Three-Dimensional Numerical Modelling of Tidal Current in Balikpapan Bay Using Delft3D

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Abstract. Balikpapan is one of the main port cities with residential areas, industry, trade, and vital objects scattered from north to south along the coast of Balikpapan Bay. This dense activity increases traffic in Balikpapan Bay. Thus, the hydrodynamic conditions in these waters are essential to be reviewed. The purpose of this research is to simulate hydrodynamics in Balikpapan Bay. The simulation results of the hydrodynamic model for sea-level elevation values are close to the conditions in the field, as indicated by the correlation coefficient 0.98, skill 0.99, and RMSE 0.15 m.

The ocean current velocity verification includes the average correlation for x-direction and y-direction, up to 0.93, RMSE 0.05 m, and the percentage error of 6.7%. The significant current velocity is at low tide during spring tide with an average of 0.1 m/s and a maximum speed of 1.62 m/s. Temporally, the observation point at the mouth of Balikpapan Bay has the most significant Bed Shear Stress magnitude with an average of 0.05 N/m². Spatially, the highest Bed Shear Stress magnitude is at the time of spring tide when it recedes towards the tide with an average Bed Shear Stress in the bay of 0.16 N/m². The most dominant tidal components are M\textsubscript{2} and S\textsubscript{2}, with a contribution value of 65.3%. The phase propagation from mouth to upstream of Balikpapan Bay for the M\textsubscript{2} component in Balikpapan Bay is 10.5° (22.77 minutes) and 5.5° (11 minutes) for the S\textsubscript{2} component.

1. Introduction

Balikpapan is located on the East Coast of Kalimantan Island, directly adjacent to the Makassar Straits, and functions as a shipping and port city. As one of the main port cities, Balikpapan has many residential areas, industry, trade, and vital objects along its coast. The entire area is scattered along the coast from the north coast to the south [18].

The coastal area of Balikpapan Bay has a coastline of 79.6 km. There are about 31 small uninhabited islands with a total land area of around 1018.86 hectares [31]. Balikpapan Bay is also included in the new capital area of Indonesia. With these facts, the coastal area of Balikpapan Bay is attractive for the development of various activities, which increase in industrial, residential, and commercial activities. In addition, those activities will increase waste production, which will generally be carried by the river flow into Balikpapan Bay and will be impacted various aspects, such as water pollution and deposition. Hence, the hydrodynamic conditions in these waters must be reviewed. It is essential to know about the hydrodynamic condition of the water because it dramatically influences the processes, for example, the distribution of sediments, pollutants, and oil spills, as well as the biotic activities of waters which are influenced by the distribution of nutrients, temperature, and salinity. The hydrodynamic condition of...
the water is influenced by several factors, including coastal morphology, bathymetry, river run-off, air mass effects, and tides. One of the physical and dynamic phenomena encountered in coastal areas is the periodic rise and fall of the water surface caused by tidal waves and river flows [27]. Tides also play an essential role in vertical mixing, so developing high-resolution 3D tidal models is necessary to investigate the source and internal tidal variability [7].

Balikpapan Bay are dynamic waters due to the domination of rivers and tides, which impact salinity, circulation patterns, and sedimentation [13]. The effect of tidal forces will cause different seawater mass input based on the conditions of the water. The mass of seawater will flow towards the estuary with a further distance at high tide, while at low tide, the seawater will return to the sea [32].

Research on hydrodynamic modeling in Balikpapan Bay has been carried out, especially in the study of hydrodynamic models to determine tidal front patterns using cophase and corange maps in Balikpapan Bay [24], 2D hydrodynamic modeling with a focus on the domain area in the bay [28], and a study of 3D tidal flow patterns in Balikpapan Bay using MOHID [11].

This study will analyze the hydrodynamic pattern of Balikpapan Bay with a more comprehensive three-dimensional domain area using the Delft3D numerical model. Numerical models describe hydrodynamic patterns spatially and temporally from phenomena in the field so that predictions can be made of various scenarios. As a result, it can be used for further research. This study simulates hydrodynamics in the Bay of Balikpapan, East Kalimantan, with tidal forces and river discharge. This research also analyzes the bottom currents, bed shear stress, cophase, and corange to understand the dynamics of the Balikpapan Bay area.

