

This area is situated between 1º15' N and 0º48' S, and extends from 104º E to 108º E (Ferdiansyah *et al*., 2015). Furthermore, Bintan Regency encompasses smaller islands, such as Mantang Island, which lies between the Malacca Strait, Natuna Sea, and Karimata Strait. The geographical location of these islands, which are exposed to the open sea, has a direct impact on oceanographic dynamics. At the time the research was conducted, the region was experiencing extreme weather conditions, likely attributed to the influence of strong southern winds. The activities of local people such as coral reefs, fishing, sailing, and others in this area still depend on wind and sea tides. According to Novitasari *et al*., (2018), one of the factors affecting the tidal flow of seawater is a strong wind, which can hinder people's activities. Muldiyatno *et al*., (2016) also explained the challenge in predicting tidal metrics such as Mean Sea Level (MSL), Highest High-Water Level (HHWL), and Lowest Low Water Level (LLWL), as these metrics were still highly dependent on specific situation and area. Considering this context, the current study aims to provide valuable information on wind characteristics and sea surface elevation patterns using Wrplot, Admiralty, and Least Square analysis methods. The methods are used to determine the harmonic component value and level of relationship with wind in coastal waters on Mantang Island, Bintan Regency

MATERIALS AND METHODS

This study was conducted for 1 month starting from September 6, 2023, to October 7, 2023. The determination of the study station point was performed using the purposive sampling method, where the station point had been surveyed and had not been conducted in a similar study. Relating to this discussion, the station point was in Belakang Sidi, Mantang Island, Bintan Regency. The data measurements collected included wind direction, the wind data used in this study was collected through direct observation or field monitoring over a period of one month. The instrument used for monitoring weather information was the *AWS* Vantage Pro 2, The recording interval was every 1 minute which is a tool for measuring data, specifically wind speed and wind direction at specific locations. The instrument was positioned at the end of the pier, facing the sea, and tides the tidal data used in this study was also obtained through direct field observation using an instrument called the *Tide Master*, a portable water level measurement tool with a longer unit. The instrument was positioned at the end of the pier, approximately 2 meters above the seabed during data recording. This tool is capable of storing long-term data and consists of a transducer and a display panel. The working principle of this instrument is the measurement of water pressure, which is then converted into water height. The transducer is placed at the water's bottom, which remains submerged even during the lowest ebb tide. The data recorded on the data logger is stored every 2 seconds during the measurement period.

Methods and Procedures

Quantitative methods were employed in this study to perform calculations and analyses relevant to the area of interest. In accordance with theoretical frameworks, data were collected, processed, and analyzed in alignment with the study's objectives and research questions. The collected data included coordinate points and wind information, such as direction and speed. This data was processed using Wrplot and visualized as a wind rose diagram to illustrate wind patterns in the region. Time series wind data were subsequently correlated and regressed against non-tidal values, which were first separated by elevation into tidal and non-tidal components. This analysis was conducted using the t-tide v1.3beta software in the Matlab 2017 environment, employing the Least Squares method to obtain both significant and non-significant component values. The harmonic constants were then extracted and used to calculate the FormZahl number. To compare the FormZahl values from each method, the Admiralty method was also applied. This approach enabled a detailed analysis of sea surface elevation dynamics. A combined analysis of wind rose data, correlation, and regression results between wind and non-tidal components was conducted to draw conclusions regarding the relationship between wind dynamics and sea surface elevation in the waters of Mantang Island, Bintan Regency.

Wind Analysis

According to Fadholi (2013), wind rose was a method of analyzing the direction and speed of wind in a particular area to compare wind that frequently blew from each direction:

$$F = \frac{\sum dd}{\sum n} \times 100\%$$

Note: F = Relative distribution; $\sum dd =$ Number of wind directions from each interval class; $\sum n =$ Number of data from each wind direction

Analysis of Elevation and Tidal Type

In a study by Kurniawan *et al* (2023), MSL (Mean Sea Level), LLWL (Lowest Low Water Level), HHWL (Highest High Water Level), MLWL (Mean Low Water Level), MHWL (Mean High Water Level), and values were obtained from the constant results of tidal data analysis using the following formula:

MSL = A (So)
LLWL = Zo-(M2+S2)-(K1+O1)
HHWL=Zo+(M2+S2+K1+O1)
Zo = M2+S2+N2+K2+K1+O1+P1+M4+MS4
MLWL = Zo – (M2+S2)
MHWL = Zo + (M2+S2)

The water surface height was calculated using tidal components obtained from tidal analysis with Admiralty method:

$$F = \frac{AK_1 + AO_1}{AM_2 + AS_2}$$

Note : F = Formzhal Number; AO1 = Harmonic constant affected by the declination of moon; AK1 = Harmonic constant affected by the declination of moon and sun; AM2 = Harmonic constant affected by the position of moon; AS2 = Harmonic constant affected by the position of sun.

