Modelling sea surface currents in the eastern coast of Bawean Island, East Java

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Abstract. Bawean Island is located in the middle of the Java Sea, approximately 80 km north of Gresik Regency, East Java Province. The coastal area of Bawean Island is famous for its potential as a marine tourism area because it has a well-preserved coral reef ecosystem. The potential for tourism development on this island requires the support of environmental suitability. The dynamics of ocean currents as an important parameter for small island development is important to be analyzed. This study aims to determine the characteristics of currents in the eastern coast of Bawean Island through the hydro-oceanographic model. The data used in this modelling was hourly wind and tide data from the period of 2020-2021. The results showed that the velocity of surface current speed in the study area was weak (<0.5 m/s). There was a significant difference of current direction during the west monsoon season and the first transitional season. Validation of model simulation and ADCP measurements produce MAE values 0,014 and 0,035 as well as MAPE values 12,75% and 27,48%.

1. Introduction

Bawean Island is a small island located in the middle of the Java Sea. The distance between this island and the northern part of East Java is about 80 nautical miles. The sea surrounding the island is relatively shallow (<100 m) with coastal environmental conditions influenced by the west and east monsoons that change every half year [1], [2]. Bawean Island is famous as a marine tourism destination in East Java because it has a stretch of white sandy beach and natural conditions of seagrass and coral reef ecosystems. Based on the coastal zoning plan and small islands of East Java Province, Bawean Island is designated as a priority area for marine tourism. Furthermore, this island has long been a stop-over for commercial ships sailing from or to Kalimantan and Sulawesi.

The dynamics of the sea waters around the small island is quite complex. The interaction between the ocean, the atmosphere and tides causes variations in the conditions of oceanographic parameters such as currents and waves. Therefore, understanding the characteristics of environmental parameters is very important, especially for the development of marine infrastructure or other related development of coastal and small islands areas [3]. Coastal spatial planning requires adequate hydro-oceanographic data.
in preparing zoning and spatial use for coastal areas, especially on small islands that have limited land carrying capacity [4].

Ocean currents are the movement of seawater masses from one place to another. The result of this water mass movement is a vector that has a magnitude of velocity and direction. Ocean currents occur because of the process of moving water masses towards an equilibrium which causes horizontal and vertical displacement of water masses [5]. The movement is the resultant of several forces and natural factors that influence it, such as tide. Surface currents play an active role in influencing processes that occur in the sea, such as chemical, biological and physical processes. Moreover, current data is needed in ocean-related activities such as port layout, shipping lanes, coastal structures, marine environmental management, determination of marine recreation areas and marine aqua-culture [4], [6], [7]. Understanding marine environmental conditions are very important to ensure the success of planning and developing coastal areas. In addition, the pattern of current movement can be known by measuring field data or using a numerical approach. Natural state modelling is an alternative to obtain an overview of the distribution and movement of surface currents that occur in the present and their predictions in the future.

Numerical modelling of ocean surface currents has been widely used to provide information about the movement of water masses and their effects on environmental processes. Previous studies that used hydrodynamic modelling for instance the distribution of hot water masses around the power plant in Muara Karang [8] and total suspended solids (TSS) in Teluk Lamong Terminal of Surabaya [3]. Other studies have also applied hydrodynamic modelling to measure the potential of harvesting renewable energy resources from tidal, waves and current movement [9], [10]. On a global scale, studies on ocean currents using modelling approach were applied to analyze the distribution and transport of marine debris in the Great Barrier Reefs and the Adriatic Sea respectively [11], [12].

Hence, this present research attempted to study the characteristics of surface currents particularly on the eastern coast of Bawean Island. The hydrodynamic of current speed and direction were simulated to describe the physical characteristics within the study area. This research utilized the Mike 21 which is a numerical-based application that is commonly used in modelling currents, waves, sediments transport in coastal areas, open seas and estuaries [13],[14],[15]. Furthermore, the module used to determine the circulation pattern of ocean current in this study was the Hydro Dynamic (HD) Flow Model.

2. Methods

Sea surface current of the study area was simulated using MIKE 21 Hydrodynamic Module (HD), developed by Danish Hydraulic Institute (DHI). This module is applicable for the simulation of hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas and seas [16]. The modeling simulation in this study focuses on current movement during the west monsoon season (December - February) and the first transitional season (March - May). The basic equation used in sea water displacement generated by MIKE 21 HD Module were continuity equation and XY axis mass momentum (Equation 1-3).

