Surface currents modeling based on tidal cycles and monsoon in tropical estuary, Indonesia

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Abstract. The modeling uses a software-based numerical model DHI MIKE user interface developed by The Danish Hydraulic Institute (DHI) Water and Environment, Denmark. Simulation of current uses a 2-dimensional model (averaging to depth) with a finite element approach. Modeling of currents was conducted to know current dynamics by tidal cycle and seasonal variation (west and east monsoon). The models were validated using correlation coefficient value (r) by comparing direct measurement and model output. The r-value for current velocity during west monsoon was 0.653 and east monsoon was 0.697 and for current direct during west monsoon was 0.887 and the east monsoon was 0.857. While the r-value for the tide was 0.858. All these r values showed a strong correlation and these indicated the models were valid. The result of the simulation of the current models showed that the surface currents were strongly influenced by the tidal cycles. The currents direct flowed to the south at flood tide and to the eastern at ebb tide. The maximum current velocity during the west monsoon was 0.50 m/sec and during the east monsoon was 0.40 m/sec. The averages of current direct were more dominant eastward of Jeneberang estuary.

1. Introduction
Current is the horizontally and vertically movement of water masses generated by wind and tides [1][2][3]. Currents play an important role in determining various processes in the ocean. One of the important chemical processes in the ocean is the dynamics of chemical elements such as pollutants, nutrients, and suspended materials played by currents. The process of transport of chemical elements from one place to another in water column is moved by currents through advection process. The transfer of chemical elements due to current is a material transport mechanism in environment which then causes the process of dispersion and accumulation. The material transport follows the direction of currents that move horizontally and vertically [4][5][6]. Therefore, study of the dynamics of chemical elements in sea waters cannot be separated from the study of oceanographic aspects such as currents and tides.

One alternative in studying surface currents is to use a numerical model approach. Mike 21 is a numerical-based application that is widely used in modeling currents, waves, and sediment transport in
coastal areas, open seas, estuaries, and rivers [7]. Surface current modeling using DHI MIKE 21 Flow Model FM is a model package used for 2-dimensional modeling (average to depth) with the consideration that the study location is shallow water and the estuary type is classified as unstratified estuary (water mass is perfectly mixed).

The complexity of the estuary waters becomes interesting to study because of the mixing of seawater and freshwater masses. The Jeneberang River flows through Makassar City, including the upstream area in the Bawakaraeng Mountains, Gowa district, and the downstream area in the Makassar Strait. The dynamics of surface currents at the study site are very dominantly influenced by tidal currents and seasonal variations (monsoon). The existence of a rubber dam near the downstream of the river causes the influence of the river current to be very weak. The distinctive characteristics of the Jeneberang estuary are very important to study. Several previous studies were conducted in this location such as [8][9][10][11][12]. The objective of this study was to analyze the dynamics of surface currents in the Jeneberang estuary based on the tidal and monsoon periods with a numerical model approach.

2. Research methods

2.1. The area study

The area study is located in the waters of the Jeneberang Estuary, South Sulawesi Province which is geographically located between 5º 09’ 40” to 5º 13’ 40” south latitude and 119º 22’ 00” to 119º 26’ 10” east longitude. Measurement of surface currents was using a current meter type flowatch fl03 was carried out at 14 points consisting of 7 points in estuary waters and 7 points in coastal waters. The research location is a modified estuary with a dam that limits the river area and the estuary. The existence of the dam still carries water from the river to the estuary through the surface of the dam, but the tide flow from the coastal area cannot pass through the dam into the river. The position of the dam is approximately 3 km before the mouth of the estuary. The map of the research location is in Figure 1.

Figure 1. Research site map
2.2. Model Parameters

This research used a numerical model with a finite element approach based on the DHI MIKE user interface software developed by the Danish Hydraulic Institute (DHI) Water and Environment, Denmark [7]. The modeling simulation time was 720 hours. The equations used in the model are continuity and momentum equations [13].