Non-Linear Regression Analysis of Wind and Sea Surface Elevation

After processing wind speed data as variable X and non-tidal elevation residual from observation data as variable Y, a simulation test was conducted using both linear and non-linear regression to find the model with the highest value. In the context of this exploration, the examination was performed by entering a certain wind speed value as X, then producing the height of the non-tidal sea surface elevation as Y. Concerning this discussion, a Simple Polynomial Regression Analysis Formula was shown below (Darmawan & Antonius, 2017):

$$y = a_n x^n + a_{n-1} x^{n-1} + a_{n-2} x^{n-2} + \ldots + a_0$$

Note: y = Dependent variable (non-tidal elevation); x = Independent variable (wind Speed); n = Highest power; i = Whole number

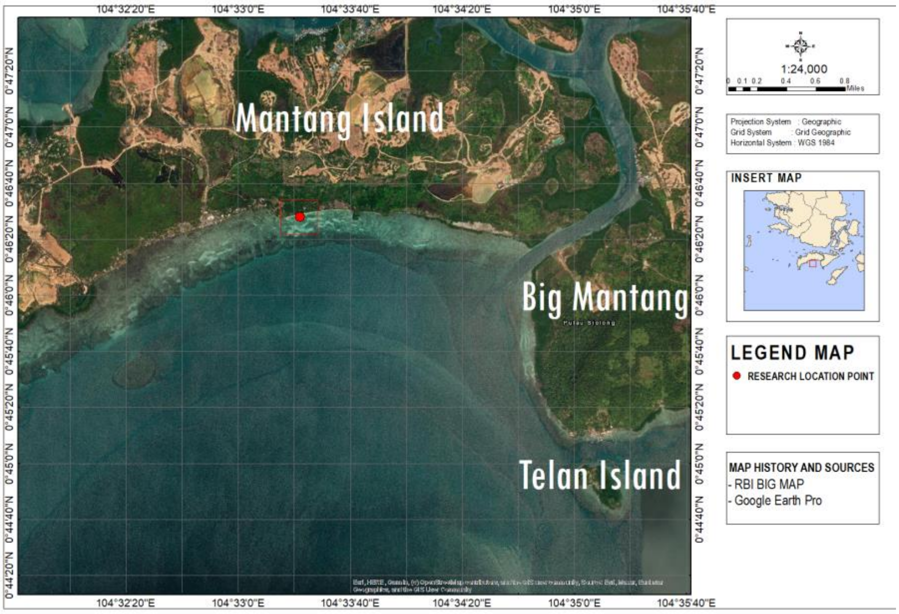

Figure 1. Study Area Map

RESULT AND DISCUSSION

Wind Characteristics

Data processing using WRPLOT yielded the following results for the wind measurements over the four-week period. In the first week, the wind predominantly blew from the southeast, with an average speed ranging from 3.76 to 5.80 m/s. In the second week, the wind continued to be dominated by the southeast and south, with an average speed varying between 3.60 and 8.80 m/s. During the third week, the wind direction shifted towards the northwest and north; however, as shown in Figure 2, winds from the southeast were also observed, with speeds ranging from 0.50 to 2.50 m/s. In the fourth week, the southeast wind direction again dominated, with average speeds ranging from 5.70 to 8.80 m/s. The results obtained are based on the methods applied, and standard deviation values were calculated for the mean data in each week. All data are presented either in tables or graphs to avoid redundant presentation, and no raw data is included in the results section.

