Hydrodynamics modeling with MIKE system in the Semak Daun Lagoon, Seribu Islands Indonesia

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Abstract. At low tide condition, the Semak Daun Lagoon (SDL) barrier reef is drowned during high tide and appeared to the surface during low tide. How are hydrodynamics in low tide and tidal conditions? This study aims to examine the pattern and current velocity in the SDL under four tidal conditions. The two-dimension model is built based on two motion generations namely wind pressure and tides. The discretization of the equation uses the finite volume method. Domain discretization is divided into 14,575 triangular elements with a grid area of 1,000 m². The results of the model, verified with observational data in the field, show the similarity of tidal patterns and current velocity as indicated by the MAPE value of 7.9%, meaning that the model is well constructed. Current patterns generally move from southwest to northeast at high tide to low tide condition and vice versa at low tide to high tide condition. At low tide, there is a buildup of water mass in the lagoon because the only channel north is functioning as an outlet. This causes a slowing of current flow inside the lagoon and acceleration in the northern canal. Current velocity ranges from 0.02-0.51 m.s⁻¹. The pattern and speed of the current in the lagoon are dominantly influenced by tidal dynamics. Residual current velocity varies in the range of 0.01-0.04 m.s⁻¹.

1. Introduction
The lagoon is defined as a body of water that is separated from the open sea by a barrier in the form of sand dunes, coral reefs or islands and is connected to the surrounding waters through several channels [1]. Hydrodynamic systems in these waters, 70% variability of surface elevation and 65% variability in inlet-outlets are affected by tides [2,3,4,5] while the influence of wind is very small [2,3,4]. Previous studies on observations and numerical models of coastal lagoons have been carried out by [2,6] related to the dynamics and variability of a tidal coastal lagoon. The generation of hydrodynamics in the lagoon has been modeled by [3] and changes in inlet geomorphology affect the hydrodynamics of the lagoon [4]. The interaction between the lagoon and the open sea influences the contemporary phase of the lagoon transformation [7] and this is very dependent on the number of canals [8,9]. Study changes in lagoon depth [10] and inlet cross-sectional area [11] where the channels appeared to the surface (dry) at low tide conditions [12,13].

The hydrodynamic study of the lagoon is needed to better understand the proper use of the water system, while the study of lagoon hydrodynamics such as in the SDL is still less explored. The uniqueness of this SDL ecosystem is having a barrier reef as a barrier embankment, where, drowned at high tide and appeared to the surface at low tide, there is a small island in the middle of the lagoon. This
characteristic implies that during low tide, the interaction of lagoon waters with the surrounding open sea is very limited. On the other hand, the SDL is currently used as a location for the floating net cage culture systems, which needed an ideal aquatic environment for the sustainability of these activities. Thus, for the sustainable utilization of this lagoon needed studies to use hydrodynamic modeling, this is intended to understand the pattern and speed of water mass circulation in detail. The purpose of this study is to study the pattern and speed of the current in SDL use a 2-dimensional MIKE system. This research is expected to provide basic hydrodynamic information for the utilization and development of floating net cage culture systems in the SDL.

2. Research methods
This research was conducted in the SDL waters of the Seribu Islands Jakarta in the area of 672833.83 mE, 9366754.85 mS; 673825.28 mE, 9364862.36 mS; 678545.58 mE, 9368598.58 mS; 679310.37 mE, 9366658.99 mS (Figure 1). Field measurements were carried out during 12-15 July 2018.

Hydrodynamic modeling is carried out for 17 days (4 July - 21 July 2018). The 2-dimensional model is based on wind generation and tides. This model, too, considers forces acting on seawater masses such as pressure gradients, gravity, Coriolis and friction per unit mass [14]. This modeling simulation uses the 2D MIKE tool.

Figure 1. (a) Location of the study, the red line (W-E) is a cross-section west-east, the red line (N-S) is a cross-section north-south, 1-SW is the southwest channel, 2-S is the southern channel, 3-E is the eastern canal, 4-N is the northern channel, 5-NW is the northwest channel, 6-W is the western channel and 7-C is the location of culture, (b) horizontal distribution of elements in the study area.
Domain model discretization is divided into 14,575 triangular elements with 1,000 m² grid area. The discretization of the equation uses the finite volume method [15]. Field verification is carried out for validation of tides, currents, and geographical positions. The verification time of the model is adjusted to the time of field data collection. This modeling is based on numerical solutions of the Reynolds averaged Navier-Stokes system of equations. The continuity equation can be written as follows:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = S
\]

and the horizontal momentum equations for components x and y can be written as follows:

\[
\begin{align*}
\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uu}{\partial y} &= +f v - g \frac{\partial \eta}{\partial x} - \frac{1}{\rho_o} \frac{\partial p_o}{\partial x} \rho \int_0^\eta \frac{\partial \rho}{\partial x} dz - \frac{1}{\rho_o h} (\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y}) + F_u \\
\frac{\partial v}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial uu}{\partial y} &= -f u - g \frac{\partial \eta}{\partial y} - \frac{1}{\rho_o} \frac{\partial p_o}{\partial y} \rho \int_0^\eta \frac{\partial \rho}{\partial y} dz - \frac{1}{\rho_o h} (\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y}) + F_v
\end{align*}
\]

where \( t \) is time; \( x \) and \( y \) are Cartesian coordinates; \( \eta \) is surface elevation; \( d \) is the depth of the sea when calm; \( h = \eta + d \) is the total depth; \( u \) and \( v \) are velocity components in the \( x \) and \( y \) directions; \( f = 2\Omega \sin \Phi \) is the Coriolis parameter (\( \Phi \) angle of earth's revolution and \( \Phi \) is the coordinates of the earth's latitude); \( g \) Earth's gravitational acceleration; \( \rho \) is the density of seawater; \( s_{xx}, s_{yx}, s_{xy}, \) and \( s_{yy} \) are radiation voltage tensor components; \( \rho_o \) is the atmospheric pressure; \( \rho_o \) is a reference to water density.

The horizontal stress section is explained using a gradient-stress relationship, which is simplified to:

\[
\begin{align*}
F_u &= \frac{\partial}{\partial x} \left( \frac{2A}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial}{\partial y} \left( A \left( \frac{\partial u}{\partial y} + \frac{\partial u}{\partial x} \right) \right) \right) \\
F_v &= \frac{\partial}{\partial y} \left( A \left( \frac{\partial u}{\partial y} + \frac{\partial u}{\partial x} \right) \right) + \frac{\partial}{\partial y} \left( 2A \frac{\partial v}{\partial y} \right)
\end{align*}
\]

where \( A \) is horizontal turbulent (eddy viscosity). Surface and bottom boundary conditions for \( u \), and \( v \) are:

Surface boundary conditions and bottom boundary conditions for \( u \), and \( v \):

at \( z = \eta \):

\[
\frac{\partial \eta}{\partial t} + u \frac{\partial \eta}{\partial x} + v \frac{\partial \eta}{\partial y} = 0, \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) = \nu_r \frac{1}{\rho_o v_r} \left( \tau_{sx}, \tau_{sy} \right)
\]

at \( z = -d \):

\[
\begin{align*}
u \frac{\partial d}{\partial x} + \frac{\partial d}{\partial y} &= 0, \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) = \nu_r \frac{1}{\rho_o v_r} \left( \tau_{bx}, \tau_{by} \right)
\end{align*}
\]

where \( \left( \tau_{sx}, \tau_{sy} \right) \) and \( \left( \tau_{bx}, \tau_{by} \right) \) are the components of surface wind friction and bottom friction. The integration of time and discretization of space is given a low order solution with a fast algorithm. The simulation involves flood and dry components with the following conditions:

\[
h_{dry} = 0.001 \text{ m}; h_{flood} = 0.5 \text{ m}; h_{wet} = 0.9 \text{ m}
\]

Model suitability criteria use the mean absolute percentage error (MAPE) test [16]:

\[
\text{MAPE} = \frac{1}{n} \sum_{i} \left| \frac{x_i - \hat{x}_i}{\hat{x}_i} \right| \times 100\%
\]

with an interval of suitability: MAPE <5%: very suitable, 5% <MAPE <10%: suitable, >10%: incompatible.
3. Results and discussion
The results of hydrodynamic simulations are displayed based on the characteristics of the four sea-level elevations, namely low tide, low to high tide, high tide and high to low tide conditions. The model and field verification shows the suitability of the flow characteristics shown by the MAPE value of 7.93% meaning that the model is built according to field conditions [16].

Figure 2. Validation of the model with the results of field observations (a) sea-level elevation and (b) currents (components u and v): yellow lines and dots are the results of the model, blue lines and dots are measurements of field data at the floating net cage locations.

The analysis shows variations in tidal ranged from 0.34 m at the time of the neap tide to 0.86 m at the spring tide with the mixed type prevailing diurnal (Figure 2), this is indicated by the formal value of 1.06. This type is influenced by a single harmonic component of the Indian Ocean through the Malacca strait and a dual component of the northern Pacific Ocean through the Makassar Strait [17][18].