The continuity equation;

$$\frac{\partial \xi}{\partial t} + \frac{1}{\sqrt{G_x G_y}} \frac{\partial (d + \xi) u \sqrt{G_y}}{\partial x} + \frac{1}{\sqrt{G_x G_y}} \frac{\partial (d + \xi) v \sqrt{G_x}}{\partial y} = (d + \xi) Q.$$  (1.1)

$$U = \frac{1}{d + \xi} f_{d} u \, dz = \int_{-1}^{0} u \, d\phi$$  (1.2)

$$V = \frac{1}{d + \xi} f_{d} v \, dz = \int_{-1}^{0} v \, d\phi$$  (1.3)

The momentum equation for the x and y axis;

$$\frac{\partial u}{\partial t} + \frac{u \, \partial u}{\sqrt{G_x}} \frac{\partial}{\partial x} + \frac{v \, \partial u}{\sqrt{G_y}} \frac{\partial}{\partial y} + \frac{\omega \, \partial u}{d + \xi} \frac{\partial}{\partial z} + \frac{\nu \, \frac{\partial v}{\sqrt{G_x} \sqrt{G_y}}}{\partial x} + \frac{\nu \, \frac{\partial v}{\sqrt{G_x} \sqrt{G_y}}}{\partial y} - f v =$$

$$- \frac{1}{\rho_0 G_x} P_x + F_x + \frac{1}{(d + \xi)^2} \frac{\partial}{\partial z} \left( V_x \frac{\partial u}{\partial z} \right) + M_x$$

(2)

$$\frac{\partial v}{\partial t} + \frac{u \, \partial v}{\sqrt{G_x}} \frac{\partial}{\partial x} + \frac{v \, \partial v}{\sqrt{G_y}} \frac{\partial}{\partial y} + \frac{\omega \, \partial v}{d + \xi} \frac{\partial}{\partial z} + \frac{uv}{\sqrt{G_x} \sqrt{G_y}} \frac{\partial v}{\partial x} + \frac{uv}{\sqrt{G_x} \sqrt{G_y}} \frac{\partial v}{\partial y} - f u =$$

$$- \frac{1}{\rho_0 G_y} P_y + F_y + \frac{1}{(d + \xi)^2} \frac{\partial}{\partial z} \left( V_y \frac{\partial v}{\partial z} \right) + M_y$$

(3)

The explanation: $\xi =$ Water Level (m), $G_x, G_y =$ Transformed Coefficients of Coordinates from curvilinear into rectangular, $d =$ Depth (m), $u, v, \omega =$ Water velocity in x, y, z direction respectively (m.s$^{-1}$), $Q =$ Other Contributions per unit area, $P = $ Hydrostatic pressure gradient (kg.m$^{-2}$.s$^{-2}$), $M =$ Moment Value (ms$^{-3}$), $F =$ Turbulent motion flow (ms$^{-2}$), $f =$ Coriolis impact, $V_x =$ Vertical Eddy Viscosity (m$^{-3}$), $\rho_0 =$ Reference density of water (kgm$^{-3}$).

The domain model used finite elements which were applied in discretization. The elements used were made with varying sizes to reduce the computation time. The size of the detail element is made in the study area, while for elements that were located far from the study area, a large element size is made. The description of the domain and the shape of the model elements are presented in Figure 2.

The generating factors of the model used were tides, wind, depth, and river water discharge. The research location is in the area of the Makassar Strait waters, which is water through which Indonesian through flows (Arlindo) carrying water masses from the Pacific Ocean to the Indian Ocean. However, this model did not include these variables because the observation area is estuarine and shallow (barotropic) coastal waters.

The tidal data used as the open boundary of the model is prediction data from AG95 (updated to Andersen 2006) developed by Baltazar Andersen. This model is a global tidal prediction model with a resolution of 0.125° x 0.125° which is assimilated data from TOPEX/Poseidon data using the finite element approach. The description of tidal data as model input is presented in Figure 3.

The wind data that was input into the model was obtained from the ECMWF (European Center for Medium-Range Weather Forecasts). They were resulted from reanalysis of data from the combined data of the World Meteorological Agency. Wind data had a time interval of 3 hours with a spatial resolution of 1.50 x 1.50 with global coverage. The wind data used was the west monsoon and east monsoon in the years of 2015. The direction and speed of the wind for model input are presented in Figure 4.
Figure 2. Discretization of the model in the finite element

Figure 3. Tidal data input into the model. (Source: prediction data from AG95)
Figure 4. The wind data for generating of the model (Source; ECMWF-European Centre for Medium-Range Weather Forecasts)

The model was validated by comparing the model with the measurement results. The model validation used tidal and current data which was visualized in the form of a graph and is based on the correlation coefficient value of the measurement data and model output. The configuration of the hydrodynamic model is presented in Table 1.