Figure 2 showed a visualization of wind for 1 month, blowing more from the south with the highest average speed of 34.50% at a speed of 5.70-8.80m/s. However, the results showed that wind tended to blow from the southeast. The conditions in coastal waters of Mantang Island during the exploration entered the second transition season, where wind managed to blow erratically. From the analysis results, wind blows tended to be from the southeast dan south. This occurrence was due to the apparent movement of the northern latitudes (tropic of Cancer) heading to the southern latitudes (tropic of Capricorn). At the same time, the analysis showed that the area was experiencing a dominant wind change due to the south monsoon, which showed that wind was primarily from the southeast. When the results were shown from wind direction percentage table on figure 3, the southeast direction had a very large percentage of 42.22%. Following the discussion, the direction was followed by wind blow from the south with a percentage of 26.37% with the highest average speed ranging from 5.70 m/s - 8.80 m/s. According to Beaufort scale category, wind blowing in coastal waters of Mantang Island was moderate. If we refer to Figure 3, there is a remaining 12 percent of wind gusts that are not accounted for in the graph, due to the presence of gentle breezes observed during the research. The moderacy was also proven by a study of Irawan in 2017, stating that waters of Bintan Island in September-November were dominated by southeast winds. This occurred because, during this season, sun was in the northern hemisphere (BBU). The northern hemisphere received more sunlight than the southern hemisphere (BBS), which caused high pressure build up over Australian continent and low pressure to form above Asian continent (Syafik *et al*., 2013).

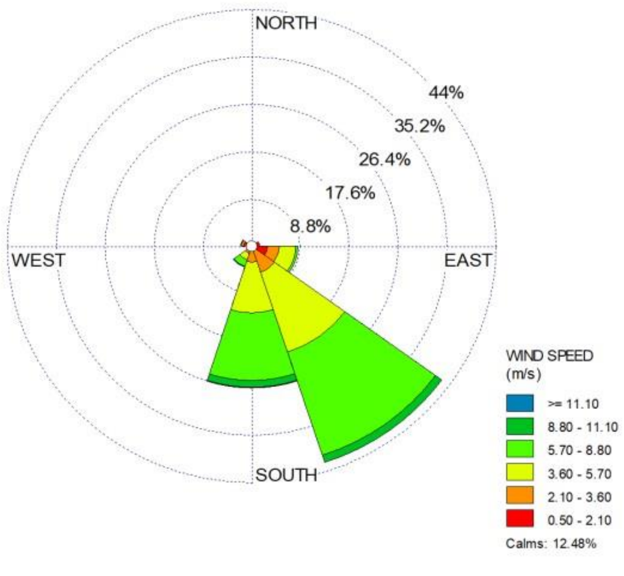

Figure 2. Wind Rose

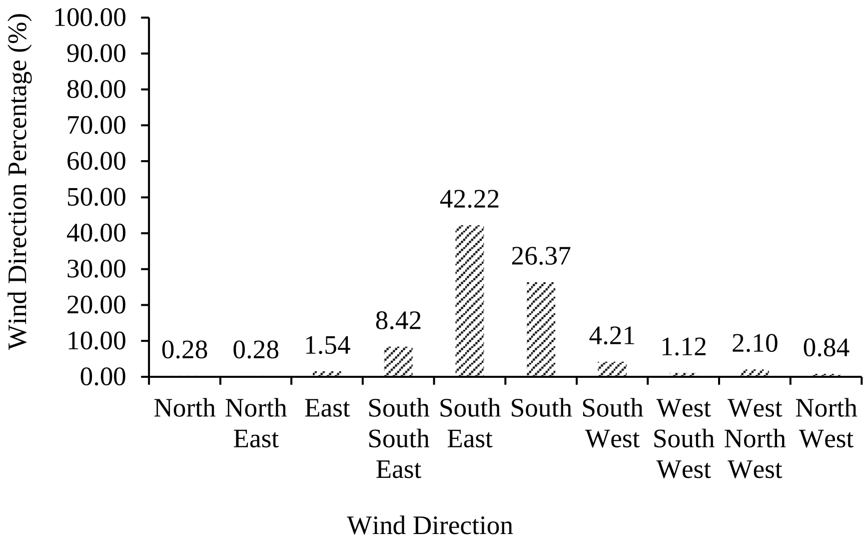

Figure 3. Wind Direction Percentage

Characteristics of Sea Level Elevation Dynamics

According to Kurniawan *et al*. (2023), sea surface elevation is crucial for determining the highest and lowest water levels. In this context, the HHWL (Highest High Water Level) is used for coastal construction planning, while the LLWL (Lowest Low Water Level) is essential for port development planning. To obtain these results, it is necessary to calculate the planned elevation levels based on tidal components, which include MSL (Mean Sea Level), Zo (Tidal Level), HHWL, MHWL (Mean High Water Level), LLWL, and MLWL (Mean Low Water Level). However, it is important to note that the planned water level values obtained in this study may be subject to change due to the varying water conditions in the area, as the data used was limited to a one-month period.