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \mathbf{v}}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t}$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial x} + \frac{gq}{C^2 h^2} + \frac{1}{\rho_s} \left[ \frac{\partial}{\partial x} \left( \mathbf{H} \right) + \frac{\partial}{\partial y} \left( \mathbf{H} \right) \right]$$

$$\Omega p - \frac{\partial \mathbf{v}}{\partial x} \left( \rho_s \right) = 0$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial x} + \frac{gq}{C^2 h^2} - \frac{1}{\rho_s} \left[ \frac{\partial}{\partial x} \left( \mathbf{H} \right) + \frac{\partial}{\partial y} \left( \mathbf{H} \right) \right]$$

$$\Omega p - \frac{\partial \mathbf{v}}{\partial y} \left( \rho_s \right) = 0$$
Where:

- $h(x,y,t)$: Water depth (m)
- $V, V_x, V_y(x,y,t)$: Wind speed component (m/s)
- $d(x,y,t)$: Variation of depth in time (m)
- $\zeta(x,y,t)$: Water elevation (m)
- $p_a(x,y,t)$: Atmospheric pressure (s$^{-1}$)
- $\Omega(x,y)$: Coriolis parameter (s$^{-1}$)
- $p_w(x,y,t)$: Water density (kg/m$^3$)
- $\rho_w$: Water density (kg/m$^3$)
- $\Omega(x,y)$: Coriolis parameter (s$^{-1}$)
- $\xi(x,y)$: Chezy barrier (m$^{1/2}$, s)
- $\gamma(x,y)$: Coordinate
- $g$: Gravitational force (m/s$^2$)
- $t$: Time (s)
- $f(V)$: Wind friction factor
- $\tau_{xx}, \tau_{xy}, \tau_{yy}$: Effective shear stress component

This study was conducted in the eastern coast of Bawean Island (Figure 1). The centroid coordinate of the island is 05°48’10’S and 112°40’00”E. The focus area for surface current modelling in this study was at the narrow strait between Bawean and Gili Noko Island. The data used include bathymetric data derived from the digitization of ocean chart published by the Indonesian Navy Hydrographic Center. The bathymetric data was used to create a domain in the form of a flexible mesh. Other essential data in this study were hourly tide, wind speed and directions from 2019 to 2020 obtained from the Meteorology, Climatology and Geophysics Agency of Sangkapura Port. These data were the main input for sea surface current modelling.

Moreover, two field data collections points were placed for the purposes of model validation. In-situ current speed and direction were observed for 5 days at each point started from the 1st December 2020. An Acoustic Doppler Current Profiler (ADCP) NORTEK-AWAC was used for the measurement at 10 minutes intervals. The device was placed at a 4.5-meter depth below the water surface. Mean Absolute Errors (MAE) and Mean Absolute Percentage Errors (MAPE) formulas were applied to compare field measurement and data simulation.

Figure 1. Map of Bawean Island East Java Province
The sea surface current model built in this study was operated using MIKE-21 software. This program is a water modelling software that can be applied to hydrodynamic simulations in two dimensions. Boundary conditions in the form of tidal data obtained from the Meteorology, Climatology and Geophysics Agency. The set-up parameters of the hydrodynamic model can be seen in Table 1.

**Table 1. Hydrodynamic Modelling Set-Up**

| Parameters               | Model Application                                      |
|--------------------------|--------------------------------------------------------|
| Simulation Period        | Number of Time Step = 359                              |
|                          | Time Step Interval = 21600 seconds                      |
|                          | Start date = 01/12/2020; End Date = 24/05/2021         |
| Mesh Boundary            | Bathymetric Chart, Indonesian Navy Hydrographic Center |
| Flood and Dry            | Drying Depth = 0.005 m                                  |
|                          | Flooding Depth = 0.05 m                                 |
|                          | Wetting Depth = 0.1 m                                  |
| Density Type             | Barotropic                                             |
| Eddy Viscosity Type      | Smagorinsky formulation; format constant value = 0.28  |
| Bed Resistance           | Chezy Number; constant value = 32 m^{1/2}/s            |
| Coriolis Type            | Varying in domain                                      |
| Wind Forcing             | Varying in Time                                        |
| Boundary Condition       | Tide data (Lat : 05°52'05'' S; Long : 112°40’00’’ E)   |