Table 1. The configuration of the hydrodynamic model

| Number | Parameters               | Remarks                                                                 |
|--------|--------------------------|-------------------------------------------------------------------------|
| 1      | Domain of model          | Finite elements                                                         |
|        |                          | Number of points = 14193                                                 |
|        |                          | Number of triangle finite elements = 26883                               |
| 2      | Time steps               | Interval time step 30 seconds                                            |
|        |                          | Number time step 43200                                                  |
| 3      | Flood and dry            | Depth 0.005 m (always dry)                                              |
|        |                          | Depth 0.05 m (sometimes dry and wet)                                    |
|        |                          | Depth 0.1 m (always wet/waterlogged)                                    |
| 4      | Density                  | 1025 kg/m$^2$ (barotropic)                                              |
| 5      | Viscosity eddy constant  | 0.28 (based on Smagorinsky formula)                                     |
| 6      | Bed resistance           | Varied by domain areas based on Manning’s number                         |
| 7      | Coriolis forcing         | None                                                                     |
| 8      | Wind forcing             | varied by time and constant in domain areas                             |
| 9      | Precipitation-evaporation| None                                                                     |
| 10     | Wave radiation           | None                                                                     |
| 11     | Initial condition        | Elevation = 0                                                           |
|        |                          | Current vectors $u$ and $v = 0$                                          |
| 12     | Boundary condition       | Tide (varied by times and domain areas)                                 |
|        |                          | River debit (varied by times)                                           |
|        |                          | Land (0)                                                                |
| 13     | Time of simulation       | West monsoon                                                            |
|        |                          | East monsoon                                                            |
| 14     | Length of simulation     | 720 hours                                                               |

3. Result and discussion

3.1. Validation of the model
Validation of the model was done by comparing the model output with measurement data on the parameters of tidal water level elevation and current components at the same position and time. The validation results showed the suitability of the model output with the measurement data which was marked by the similarity of the graphic visualization and the correlation coefficient value obtained is
greater than 50%. The model validation for the tidal level elevation parameters is presented in Figure 5 and the current parameters are presented in Figures 6 and 7.

**Figure 5.** Model validation with tidal parameter

**Figure 6.** Model validation with current velocity
The pattern of the tidal water level elevation graph from the model and the measurement data showed similarities. The results of the analysis of the correlation coefficient of tidal water level elevation of 0.858 showed a very strong relationship that indicating the model output obtained was valid.

Validation of the model with current velocity data showed a similar graphic pattern at some points but at some other points they were different. The difference was due to the data from the current velocity measurement results only available in form of instantaneous data and not using a fixed measurement point that should be measured continuously over a certain period time or time-series data. Likewise, the validation with the current vectors showed that the current vectors were the same at some points and other parts different. In general, the dynamics of the current movement tended to be very similar in the east season compared to the west season. This occurred because the current pattern in the east season was more stable due to the weak influence of the river current. The results of the analysis of the correlation coefficient of the current velocity component obtained a correlation

Figure 7. Validation model with current vectors
coefficient of 0.653 for the west season and 0.697 for the east season), while the current direction component with a correlation coefficient value of 0.887 for the west season and 0.857 for the east season.

3.2. Velocity and current direction
The pattern of surface currents at the study site was strongly influenced by tidal currents. Tidal currents flowed back and forth, where the current flowed to the south at high tide and vice versa to the north at low tide. The current flowed southward at high tide due to the strong influence of the Pacific water masses that pushed the water masses towards the south, while at low tide the water masses reversed direction to the north due to the weakening of water masses from the Pacific. At the same time, there was a decrease in the water level in the north at low tide, while the propagation of the water mass from the Indian Ocean strengthened so that the water mass flowed northward at low tide.

Figure 8. The average current velocity direction in the west monsoon (above) and east monsoon (below)
The current pattern obtained was in line with the research results of [14] that the current pattern in the coastal waters of Makassar City was influenced by tidal currents that flow from north to south at high tide and vice versa from south to north at low tide. The study area was shallow coastal water that caused current pattern formed to be dominantly influenced by tidal currents. This was also corresponding with [15] that the dominant tidal currents are observed in coastal waters.

The analysis of the average current velocity direction (Figure 9) showed the dominant current pattern towards the south which was seen in the west and east monsoons. The maximum current velocity in the west monsoon was 0.50 m/s and in the east monsoon, it was 0.40 m/s. Maximum current velocity was formed around the islands of the Spermonde Archipelago and within the estuary area. The current velocity in the west monsoon was higher than the east monsoon due to the influence of the strong winds which was greater in the west monsoon. The range of wind speed in the west monsoon was 2-8 m/s while its range in the east monsoon was 2-6 m/s. The increasing of current velocity around the islands of the Spermonde Archipelago occurs due to changes in depth which cause the water mass to accumulate when entering shallow water, resulting in a larger flow of water. As for the estuary, the increase in current velocity was due to the strong thrust of the water mass from the river in the west monsoon.