Based on the analysis data in Table 1, the value of each sea surface elevation using Admiralty or Least Square calculation method had different results. The value with Admiralty had a higher number compared to Least Square with the same MSL value of 57.4 m. The largest calculation result was HHWL with a value of 209.5 m for Admiralty and 193.6 m for Least Square. Meanwhile, the calculation result with the lowest value WAS obtained at LLWL with a value of 28.9 m for Admiralty and 20.9 m for Least Square. The length of data required for a more accurate value was 18.6 years using the same tidal data theoretically. Relating to this discussion, the period of shifting points from the moon's orbit was approximately 18.6 years. When viewed from the data for sea surface elevation that had been produced, the difference was obtained for each different level position. The values were Zo, HHWL, LLWL, MHWL, and MLWL at 11.99 m, 15.9 m, 8 m, 17.9 m, and 6 m, respectively. The analysis results obtained from the comparison of calculations using Least Square and Admiralty methods for 29 days on Mantang Island in this study were shown in Table 1.

From the table above, it is evident that each method produced different calculation results, although the values were still relatively similar. The discrepancies between the two methods stem from the Admiralty method, which involves elevation removal, meaning it uses non-tidal elevation data. As a result, the Least Squares method tends to yield smaller values since its extrapolated values are purely tidal and unaffected by external disturbances, such as wind or ship activity. In the Admiralty method, the double tidal component (semi-diurnal) was primarily characterized by the M2 component, with an amplitude of 29.4 m and a phase angle (g°) of 306.0, followed by the S2 component, with an amplitude of 15.0 m and a phase angle (g°) of 14.2.

In contrast, the Least Squares method, using the t-tide toolbox, yielded a value for the M2 component of 25.1 m with a phase angle (g°) of 95.61, which is influenced by the main lunar cycle. The S2 component, associated with the gravitational pull of the Sun and its circular orbit, had an amplitude of 13.3 m and a phase angle (g°) of 2.83, which is smaller than the Admiralty values. This discrepancy is partly due to the difference in the length of the data sets used for each method. In this study, the Admiralty method produced a total of 9 harmonic components based on constant calculations in Microsoft Excel, while the Least Squares method identified 14 significant components, 8 of which were harmonic constants, and 18 non-significant components, including 1 harmonic constant.

The FormZahl number was calculated as 1.03 using the Admiralty method, while the Least Squares method produced a value of 1.25. Based on the tidal pattern and type table, both methods classified the tidal regime as a mixed tide with a semi-diurnal double daily inclination, where $0.25 < F < 1.5$. This type of tide, characterized by two high and low tides per day of unequal size, was also observed by Irawan (2017), who identified Bintan Island's waters as having a mixed double daily inclination. Khairunissa *et al*. (2021) further supported this conclusion using the Admiralty method. Figures 3 and 4 present the results from each tidal observation method, providing additional evidence for this finding.

The highest tidal value obtained from the results of field measurements was 1.69 m and the lowest was -0.04 m. From Figure 4, the observation graph using Least Square method showed a very high spike in sea surface elevation in waters of Mantang Island for 2 days, from September 25 to 26, 2023. This occurred due to the influence of weather changes which initially experienced rain and strong winds, followed by hot weather. Furthermore, at night, a series of full moon occurred, which caused the gravitational pull of celestial bodies to affect the sea level conditions (Setyawan *et al*., 2021). The days labeled in 1975 on the Figure used Julian Day, which was a time format from the t-tide toolbox script. Although the label was adjusted to fit the manuscript, the period used still followed the actual observation time from the field.

