Analysis of wind generated wave characteristics by SWAN model in Balikpapan Bay

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Abstract. The initiative to relocate the capital of the Republic of Indonesia from Jakarta to Penajam Paser Utara requires research from various sectors in the area. Since Penajam Paser Utara is located in the coastal zone of Balikpapan Bay, it requires careful preparation. This research aims to examine the characteristics of wind-generated waves in the Balikpapan Bay area from 2016 to 2018. Bathymetry data from BATNAS with a resolution of 0.00166666⁰ and Wind data (U₁₀ wind velocity and direction) from the European Center for Medium-Range Weather Forecasts (ECMWF) with a resolution of 0.25⁰ x 0.25⁰ were utilized as input data in this study during three years (2016-2018). This research used the SWAN Model to model wind-produced waves to get significant wave values in spatial and time series form and monthly and seasonal wave energy spectrum characteristics. Based on this research, it can be concluded that significant wave height values are strongly correlated with wind speed. The highest wind speed is found in the DJF (Transition I) season. Maximum Hs (wave height) is found in DJF season, while Hs tends to be high in SON (Transition II) as well as DJF (Western Season), and Hs tends to be weak in MAM (Transition I) season.

Keywords: wave simulation, SWAN model, significant wave height

1. Introduction
Balikpapan Bay is located in Eastern Kalimantan, Indonesia, between the cities of Balikpapan and Penajam Paser Utara. This bay is bordered by several cities and important objects in Kalimantan, and it also functions as a trading route and transit. The surface area of Balikpapan Bay is approximately 15.000 hectares, with a total watershed area of 211.456 ha. There are a total of 56 rivers and streams within the basin. Most Balikpapan Bay's shoreline is still vegetated, including around 17.000 hectares of mangroves providing important habitat for fish and birds.

Regarding the Indonesian government's decision to relocate the capital to Penajam Paser Utara, the characteristics of the Balikpapan Bay area have become more crucial to analyze, particularly the wind-generated wave, which can be used to support infrastructure development near the coast and offshore. Intensive preparation is vital to preventing adverse situations, such as the unexpected occurrence of sea level rise, abrasion, sinking, and catastrophic flood that is presently occurring in Jakarta, from reoccurring in Penajam Paser Utara, the future Capital City.
Putri et al. (2020) analyzed sea level changes in Balikpapan Bay as basic data for strategic planning the new capital city of the Republic of Indonesia, which was summarized in a paper titled “Analysis of sea level changes in Balikpapan Bay as basic data for strategic planning the new capital city of the Republic of Indonesia” [1]. The impact of global climate change on sea level rise around Balikpapan Bay was examined in this paper. Furthermore, the study of tidal current patterns in Balikpapan Bay has been done by Hermansyah et al. (2020) in an article titled "Numerical Modeling of Tidal Current Patterns Using 3-Dimensional MOHID in Balikpapan Bay, Indonesia" [2]. The goal of this study was to figure out how tidal current patterns in Balikpapan Bay affect salinity and temperature distributions. Based on various prior studies on the physical oceanography features of Balikpapan Bay, we can conclude that no research focused on wind-generated waves has been conducted in this area.

Therefore, this research aims to analyze the wind-generated wave characteristics by modeling and to visualize the characteristics and significant wave height in time series and spatial form. This research will help provide quantitative information about the wind wave in Balikpapan Bay, which is critical for modeling (littoral sand transport), planning offshore infrastructure construction (for example, calculating the probability of calm sea states), coastal management, and navigation. Furthermore, scientists and engineers must better understand the wind wave and severe value conditions in the research location since these factors affect the long-term durability of offshore engineering structures and the consequences of coastal waves.