The description of the current pattern based on the tidal flow consists of four groups, they were towards high tide, at maximum high tide, towards low tide, and at minimum low tide. In the west monsoon, the current pattern when the water flowed towards high tide until it reached maximum high tide was towards the south. At towards low tide, the current reversed direction to the north and at minimum low tide it returned to the south. In the east monsoon, towards high tide showed the same pattern in the west monsoon, but at maximum high tide the current had reversed direction to the north at the shallow coast; but on the deep coast the current was still heading south. When the water flowed toward low tide, the current turned north again and at minimum low tide the current pattern returned to the same direction with period of maximum tide. Current patterns based on tidal periods were presented in Figures 10, 11, 12, and 13.

Current patterns, in addition to being influenced by tides, were also influenced by monsoons. These could be clearly seen around the high seas area because influences of land were relatively small which was barrier to wind impulses so that a larger current velocity was obtained. The current velocity in areas far from the coast ranged 0.1-0.5 m/s, while current speeds in areas near shore ranged 0.01-0.1 m/s. The maximum current velocity in the west monsoon occurred towards low tide and the maximum current velocity in the east monsoon occurred towards high tide. The maximum current velocity formed in the waters far from the coast indicated a strong influence of the monsoon. In the west season, the wind blow from the west and northwest causing the current to move northward to strengthen so that the maximum current velocity in the west season occurred when the current was heading north. In the east monsoon, the wind blow from the east and southeast, causing the southward current to strengthen.

In general, the current velocity around coastal waters tended to be stronger at high tide than at low tide. This was in line with [16] who stated that current patterns that occurred in Indonesian waters were influenced by tidal and monsoon phenomena. The main wind that blow in the Makassar Strait was the monsoon which experienced a reversal of direction twice a year due to differences in air pressure over the Asian and Australian continents. In December–February the wind usually blows from the Asian continent to Australia (from west to east) so it is called the west monsoon (northwest monsoon), so that in the Makassar Strait the wind blows from north to south. In June–August the wind tends to blow from Australia to Asia (from east to west) so it is called the east monsoon (southeast monsoon), the wind blows from southeast to south.
Figure 9. Velocity and current direction in the west monsoon
(a) = toward high tide, (b) = maximum high tide
A = current vector distribution, B = tide, C = wind
Figure 10. Velocity and current direction in the west monsoon
(a) = toward low tide, (b) = minimum low tide
A = current vector distribution, B = tide, C = wind
Figure 11. Velocity and current direction in the east monsoon
(a) = toward high tide, (b) = maximum high tide
A = current vector distribution, B = tide, C = wind
Figure 12. Velocity and Current Direction in the East Monsoon
(a) = toward low tide, (b) = minimum low tide
A = current vector distribution, B = tide, C = wind
In addition to being influenced by tides and monsoons, current patterns were also influenced by the topographic of the land and seabed as well as the presence of small islands of the Spermonde Archipelago around west coast sea of Makassar City. At points where land masses were jutting into the sea (headlands) that served as barriers, the currents from the high seas were damped by the presence of headlands, which causes the current to weaken in areas near the shoreline. Meanwhile, the maximum current velocity seen in the high seas around the Spermonde Islands was due to changes in depth and when the current passed through the gap between the islands, the current strengthened due to the accumulation of water masses that passed through the gap so that the thrust of the water mass was greater. This was in line with the principle of the continuity equation that the mass of water entering and leaving an environmental medium is the same so that when it passes through a gap, the current accelerates to reach the equilibrium point.

4. Conclusion
The dominant current pattern around the coastal waters and the Jeneberang estuary was a tidal current that flows back and forth, where at high tide, it went to the south and at low tide it went to the north. The maximum current velocity occurred towards low tide in the west monsoon and towards high tide in the east monsoon. The monsoon effect was very strong in generating a mass flow of water at the study site. The pattern of west monsoons blowing from the west and northwest produces a mass flow of water to the north following the Ekman transport (water flow is deflected to the left in the southern hemisphere from the direction of the wind) causing the maximum velocity of the current in the west monsoon to occur at low tide with the current direction was north. In the east monsoon, the current flowed to the south due to the wind from the east and southeast so that the maximum current velocity during the east monsoon occurred when the water went to high tide with the flow direction to the south.

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