Sea level elevation (Figure 3) at low tide condition, higher inside the lagoon than outside the lagoon with a difference of 0.03 m, this is different from the three sea-level condition others. This phenomenon is caused by the accumulation of water mass in the lagoon consequence input through three channels namely the west (W), southwest (SW) and south (S) channels while the output only through the north (N) channel. This causes the outer lagoon to reach the low tide faster than inside the lagoon. This phenomenon as shown by [5] that the number and size of the channel determine the elevation of the water surface in the lagoon.

The analysis of Wind and tidal show different times of time reaching the highest values. The highest wind speed was found on the third and fourth days of the simulation (Figure 5a) while the tides are neap tide conditions while the highest tides elevations (spring tides) occurred on the tenth and eleventh days while the wind speed on the weakening conditions. Overall, the current velocity in each channel follows the tidal pattern, this is as [2] says that the generation of coastal and lagoon areas is dominated by tides.
Figure 3. Contour of sea level elevation at the study domain: at (a) low tide, (b) low tide to high tide, (c) high tide, and (d) high tides to low tide condition.

Figure 4. Patterns and velocity of surface currents: at (a) low tide, (b) low tide to high tide, (c) high tide, and (d) high tides to low tide condition.

Surface flow patterns generally move from the southwest to the northeast at high tide to low tide conditions and vice versa at low tide to high tide conditions (Figure 4). This is as [19] states that at high tide conditions the currents flows to the northwest and at low tide condition the flows currents to northeast. The current flow SDL, at low tide, an inlet through the west, southwest, and south channel then then exits through the north channel, this is due to the northwest, north, east and south barrier reefs being appeared so that the exit is only through the northern channel. At low to high tide and high to low
tide inlet flows through the east (E), north (N), northwest (NW) and south (S) channel then exit through the southwest (SW) and west (W) channels. This is due to a small part of the reefs are appeared (at high tide conditions) so that the current flow looks uniform.

Figure 5. (a) Wind direction and velocity, (b) tidal elevation (c, d, e, f, g, h) the speed and direction of the current in each channels, and (i) the speed and direction of the current at the culture site, the red line on the left of the picture shows the increase in wind speed and low tidal elevation; the red line on the right of the picture shows the weakening wind speed and high tidal elevation.
Figure 6. Current speed and direction; (a) total currents, (b) tidal currents, and (c) residual currents.

The speed of the current in the lagoon and all channels follows the pattern of tidal dynamics. The lowest current speed is found in the lagoon (middle lagoon) to reaching 0.01 ms\(^{-1}\). This is caused by currents flowing in through the west and southwest channels experience a build-up in the lagoon (Figure 3). As a result, the current in the north canal accelerates to 0.51 m.s\(^{-1}\) (Figure 5e). At low to high tide conditions, high tide and high to low tide, the range currents velocity between 0.02 - 0.24 m.s\(^{-1}\).

The current velocity in each channel is different and varies with time, this follows the tidal pattern, as [2][7] says that the tides play a major role in transforming the lagoon's water mass. Tides cause differences in elevation of the water surface inside and outside the lagoon. The position of the channel in the direction of coming and going the direction of the current also determines the speed of the current. Similarly, the current direction in each channel shows back and forth directions depending on the channel position. Moreover, the size of the channel also determines the speed of the current as a consequence of the theory of continuity, as shown by [2][4] says that the size of the channel determines the speed of the current. The current velocity in each channel ranges from 0.02 - 0.51 m.s\(^{-1}\) (Figure 5) with the lowest values found in the west channel at the lowest conditions while the highest values found in the north channel also at the lowest conditions. This shows that the influence of the tidal dynamics of the Semak Daun lagoon aquatic is very large. This is as [2][3][4] says that around 70% of sea level elevation variability and 65% variability in lagoon inlet-outlets are affected by the tidal process.

Residual currents are non-tidal currents, where the circulation is formed when non-linear terms are associated with basic friction and advection components. The analysis showed the residual current velocity ranged from 0.001 - 0.043 m.s\(^{-1}\) (Figure 6c) with an average of 0.013 m.s\(^{-1}\). The residual current refers to a relatively constant speed at both the steady and spring tide conditions. Although the residual current is relatively small, it can affect the mass exchange of water and the movement of particles floating in the water. This is as stated by [20] that residual flows play a more important role in coastal waters, in material transport than tidal currents for a long period of time.
4. Conclusions
The current patterns generally follow tidal patterns. At low tide, the inflow through the west, southwest, and south channels then exits through the North Channel. At low to high tide and high to low tide, inlets through the east, north, northwest, and south channels then exit through the southwest and west channels. The lowest current speed is found in the middle of the lagoon (floating net cage culture system) while the highest is found in the North Channel. The residual current speed is relatively constant and not following tidal dynamics.

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