2. Materials and Methods
2.1. Study Area
The study area in this research is located in Balikpapan Bay, East Kalimantan, Indonesia. The model domain contains the waters of Balikpapan Bay and a small part of the Makassar Strait. Balikpapan Bay is the estuary of several rivers, including the Wain River, Semoi River, and Riko River.

2.2. Data
Input data in this study used bathymetry, tide elevation, and river discharge. This data is used to design a model to produce elevation and current velocity output, both temporal and spatial. The bathymetry data used in the model simulation were obtained from the National Bathymetry (BATNAS). The spatial resolution of the BATNAS data is six arc-second using the MSL (Mean Sea Level) datum (tides.big.go.id). This data is overlaid with observational data, which is also corrected by the MSL datum. Mean Sea Level (MSL) is a height reference for determining altitude on land and is very commonly used. The simulation time is for one month, which is February 1 – 28, 2019. The tide elevation data used in the model simulation is obtained from the prediction results taken from the TPXO 9 data (info.bwgeohydromatics.com). River discharge data were obtained from the Erosion and Sedimentation Working Group (2002), including the Semoi, Wain, and Riko rivers, with each discharge value of 2.47 m³/s; 83.496 m³/s; and 16.582 m³/s. These three rivers are the main rivers that have a significant influence on Balikpapan Bay. The river discharge value used is the monthly average and is assumed to be constant during the simulation. The analysis will be carried out based on tidal conditions for one month, which will be analyzed at spring tide and neap tide in each different sea-level elevation condition.

In this 3D hydrodynamic model, three layers will be used using sigma coordinates, with each layer having a different thickness. The top layer near the surface has a greater thickness (50%), and the layer near the bottom has the smallest thickness (20%), while the middle layer is the rest (30%). The grid used is rectangular with spherical coordinates with origin x and y, respectively 116.53 and -1.48. In figure 1 shows the verification and observation points in the model domain.
2.3. Hydrodynamics model

The hydrodynamic simulation in this study uses a model from Delft3D-FLOW. Delft3D-FLOW solves the Navier Stokes equation for incompressible fluids in shallow water using the Boussinesq approach [4]. In the 3D model, the vertical velocity is calculated from the continuity equation. The partial differential equation is converted into discrete with a finite-difference grid. Delft3D-FLOW uses curvilinear orthogonal coordinates in both cartesian ($\xi, \eta$) and spherical ($\lambda, \phi$) coordinates. The Delft3D model continuity equation used is as follows.

$$\frac{\partial \xi}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial}{\partial \xi} \left( (d + \xi)U \sqrt{G_{\eta\eta}} \right) + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial}{\partial \eta} \left( (d + \eta)V \sqrt{G_{\xi\xi}} \right) = (d + \xi)Q \tag{1}$$

where,

$$U = \frac{1}{d + \xi} \int_{d}^{\xi} u \, dz = \int_{-1}^{0} u \, d\sigma \tag{2}$$

$$V = \frac{1}{d + \eta} \int_{d}^{\eta} v \, dz = \int_{-1}^{0} v \, d\sigma \tag{3}$$

$$Q = \int_{-1}^{0} (q_{in} - q_{out}) \, d\sigma + P - E \tag{4}$$

The momentum equation for the Delft3D model is used as follows.