Table 1. Sea Surface Elevation

Sea Surface Elevation	Method	
	Admiralty	*Least Square*
MSL	57.4	57.4
HHWL	209.5	193.6
LLWL	28.9	20.9
MHWL	163.6	145.7
MLWL	74.8	68.8
Zo	119.22	107.23

Table 2. Comparison of Harmonic Constanta

Tidal Constant	Amplitude (m)		Phase (deg)	
	Admiralty	Least Square	*Admiralty*	Least Square
M_2	29.4	25.1	306.0	95.61
S_2	15.0	13.3	14.2	2.83
N_2	7.4	5.18	333.6	68.31
K_2	3.5	3.63	14.2	25.23
K_1	17.6	21.6	135.6	132.17
O_1	28.3	26.3	58.2	208.15
P_1	5.8	7.15	135.6	139.24
M_4	8.8	3.38	275.9	212.23
MS_4	3.5	1.57	23.0	209.16

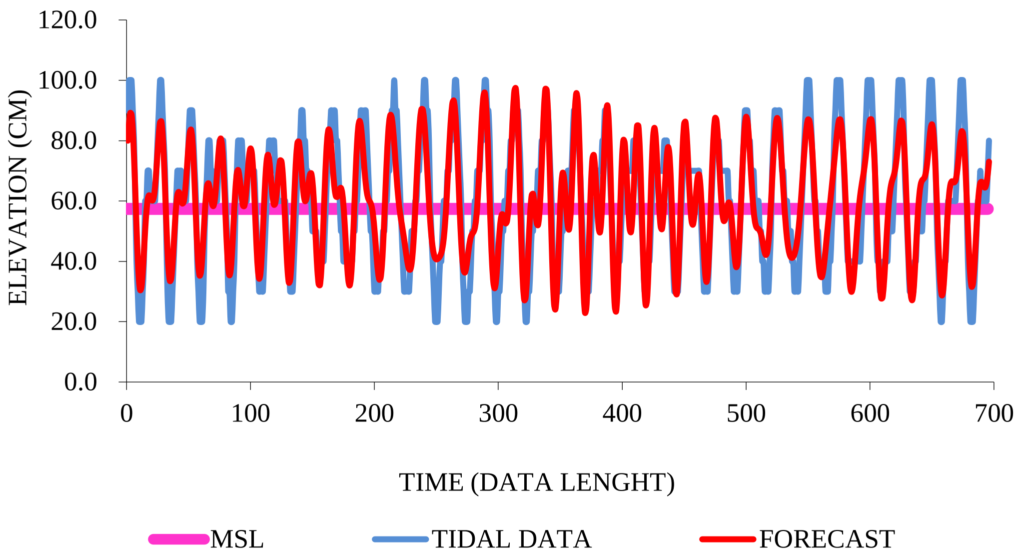

Figure 4. Admiralty Observation Chart

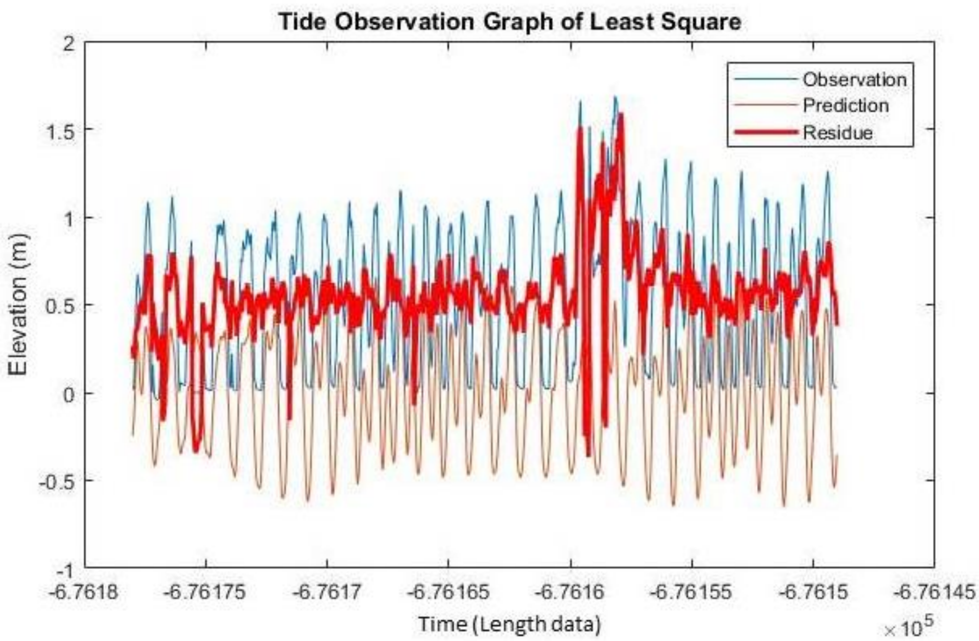

Figure 5. Least Square Observation Graph

Wind and Sea Surface Non-Tidal Elevation Regression

Both the analysis of wind characteristics and the dynamics of sea surface elevation highlighted the significant role of oceanographic parameters. The relationship between wind and sea surface elevation required further examination through linear and non-linear regression analyses. In this context, a correlation was established between wind speed and sea level elevation, with the coefficient of determination (R^2) being calculated to assess the strength of the relationship between the dependent and independent variables. The regression analysis demonstrated that the highest R^2 value approached 100%, indicating a strong correlation between the variables. Non-tidal elevation is the residual value obtained from the observed tidal measurements conducted in the field, compared to the pure tidal values obtained after separating the elevation using the least squares method, which is represented by the red line in Figure 5.