2. Materials and Methods
This research utilized bathymetry data from the BATNAS and wind data from the ECMWF as inputs to the model. The spatial resolution of the wind data is 0.25°x 0.25° (about 28 km), and the bathymetry is about 0.00166666°. The study area bathymetry condition is shown in Figure 1. The open boundary values for the simulation were assumed to be 0 m in this investigation. In this study, the SWAN model was used, a third-generation discrete spectral wave model that can describe the evolution of the wave energy spectrum in a two-dimensional model as a function of bathymetry and wind conditions. In this model, the equilibrium equation of action was used, which implicitly considers the interactions of currents and waves. The evolution of action density \(N\) in this model is governed by the action balance equation as follows:

\[
\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S(\sigma, \theta, x, y, t)}{\partial \sigma}
\]

\((\sigma, \theta):\) action density spectrum
In the equation above $c_x$ and $c_y$ represent x and y components of group velocity. The propagation velocities (quantities of the $c_x$ and $c_y$) are in spectral space $(\sigma, \theta)$. Meanwhile, the first term on the left-hand represents the local rate of change in action density in time, while the second and third terms reflect action propagation. The fourth term represents the shifting of the relative frequency following the change in currents and depths. The fifth term represents the impact of depth and current-induced refraction. The $S(\sigma, \theta, x, y, t)$ in the right-hand is the source term that represents the effects of generation, dissipation, and non-linear wave interactions. The formula below describes the source term:

$$S = S_{in} + S_{nl3} + S_{nl4} + S_{ds,b} + S_{ds,br}$$  \hspace{1cm} (2)

$S$ \hspace{0.5cm} = \hspace{0.5cm} Source and sink terms of energy density

$S_{ds}$, $S_{bot}$ \hspace{0.5cm} = \hspace{0.5cm} Dissipation process

$S_{in}$ \hspace{0.5cm} = \hspace{0.5cm} Source generated wind

$S_{nl3}, S_{nl4}$ \hspace{0.5cm} = \hspace{0.5cm} non-linear wave-wave interaction triad and quadruplet

These formulas represent the deep-water source term for dissipations due to triad wave-wave interactions, bottom friction, and depth-induced wave breaking and the shallow water source term for dissipations due to white-capping and non-linear quadruplet wave interactions [4]. In this study, the SWAN model was utilized to simulate waves based on wind data. The simulation was conducted with a 15-minute time step from December 2015 to December 2018. The model’s domain was discretized with a regular grid in spherical coordinates with a resolution of 0.0025 x 0.0025. 24 directional bins are used for discretized directional wave propagation and the discretization of the frequency bins using 0.05-1 Hz. Surface current fluctuation is not included in this study. However, physical phenomena like quadruplet wave-wave interactions and the dissipation component of wave energy are represented by the total depth-induced breaking, bottom friction, and white-capping contributions.

This study is conducted in the following process. The initial step is to choose the research area and gather wind and bathymetry data. The second step is to configure the SWAN with the model domain, bathymetry, and grid. The simulation output is examined in a spatial form in the third step. After finishing the study for each simulation, we continued to collect data from 10 locations that represent key areas on the nearshore and then analyzed the data in time series form. The model result is compared to ECMWF significant wave height data in the fifth step. Afterward, the output of SWAN proceeded in MATLAB program, which included the process of wave energy calculation through the equation of wave energy below:

$$\text{wave energy} = \frac{1}{8} \rho g h^2$$  \hspace{1cm} (3)

$\rho$ : density (kg/m$^3$), $g$ : gravity (m/s$^2$), $h$ : wave height (m).

3. Result and Analysis
In this research, we simulate waves using wind data. The result was compared to ECMWF significant wave height data. Spatial patterns analysis was conducted for wind and waves output from the model and time series analysis for the significant wave height and spectrum in 10 observation points to understand the characteristics of the modeling results.

3.1 Wind Characteristics During 2017
The wind data from ECMWF that have been processed in the form of wind roses are shown in Figure 2. From the wind roses, the dominant wind direction in Balikpapan Bay from January until April 2017 was blowing from WSW. From May until August 2017, the dominant wind began to blow from SE, except for the wind direction in June 2017-the, the dominant wind direction blow from WSW. During September, the wind that blew from WSW was dominating. Furthermore, the wind from NE dominated
in October and the wind from N dominated in November. In December, the wind from WSW began to dominating again.