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + \frac{w}{d + \xi} \frac{\partial u}{\partial \sigma} - \frac{v^2}{G_{\eta\eta}} \frac{\partial}{\partial \eta} \sqrt{G_{\xi\xi}} \frac{\partial \xi}{\partial \xi} + \frac{uv}{\sqrt{G_{\xi\xi}}} \frac{\partial}{\partial \eta} \sqrt{G_{\eta\eta}} \frac{\partial \eta}{\partial \eta} - fv \tag{5}$$

$$= - \frac{1}{\rho \sqrt{G_{\xi\xi}}} \partial P_{z} + F_{z} + \frac{1}{(d + \xi)^2} \frac{\partial}{\partial \sigma} \left( \nu \frac{\partial u}{\partial \sigma} \right) + M_{z}$$
y-axis:
\[
\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial v}{\partial \xi} + \frac{w}{\sqrt{G_{\eta\eta}}} \frac{\partial v}{\partial \eta} + \frac{v}{\sqrt{G_{\xi\eta}}} \frac{\partial v}{\partial \xi} + \frac{u^2}{\sqrt{G_{\xi\xi}}} \frac{\partial v}{\partial \eta} + fu = -\frac{1}{\rho_0 \sqrt{G_{\eta\eta}}} \partial P + F + \frac{1}{(d + \xi)^2} \partial \left( \frac{v^2}{P} \frac{\partial v}{\partial \sigma} \right) + M
\]

where,
\( U, V \): average velocity concerning horizontal depth (m/s)
\( u, v \): velocity in directions \( \lambda \) and \( \phi \) (m/s)
\( f \): Coriolis parameters (1/s)
\( \rho_0 \): water density (kg/m\(^3\))
\( \lambda \): longitude in spherical coordinates
\( \phi \): latitude in spherical coordinates
\( P_{\xi}, P_{\eta} \): hydrostatic pressure gradient (kg/m\(^3\)s\(^2\))
\( F_{\xi}, F_{\eta} \): horizontal stress Reynold (m/s\(^2\))
\( M_{\xi}, M_{\eta} \): external momentum (m/s\(^2\))
\( H \): total depth (m) = \( d + \xi \)
\( d \): water depth (m)
\( \zeta \): water level elevation (m)
\( Q \): discharge (m\(^3\)/s)
\( R \): earth radius (6378.137 km)
\( \nu_v \): vertical eddy viscosity (m\(^2\)/s)
\( q_{in} \): inflows (sources) per unit volume (1/s)
\( q_{out} \): discharge (sinks) per unit volume (1/s)
\( P \): non-local precipitation (source)
\( E \): non-local evaporation (sink)

2.4. Bed Shear Stress
Shear stress measures the friction force of the fluid on the object in which the fluid passes. Bed shear stress can be defined as the measurement of friction force of the fluid on the waterbed. In this study, the Delft3D model calculates the shear stress at the bed:

\[
\tau_{b3D} = \frac{g \rho_0 |\vec{u}_b|}{C_{3D}^2}
\]

where,
\( |\vec{u}_b| \): the amount of horizontal velocity in the first layer just above the bed (m/s)
\( g \): gravitation (m/s\(^2\))
\( \rho_0 \): density (kg/m\(^3\))
\( C_{3D} \): chezy coefficient (m\(^{1/2}\)/s)

3. Results and Discussion
3.1. Model Verification
Tide elevation verification is carried out on time series data throughout the simulation from February 1 – 28, 2019, at the tide measurement location for the Geospatial Information Agency (BIG) (-1.27°S and 116.80°E) (figure 2). In addition, the model result data is overlaid with BIG measurement data at the same time and location. The results of the elevation overlay can be seen in figure 2.
Figure 2. Verification of sea level elevation from February 1 – 28, 2019, at the tide measurement location for the Geospatial Information Agency (BIG) (-1.27°S and 116.80°E)

Verification for the correlation coefficient is 0.98 (close to 1), which means that the relationship between the model results and the data is excellent. The result of skill calculation is close to 1 (0.99). The error value from the RMSE calculation is 0.15 m, which means that the model results are acceptable. For all the calculations to assess the accuracy of the model results, it can be concluded that the simulation results of the hydrodynamic model of sea-level elevation can represent the actual conditions.

Current velocity verification is done by comparing the digitized observation data with the model simulation data. The result of observation of current velocity refers to a study entitled 'The dynamics of water mass in Balikpapan Bay' [21]. The current verification points are at -1.12°S and 116.75°E. The results of the flow verification can be seen in figure 3.

Figure 3. Verification of the current velocity between the model results and observations.