The results of the regression tests revealed notable differences between linear and non-linear equations. Linear equations involve simple calculations where the dependent variable is multiplied by a fixed coefficient, resulting in linear relationships. In contrast, non-linear equations incorporate more complex elements, such as polynomials, exponents, and logarithms, which make the equations more intricate compared to linear ones (Utami *et al*., 2021). As noted by Awang (2023), linear equations can be solved using methods like elimination or matrix techniques. In contrast, non-linear equations typically require numerical methods, such as iteration, or analytical methods, including transformation. Linear equations are widely used in various fields, such as mathematics, economics, and physics, while non-linear equations are more common in disciplines that require complex modeling, particularly in biology and advanced physics. This study demonstrated the significant differences between linear and non-linear equations in terms of their characteristics, solutions, and practical applications.

The results showed that Non-linear Polynomial Regression of Order 6 produced a higher test value compared to other methods, with the equation being y = 0,0095x6 – 0,1927x5 + 1,5651x4 – 6,4689x3 + 14,313x2 – 16,077x + 7,7119. Order 6 Polynomial Equation Test was performed by entering one of the X Variable values, namely Wind Speed from the equation of y = 0.45 and R^2 = 0.2192.

Based on the data presented in Table 3, the correlation between wind speed and non-tidal elevation was found to be weak. According to Serodja *et al*. (2022), the dominant current direction, primarily flowing southwest, is closely related to currents from the Karimata Strait crossing the Indian Ocean. Table 3 illustrates the relationship between wind and non-tidal elevation, highlighting this weak correlation. Additionally, the higher residual tidal current speeds observed in deeper waters indicate that tidal currents are not directly driven by wind alone. This phenomenon occurs because wind-generated currents exhibit high speeds at the surface due to wind stress, but the speed of these currents decreases with increasing depth.

Table 3. Relationship Level

R^2 Coefficient Interval	Relationship Level
0.00-0.199	Very Weak
0.20-0.399	Weak
0.40-0.599	Moderate
0.60-0.799	Strong
0.80-1.00	Very Strong

(Source: Jabnabillah & Margina 2022)

Besides wind, other factors also influence tidal currents, such as the topographic conditions of the water body and the gravitational forces exerted by celestial bodies like the Sun and Moon (Setyawan *et al*., 2021). Mahardiananta *et al*. (2017) further explained that wind blowing across the sea surface does not directly generate surface currents. Instead, surface current movement is influenced by the seabed topography. As a result, currents in deep-sea or open-sea regions tend to be stronger compared to those in shallow seas, where bottom friction plays a more significant role in current dynamics.

CONCLUSION

The results of the wind characteristic analysis in the coastal waters of Mantang Island, obtained through measurements using AWS and processed with WPLOT, indicate the influence of monsoon winds. The dominant wind direction came from the west, with a wind speed percentage of 42.22%, and the highest wind speeds ranging from 5.70 to 8.80 m/s. According to the Beaufort scale, the waters around Mantang Island fall into the moderate wind category. This phenomenon is attributed to the position of the sun in the northern hemisphere during the season. The harmonic constant analysis using two methods showed that the same tidal type was a mixed double daily inclination or mixed prevailing semi-diurnal. This type of tide included two high and low tides, occasionally one high and low tide with different heights and periods. Moreover, the analysis produced different sea surface elevation values which included Zo, HHWL, LLWL, MHWL, and MLWL at 11.99 m, 15.9 m, 8 m, 17.9 m, and 6 m, respectively.Based on the regression results between wind and sea surface elevation, an R^2 value of 0.21, or 21%, was obtained. This indicates that wind does not significantly affect sea surface elevation, with a weak relationship category. However, the remaining 79% is influenced by factors such as the topography of the waters and celestial bodies, including the moon and the sun.

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