3. Results and Discussions

3.1 Bathymetry

The process of making a bathymetric map of the Bawean map begins with the process of rectifying and digitizing the depth of the sea using a map produced by the Indonesian Navy. This process requires additional shoreline data obtained from Google Earth with polyline manual digitization and Digital Elevation Model (DEM) for land surface of the island. The DEM data was downloaded from the official web site of Geospatial Information Agency (http://tides.big.go.id/DEMNAS/index.html). Furthermore, to produce the depth profile of Bawean Island, this process applied the WGS 84 chart datum and the Universal Transverse Mercator Zone 49 South (WGS 1984 UTM Zone 49S) projection for the coordinate system. The depth profile of the east coast of Bawean Island was dominated by shallow water ranging from 0-10 meter depth. The maximum depth of the study area was 50 meters with an average distance off the coastline of about 300-350 meters. The rise of the seabed structure on the east side formed small, hilly islands around the mainland (Figure 2).

![Figure 2. Bathymetric Map of The Study Area](image-url)
3.2 Tides

Tide data analysis was carried out to obtain tidal component, reference water level elevation and other important elevations. To obtain these parameters, tidal data analysis is performed using the Least Square Model. In addition, the data was also used in the modelling because in the Java Sea, surface current was highly affected by the propagation of tides [4]. The results showed that the tidal type in the study area was diurnal (Formzahl Number = 3,97; RMSE = 0,026) with a Mean Sea Level (MSL) of approximately 1,05 meter (Figure 3).

![Figure 3. Tide Analysis (15 days) of Bawean Island](image)

The type of tide on Bawean Island is diurnal, where in 24 hours there is 1 high tide and 1 low tide. During the field observation period the spring tide was around 1,9 – 2,1 meters, occured in 8 to 11 December 2020. Tidal conditions in the Java Sea are the result of the interaction between seawater masses coming from the Pacific and Indian Oceans which then enter the Java Sea from the east. Whereas seawater masses coming from the South China Sea entering the Java Sea from the west through the Karimata Strait [17]. Due to this complex interaction and different geographical condition, there is a variation of tidal types in the coastal area of North Java i.e diurnal and mixed-tide prevailing diurnal [17][18].

3.3 Model Validation

The modeling results obtained from the simulation were compared with the results of field observations using ADCP which were carried out for 5 days at 2 observation points. Based on the comparison results, the MAE values were 0,014 and 0,035 whereas MAPE values were 12,75% and 27,48% at each point (Figure 4). Due to the MSE and MAPE results, it can be seen that there was no significant difference of current velocity between model and ADCP measurements.

![Figure 4. Comparison of Simulation Results and ADCP Current Speed Measurements](image)
Moreover, another validation approach using comparison of current direction were also conducted. Based on the current rose in Figure 5, it can be seen that there was a significant difference between current direction of the ADCP measurement results and model simulation. At the first observation point, the ADCP results show that the dominant direction of current movement was towards the southeast and south, there was also movement of currents to the west. In the simulation results, the dominant current direction was towards the south and southeast. At the second observation point, the difference in the direction of current movement appears to be larger. The ADCP results showed that the dominant current was moving towards the west and southwest. Meanwhile the simulation results showed irregular current directions with dominant current seemed to move towards the north. Variations that occur in the direction of surface currents can be caused by several factors. The tidal data used in the model was the result of BMKG predictions which may differ in terms of water elevation from the real conditions. In addition, the coefficient of sea bed roughness (bed resistance) used in model set up was not in accordance with the actual bottom conditions of the waters. Other factors that may have influence on a smaller scale were the viscosity and temperature of seawater at the time of measurement.

3.4 Simulation Results

The results of modeling the average of speed and direction of currents carried out in the west monsoon (December 2020 to February 2021) showed that the dominant surface current in the eastern part of Bawean Island moved from north to south and was slightly deflected to the southwest (Figure 6). The maximum current speed on the surface reached 0.07 m/s, while the minimum current speed was 0.005 m/s and the average speed was approximately 0.028 ± 0.014 m/s. Moreover, the modeling results in the first transitional season (March to May 2021) showed a change in the direction of surface currents. In this period the current moved from the south to the north and northeast. The maximum current speed was 0.17 m/s, while the minimum current speed was 0.03 m/s and the average current speed was 0.06 ± 0.04 m/s.