The average correlation coefficient is 0.93, which means that the observation and model data are related. Furthermore, the error value of the RMSE calculation, which is relatively small (0.05 m), indicates that the model is acceptable. Moreover, the last one is the average from the Mean Absolute Percentage Error (MAPE), which is 6.7%, the MAPE value at the x-direction and y-direction current velocity vectors are 5.86% and 7.53%, respectively.

3.2. Cophase and Corange
Tidal wave propagation in Balikpapan Bay is carried out with corange (amplitude) and cophase (phase) maps of the semidiurnal and diurnal harmonic components, including M$_2$, S$_2$, K$_1$, and O$_1$. Figure 4 shows the corange of each component. The amplitude value at the open boundary ranges from 0.46 m, then increases at the bay's mouth to about 0.49 m, and when arriving at the upper reaches of the bay, about 0.50 m. Figure 5 shows the cophase of each component. The M$_2$ tidal wave amplitude propagation pattern shows a regular pattern, where the tidal wave amplitude moves into the bay from the Makassar Strait. The cophase map shows that the M$_2$ tidal wave propagation moves from the Makassar Strait and enters Balikpapan Bay. At the bay's mouth, the M$_2$ phase is about 289°, and arriving at the upstream or bay head is about 300°. The time required for the M$_2$ wave component in Balikpapan Bay is about 22.77 minutes, with a distance from the mouth to the upstream of the Bay ± 33 km, so the wave propagation velocity of M$_2$ is 24.18 m/s.

![Figure 4](image)

Figure 4. Corange of components (a) M$_2$; (b) S$_2$; (c) K$_1$; and (d) O$_1$

The wave propagation pattern of the S$_2$ component shows that the smallest amplitude value is in the open boundary area. The cophase map shows that the tidal wave propagation of S$_2$ moves from the Makassar Strait and enters Balikpapan Bay. At the bay's mouth, the S$_2$ phase is about 334.5°, and upon arrival at the head, the value is around 340°. The time required for the S$_2$ component wave in Balikpapan Bay is about 11 minutes, with a distance from the mouth to the Bay ± 33 km upstream, so the wave propagation velocity is 50 m/s.

The K$_1$ tidal wave phase propagation moves from the Makassar Strait and propagates into Balikpapan Bay. At the bay's mouth, the K$_1$ phase is about 155.5°, and at the head of the bay, it is about 158°. The amplitude of the K$_1$ component at the open boundary ranges from 0.26 m, then increases at the mouth of the bay to about 0.27 m, and when it arrives at the bay head, about 0.29 m. The time required for the K$_1$ wave component in Balikpapan Bay is about 10 minutes, with a distance from the mouth to the head of the Bay ± 33 km, so the wave propagation velocity of the K$_1$ wave is 55.22 m/s.

The amplitude of the O$_1$ component at the open boundary ranges from 0.16 m, then increases at the bay's mouth to about 0.179 m, and at the bay head, about 0.19 m. Cophase of component O$_1$ shows that the tidal wave phase propagation O$_1$ moves from Makassar Strait and enters Balikpapan Bay. At the bay's mouth, the O$_1$ phase is around 135.5°, and at the head of the bay, it is about 138°. The time required...
for the wave $O_1$ component in Balikpapan Bay is about 10.75 minutes, with a distance from the mouth to the head of the Bay ± 33 km, so the wave propagation velocity $O_1$ is 51.21 m/s. Based on the corange map of model simulation results, $M_2$ and $S_2$ components are relatively more dominant than diurnal components ($K_1$ and $O_1$). This is influenced by the tidal type of Balikpapan Bay which is a mixed type inclined semidiurnal. Components $M_2$ and $K_1$ are the dominant components that affect tidal patterns in Indonesian waters. The $M_2$ component waves in the Banda Sea will move to the north of the Maluku Sea, while from the Flores Sea, it will move north through the Makassar Strait and west to the Java Sea [34].