Figure 2. Monthly wind speed and direction in 2017 in Balikpapan Bay
(a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, (l) December

In this study, we simulate wind generated waves so important to understand the characteristics of the wind data deeper. For this purpose, we calculate the descriptive statistics with the results shown in Table 2 below. During 2016, maximum wind magnitude occurred in JJA. Meanwhile, in 2017 and 2018, maximum wind magnitude occurred during SON. The most significant average wind magnitude occurred in SON 2018, which was 0.929 m/s, yet the least average wind magnitude occurred in MAM 2018, which was 0.656 m/s. Howsoever, the table merely shows wind magnitude excluding wind direction. Therefore, the Spatial Wind plots in Figure 3 below explain snapshot data that includes wind magnitude and direction.
Table 1. Seasonal Wind Magnitude in 2016-2018

| No | Descriptive Statistics | DJF  | MAM  | JJA  | SON  |
|----|------------------------|------|------|------|------|
|    |                        | 2016 | 2017 | 2018 | 2016 | 2017 | 2018 | 2016 | 2017 | 2018 |
| 1  | Mean                   | 0.704| 0.698| 0.766| 0.758| 0.870| 0.656| 0.784| 0.761| 0.738|
| 2  | Standard Error         | 0.011| 0.013| 0.011| 0.010| 0.014| 0.009| 0.012| 0.014| 0.010|
| 3  | Maximum                | 3.071| 3.071| 3.514| 2.522| 2.321| 2.192| 3.448| 2.732| 3.043|

The snapshots of the monthly wind data in spatial form during 2017 are shown in Figure 3. We can observe that the distribution of monthly wind speed and direction spatially from that snapshots. The strongest wind blows in September and October. In September, the dominant wind direction blew to the southwest. In October, the dominant wind direction blew to the northeast. This corresponds to the wind rose plots shown in Figure 2. It is also shown that the wind speed in Balikpapan Bay during the eastern season is generally lower than the wind speed during the western season. Furthermore, higher wind speed occurs in areas with deeper bathymetry, such as in the body of the bay and the central side of the bay.
3.2 Significant Wave Height Analysis during 2017
The snapshot of wind generated waves from SWAN modeling results is shown in Figure 4. The modeling result can observe the significant wave height (Hs) and direction in Balikpapan Bay. In the snapshot of the significant wave height (Hs) distribution pattern shown in Figure 4, it can be observed that the direction of wave propagation follows the wind flow pattern shown in Figure 3. This indicates that the model built has described the natural phenomenon of wind-generated waves with the direction of wave propagation that follows the wind direction.

Figure 3. Snapsho of monthly spatial wind data in Balikpapan Bay in 2017
(a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, (l) December
Figure 4. Snapshot of monthly spatial significant wave height data in Balikpapan Bay
(a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September,
(j) October, (k) November, (l) December

Based on BATNAS bathymetry data shown in Figure 1, it is known that Balikpapan Bay in general
tends to have ramp morphology. Blue color gradations indicate different depths within the depth range
of 0–50 m. Moreover, it is known that some area in the bay has a depth of more than 30 meters with a meandering pattern starting from the mouth of the river to the bay. The basic morphology of Balikpapan Bay generally indicates the type of slope, which is divided into several areas: ramps, flat-almost flat, and rather steep. Furthermore, the basic sediment type in Balikpapan Bay consists of three types: silt, sandy silt, and sand [5].

The wave simulation results showed a reduction of significant wave height, resulting from the wave propagation deflection due to the depth difference that causes the refraction process, which could be seen in July, September, October, and November. Another physical process that occurred is white-capping, steepness-induced wave-breaking, which could be seen in September. Based on previous research, the influences of bathymetry and river discharge as a local influence are very dominant in affecting hydrodynamic occurrence within Balikpapan Bay. While off the coast of Balikpapan Bay, the smaller residual current value represents the dominant tidal movements in the location [6].

3.3 Significant Wave Height Analysis in 10 Observation Points during 2017
In this study, we consider several places located in Balikpapan Bay's nearshore area, which is vital for people's activities. These places then become the consideration for defining ten observation points in this study (Figure 5).