Based on the modelling results, the dominant surface current direction was flowing from north to south in the west monsoon and vice versa during the first transitional season. The characteristics of ocean currents in Indonesian waters are generally influenced by wind and tides. The currents influenced by the wind are generally seasonal, where in one season the current flows steadily and in the next season, the direction could change according to the direction of wind movement [19].
The eastern coast of Bawean Island was characterized by shallow water, with a depth of < 50 meters. The eastern coastal area of Bawean Island is known to have coral reef ecosystems in a well preserved and natural condition [2], [20]. The morphology of the shallow water base dominated by coral reefs affects the vertical distribution of current velocity. Shallow water depths will cause greater bottom friction. Therefore the movement of water mass will experience a heavy friction with the sea bed, resulting in the speed reduction of the current. The current velocity in the study area was classified as low to moderate, (< 0.5 m/s). The weak sea surface currents in the study area were predicted as the results of ecological role of coral reefs in spreading and weakening the strength of currents flowing into the area [21], [22].

Langragian and Euler methods are two types of methods that are often used for direct current measurement. Basically, the Langragian method use buoys equipped with GPS and other sensors that are drifted away following the movement of ocean currents. The buoy will send position data and other sensor readings (sea surface temperature, current speed, direction etc). The data from the transmission is then analyzed to determine the real-time sea conditions. There are at least two major issues when
using a Lagrangian drifter to observe ocean parameters. Firstly, there is a high possibility of losing a device due to bad weather conditions or un-expected acts due to people’s interference. Secondly, it is very important to get data in real time in order to understand a current hydrodynamic situation in the region. This defines the necessity of transmitting the information obtained by a drifter immediately after it has been received. Drifters with a cellular communication (Global System for Mobile Communications) channel for data transmission are by far the best solution. However the limited GSM service range are still a major obstacle for ocean-scale observations [23].

Meanwhile, the Euler method is done by installing a tool at a point for observation for a certain period of time. Commonly used measurement devices include current meters and ADCP. A current meter is equipped with a temperature sensor, conductivity to measure salinity, a rotor for speed and a magnetic compass to determine direction. The basic principle of ADCP is using hydro-acoustic theory. A transducer, also usually acting as a receiver emits short pulses of a certain frequency. The pulses are reflected or propagated by the particles in the water. A shift in frequency which is received back by the receiver can be measured as the velocity of the water current [24].

In addition, a global scale mooring buoy observation and monitoring infrastructure has been established by NASA, the program is known as the National Data Buoy Centre with the main objective is to provide quality observations in the marine environment safely and sustainably to support the understanding of and predictions to changes in weather, climate, oceans and coast (www.ndbc.nasa.gov). The NDBC consists of 1320 stations deployed throughout the Atlantic and Pacific Oceans. This moored buoy network and coastal stations have provided real-time oceanographic and meteorological observations to a wide variety of users.

Along with the development of computer technology, oceanographers have developed hydrodynamic models to predict the movement patterns of water masses in the sea. By understanding the principles of physics and with mathematical and computer aids, analytically difficult problems can be solved by numerical methods. Examples of hydro-dynamic models that have been used in many research including Princeton Ocean Modelling (POM), Modular Ocean Model (MOM) and Hamburg Shelf Ocean Model (HAMSON). Based on these models, marine institutions around the world develop software packages that can be used to visualize numerical analysis results for various oceanographic applications. Commonly used software include Mike, SMS (Surface Water Modeling System) and Delft 3D.

Information regarding surface current is important for further use, especially for a small island with great potentials. The development of marine aquaculture requires information about currents to determine the structural design of floating net cages and the calculation of the load of the resulting fish feed waste[25], [26]. Current speed and direction are also the main consideration in determining the suitability status for marine tourism activities particularly swimming, snorkelling and diving [27], [28]. Hence, it can be stated that periodic availability of current data is necessary. Continuous field measurements will be difficult to do in a small and remote island such as Bawean, unless using mooring buoys. Therefore numerical modelling supported by field data validation is one solution that can be done to obtain the surface current.

4. Conclusions
This study has demonstrated the combination of field data collection and hydro-dynamic modelling to examine the movement pattern of sea surface current in eastern coast of Bawean Island. The simulation was conducted in the west monsoon (December 2020 to February 2021) and the first transition seasons (March to May 2021). The simulation results showed that current speed in the study area was weak (< 0,5 m/s). The dominant surface current direction was flowing from north to south in the west monsoon and from south to north in the first transitional season. The current speed pattern of the simulation results and field data measurements were not significantly different (MAE ranged from 0,014 to 0,035 and MAPE < 30%). Furthermore, information on sea surface currents as the results of this study can be useful for planning and developing the coastal area of Bawean Island.
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