![Figure 5. Cophase of components (a) $M_2$; (b) $S_2$; (c) $K_1$; and (d) $O_1$ at Balikpapan Bay](image)

3.3. Tidal current patterns
The spatial pattern of sea-level elevation and the currents magnitude and velocity are plotted under two different conditions, namely during spring tide and neap tide. Spring tide is a condition when the sun, earth, and moon are in a straight line. This position causes the two bulges of the sea level by the gravitational and centrifugal forces acting on the earth to be slightly larger than usual. This condition causes the water level elevation to be higher than the average water level, and at high tide, the water level to be lower than the average water level. Then, four conditions were sampled in these two conditions: high tide, low tide, flood tide, and ebb tide. These four conditions are expected to describe the hydrodynamic conditions in these waters well. Variations in sea level can be seen from the movement of tidal currents from the open boundary (Makassar Strait) to Balikpapan Bay. A sampling of the state of the spring tide was taken on February 19, 2019, where based on data calculations by BMKG, there was a high tide caused by the full moon, which coincided with perigee.

At low tide, the elevation height ranges from about -1 m to 0 m. The current velocity at low tide has a low velocity with an average of 0.06 m/s, with a range of 0 m/s to 0.70 m/s. The highest current velocities are seen in the narrow area at the head of the bay. During low tide, the current moves from inside the bay to the outside of the bay. At the bay head, the current velocity magnitude is 0.08 m/s. The current continues to move until it reaches the center of the bay and reduces to 0.04 m/s.
The increase and decrease from one condition to another at each observation point has a different pattern. The change in velocity magnitude between tidal conditions is calculated by reviewing the velocity value at each observation point (one grid) and then calculating the difference in the percentage magnitude of the velocity magnitude between the grids. When the current reaches point C at the river mouth (figure 1), the magnitude continues to decrease by 33%. At the mouth of the bay, the current velocity magnitude increases again by 48%.

During flood tide, the elevation is in the range of about -0.24 m to 0.13 m. At this condition, the lowest elevation is still upstream of the bay but slightly higher than at low tide. The variation in sea level in the bay is very significant, with a height difference of 0.37 m, while the variation in sea level outside the bay tends to be uniform. The current velocity in this phase has the highest value, which is in the range of about 0 m/s to 1.62 m/s, with the highest speed spread almost evenly from upstream to the mouth of the bay. This is because flood tide or ebb tide is a condition where the current velocity will be maximum. Current velocity weakens around the Rico River, Wain River, and Semoi River, shallower locations.

Meanwhile, certain parts upstream to the mouth with deeper bathymetry have higher current velocities than those around the coast. The relatively deeper depth in the Semoi River's body and the central part of Balikpapan Bay results in greater current velocity in the area compared to the surrounding area [30]. Compared to the previous situation, at flood tide conditions, the magnitude of the current velocity increases very significantly, reaching 50% in the bay head (point A), 659% in the bay (point B), 680% at the river mouth (point C), and 481% at the mouth of the bay (point D).

Figure 6. The spatial plot of the depth-averaged velocity vector at spring tide (a) lowest tide; (b) flood tide; (c) highest tide; (d) ebb tide.
The current velocity has a small value (figure 6), ranging from 0 m/s to 0.67 m/s. The current movement moves from outside the bay to the bay (northwest). The highest current velocity magnitude is 0.15 m/s (point C). The velocity at the observation point at the head and mouth of the bay is 0.13 m/s and 0.06 m/s, respectively. The elevation is in the range of 0 m to 1.55 m. In high tide conditions, the highest sea level elevation is at the head of the bay, and the elevation decreases when it gets closer to offshore with an average elevation value of 1.18 m. Compared to the previous situation, the current velocity magnitude decreases to 72% at the mouth of the bay (point D), 32% at the mouth of the river (point C), 57% at the center of the bay (point B), and 88% at the head of the bay (point A).

Then at ebb tide, the current velocity increases with a magnitude reaching 1.43 m/s—the current moves from inside the bay to the open sea (southeast). The elevation is in the range of -0.05 m to 0.24 m. In ebb tide conditions, the highest sea level elevation is at the head of the bay, and the elevation decreases as it gets closer to the open sea. The current velocity in the ebb tide condition is quite varied, with the highest current speed being at the bay's mouth, which is 0.25 m/s (increases 270% from the previous condition).