![Figure 5. Location of 10 Observation Points](image-url)
Table 2. Coordinate of 10 Observation Points

| Point   | Benchmark                      | Lon          | Lat            |
|---------|--------------------------------|--------------|----------------|
| 1       | International Airport Sepingan | 116°54'7.25" S | 1°16'20.17" S |
| 2       | Habitations (next to the airport) | 116°52'41.27" S | 1°16'45.68" S |
| 3       | Industrial area                 | 116°50'46.96" S | 1°16'48.39" S |
| 4       | Habitations (along the bay)     | 116°48'26.67" S | 1°14'3.73" S  |
| 5       | Sedimentation Area              | 116°44'58.13" S | 1°16'49.53" S |
| 6       | Northeast of Penajam Kabupaten  | 116°42'25.22" S | 1°22'33.91" S |
| 7       | Habitations Muarasempupu        | 116°40'18.07" S | 1°24'41.04" S |
| 8       | Selulu Pond                     | 116°38'49.30" S | 1°15'35.63" S |
| 9       | Port of Balikpapan              | 116°36'2.59" S  | 1°14'18.83" S |
| 10      | Labangka Mangrove Area          | 116°34'8.80" S  | 1°29'28.40" S |

Figure 6 below describes wind sea waves' significant wave height value at ten vital points in time series. Based on the simulation results, the maximum wave height occurs in the SON season (September-October-November), the transition season II and JJA (June-July-August), East monsoon, which has greater wind speed. From Figure 5 (b), we also can observe a similar pattern of significant wave height at locations 6, 7, and 10. While in Figure 5 (c) shown similarity pattern of significant wave height at locations 1, 2, 3, 4, 5, 8, and 9. Besides, based on previous research, location 3 is an industrial area affected by large significant wave height value, therefore need more careful review and actions to avoid erosion processes. Moreover, through their research, R. Malik et al. (1999) concluded that environmental degradation mainly occurs in industrial areas [7].

![Figure 6](image_url)

**Figure 6.** Time Series of Significant Wave Height in 10 Observation Points
Bays with sloping geographical conditions and small to moderate energy waves are suitable to develop as a natural port. A previous study said that in 1897, oil drilling was conducted in East Kalimantan. Therefore a petroleum storage depot was built around the coast of Balikpapan Bay. There are eleven ports located in the area that juts out towards the offshore in Balikpapan Bay, thus protect the ports from the waves. This type of location also supports the loading and unloading activities [8].

![Figure 7. Wave Spectrum of SWAN Model Significant Wave Height Data February 2017](image)

![Figure 8. Wave Spectrum of ECMWF Significant Height Data February 2017](image)

The waves that propagate to the beach will deform and eventually break when they reach the requirement of breaking waves. The wave spectrum is depicted on the 1D spectrum graph of the SWAN (Figure 7) and ECMWF (Figure 8) models, explaining the estimated energy conditions during the wave propagation. In the spectrum snapshot from the swan simulation results of February 2017, the wave propagation was recorded at a frequency of 8.297x10^{-3} Hz, the range of wind sea waves. Compared with ECMWF data, the energy spectrum consists of two energy components: 1) 2.976x10^{-3} Hz, which is in the swell waves, and 2) 2.976x10^{-2} Hz, which is in the range of wind sea waves. Based on the calculation of the wave spectrum above, we can understand that the largest energy of waves in Balikpapan Bay occurs in the second transition season. This is because any obstacles do not hinder the
direction of the wind towards the wave-forming area, thus creates greater fetch value that will also form larger waves compared to other seasons [9].

The wave spectrum calculation results show that the relationship between significant wave height and ocean wave energy is that the higher the wave significant height, the higher the wave energy generates. It is also reinforced by Setiawan et al. (2005) statement that the higher the significant wave height, the greater the wave energy value and vice versa. In this paper, we only show the characteristics of significant wave height and its spectrum from the data 2017 because there are no significant differences in the modeling result of the data from 2016-2018 [10].

4. Conclusions
We may deduce from the study that Balikpapan Bay features ramp morphology bathymetry, which influences the significant wave height model outcome. According to simulation findings, in 2017, the greatest winds blew during SON (transition season II) and JJA (East Monsoon), causing significant wave height to reach its maximum in both SON and JJA. The result from the analysis of 10 observation points in this study shows two groups of a similar pattern of the significant wave height model results. The first group is at locations 6, 7, and 10, and the second group is at locations 1, 2, 3, 4, 5, 8, and 9. Location 3 is an industrial area affected by large significant wave height values, requiring more thorough study and action to prevent erosion. Based on the modeling results, the wind-generated wave in this study will deform and break when it reaches the nearshore. Furthermore, the energy of the wind-generated wave may also be measured using the 1D spectrum calculation findings.

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