From the four observation points observed under these conditions, the magnitude of the current velocity upstream of the bay is 0.31 m/s. The area around the mouth of Balikpapan Bay also has a high current velocity due to the shape of the bay's mouth, which is larger than the body of the bay. In this condition, the velocity magnitude at the bay's mouth at the observation point is 0.24 m/s. Due to the geographical condition of the bay, where the mouth is wider than the body of the bay and the head of the bay, the current velocity when entering the bay looks stronger [21].

Weakening and strengthening of tidal waves can occur due to the influence of the morphology of the bay estuary and bottom friction. The morphology of the Bay estuary, which has a bathymetry in the form of a narrow slit, can cause reinforcement to occur [16]. This shows that bathymetry and local influences (river discharge) affect the hydrodynamic conditions in Balikpapan Bay. Meanwhile, off the coast of Balikpapan Bay, the smaller residual current values represent the dominant tides at that location [30].

This neap tide condition was selected on February 13, 2019, and four different conditions were reviewed. The time is selected based on the water level's time series, which coincides with the conditions of the lowest high tide and the highest low tide. At high tide, the sea level is in the range of 0 - 0.62 m, with the highest elevation at the head of Balikpapan Bay. The current velocity is higher outside the bay at around 0.47 m/s, precise in the eastern and western parts of the domain (figure 7). The current speed, which tends to be calm, is caused by the state of slack water where no energy can generate currents [11]. The current on the east side moves towards Balikpapan Bay in the southwest direction, while the current on the west side moves towards Balikpapan Bay in the northeast direction. The current around the mouth of Balikpapan Bay is seen back and forth from and into the bay. The lowest current velocity magnitude is 0.02 m/s at point A, while at point B, it is 0.04 m/s, at the mouth of the river (point C), it is 0.04 m/s, and at the mouth of the bay (point D) of 0.06 m/s.

During the ebb tide, the sea level is higher in the open sea than at the head of the bay. The current velocity in the bay ranges from 0 - 0.40 m/s, the values at each observation point from point A-D are 0.05 m/s; 0.02 m/s; 0.04 m/s; and 0.07 m/s, respectively. From high tide to this flood tide condition, there is a 15% increase in the magnitude of current velocity at point D, a decrease of 19% at point C, a decrease of 51% at point B, and an increase of 105% at point A.

During low tide, the sea level elevation is lower than before, in the range of -0.20 m to 0.19 m. As a result, the current velocity in the bay tends to be very small in the range of 0 - 0.05 m/s and tends to move out of the bay. The maximum current velocity is around the bay mouth moving outward towards the southwest with a value of about 0.34 m/s. At the four observation points, there was a decrease of 61% at point D, 17% at point C, 65% at point B, and 32% at point A.

Then during the flood tide, the sea level elevation conditions increased again from the previous condition with a height of around -0.07 - 0.19 m. In this flood tide condition, it can be seen that the current velocity magnitude is in the range of 0 - 0.44 m/s. There is an increase of 689% at point B, while the increase in current speed at point C is 48%, and at point D is 54%. At point A, under the same
conditions, there is a decrease in the magnitude of the current velocity by 71%. Thus, the current velocity vector moves uniformly into the bay (southwest). In the neap tide conditions sampled on February 13, 2019, the highest elevation value was 0.62 m, and the lowest elevation value was -0.57 m, so the tidal range was around 1.19 m. The current velocity magnitude in the narrow area at the head of the bay at high tide has the maximum value of 0.47 m/s, and the minimum current velocity is almost close to 0 in the open sea.

3.4. Bed Shear Stress: Temporal
Temporal bed shear stress is observed at four locations. Observation points A, B, C, and D represent a point at the bay head, a point in the bay, a river estuary, and a bay mouth point. The magnitude of bed shear stress at point A ranges from 0 to 0.08 N/m² with an average magnitude over the simulation time of 0.01 N/m² (figure 8). The fluctuation between the current velocity magnitude and the bed shear stress has a similarity. When the current velocity magnitude increases, the bed shear stress magnitude also increases.
At point B, the magnitude of bed shear stress ranges from 0 to 0.23 N/m$^2$ with an average magnitude over the simulation time of 0.04 N/m$^2$ (figure 9). Then if we move to point C, the magnitude of bed shear stress ranges from 0 to 0.16 N/m$^2$ with an average magnitude over the simulation time of 0.04 N/m$^2$ (figure 10).

Then at a point D (figure 11), the magnitude of bed shear stress ranges from 0 to 0.26 N/m$^2$ with an average magnitude over the simulation time of 0.05 N/m$^2$. Compared with the four observation points, point D has the most significant magnitude of bed shear stress, and point A is the opposite. This is due to the enormous magnitude of the high current velocity around the bay mouth by the deeper bathymetry.
3.5. **Spatial Bed Shear Stress**

Knowledge of bed shear stress is needed to relate sediment distribution and hydrodynamics. Types of sediment classify Balikpapan Bay as cohesive sediments with a maximum critical shear stress of 0.07 N/m². Critical shear stress in the cohesive area ranges from 0.02 to 0.07 N/m² and varies spatially and temporally [6]. In other words, if the magnitude of the bed shear stress exceeds the magnitude of the critical shear stress, erosion will occur due to the current at the bottom.

**Figure 12.** The spatial plot of bed shear stress (left) and current velocity magnitude at the bottom (dz = 1 m) (right) at low tide during spring tide

**Figure 13.** The spatial plot of bed shear stress (left) and current velocity magnitude at the bottom (dz = 1 m) (right) at flood tide during spring tide

**Figure 14.** The spatial plot of bed shear stress (left) and current velocity magnitude at the bottom (dz = 1 m) (right) at high tide during spring tide
At low tide during the spring tide, the pattern shown from the two is quite similar, with the magnitudes of both being the most dominant on the northeast and southwest side of the domain (figure 12). Again, the white area is a location where the BSS value is minimal (close to 0) because this area is the location of the deeper open seas so that the current velocity at the bottom is minimal (close to 0).

During the flood tide (figure 13), when the magnitude of the current speed increases significantly, especially from the head to the inside of the bay, the BSS magnitude value in the same area also increases significantly (BSS average increases by 0.03 N/m²). This very high BSS value indicates that massive erosion can occur in Balikpapan Bay under these conditions. At high tide, the magnitude of the current velocity decreases as the BSS decreases. Several red spots indicate high BSS magnitude in some parts of the bay with deeper bathymetry (figure 14).

The BSS spatial pattern was similar to the previous flood tide conditions at ebb tide, increasing significantly in the bay area with an average BSS of 0.06 N/m² for the entire domain area (figure 15). However, the average BSS value in this condition is still lower when compared to the previous flood tide condition, which had an average BSS in the Bay of 0.16 N/m².

4. Conclusion

The simulation results of the hydrodynamic model for the sea level elevation value can represent the condition of the waters in Balikpapan Bay, as indicated by the correlation coefficient value obtained of 0.98; 0.99 for skills value; and 0.15 m for RMSE. Current verification obtained includes the mean x-direction and y-direction vector correlation of 0.93; RMSE 0.05 m; and a percentage error of 6.7%. The corange map shows the amplitude values of M₂ and S₂ components dominating the tides in Balikpapan Bay by 65.3% of the other tidal components. The phase propagation from mouth to head of Balikpapan Bay for the M₂ component in Balikpapan Bay is 10.5° (22.77 minutes) and 5.5° (11 minutes) for the S₂ component. Significant current velocity is at flood tide during spring tide with an average current speed of 0.10 m/s and the highest speed of 1.62 m/s in a narrow area at the head of the bay. The magnitude of the current velocity largely determines the value of the BSS magnitude. The observation point at the mouth of Balikpapan Bay (point D) has the most significant BSS magnitude value with an average of 0.05 N/m². Spatially, the highest BSS magnitude value is at flood tide during spring tide with an average BSS of 0.16 N/m².

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