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Beach Morphology Changes Due to Sediment Transport Generated by Wave and Current in The Sea Waters of Bengkulu City, Indonesia

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Abstract

Bengkulu City which is located on the west coast of Sumatra Island has a very prospective to be developed for marine, fisheries, tourism, and maritime businesses. However, the coast of Bengkulu has recently changed in its morphology as a result of high sedimentation processes. The purpose of this study is to determine the direction and speed of currents, waves, and sediment transport that cause the changes in the coastal morphology of Bengkulu City. In this study, numerical modeling and field measurements of the current velocity and wave height of the ocean were used. The results of the research show verification of wave height and velocity of ocean currents between model simulation and field measurement is a fairly good fit, with a Mean Absolute Percent Error (MAPE) of 1.5% for wave height and 1.9% for the current velocity. The hydrodynamic simulation shows that the direction of the waves and currents dominantly come from the West and move towards the Northeast of the coastal of Bengkulu City with an average wave height of 2.5 m and the highest wave height of 6.5 m, the lowest wave height of 0.5 m, and the highest and the lowest of current speed is 2.5 $m.s^{-1}$ and is 0.5 $m.s^{-1}$, respectively. The simulation of sediment transport shows that the overall net volume is sedimented at about 20.25 $m^3.y^{-1}$. The model of coastal morphology changes shows that the sedimentation occurs in the northeast direction of the coastal of Bengkulu City, from Sungai Hitam Beach to Tapak Paderi Beach, and at Pulau Baai Beach.

Keywords: *Hydrodynamic, sedimentation, abrasion, model simulation*

Introduction

Bengkulu City is located on the west coast of West Sumatra and its coast is directly influenced by the Indian Ocean. Therefore, these coastal areas of Bengkulu City have the potential to be developed for many purposes including fisheries, sea transportation, tourism, and others (Supiyati *et al*., 2011; Alifdini *et al*., 2018). However, recently, those coastal areas have experienced serious problems caused by changes in coastal morphology due to high sedimentation processes (Suwarsono *et al*., 2011; Supiyati *et al*., 2016; 2021).

Sedimentation is the entry of sediment loads into a certain aquatic environment through the water as media and deposited in that environment (Suresh and Sundar, 2011). Sedimentation, along with abrasion are problems that often occur in coastal areas. A large number of the residential area, infrastructure, and facilities are developed and cannot function properly (Suwarsono *et al*., 2011; Supiyati *et al*., 2017). Sedimentation also caused beach morphology changes by narrowing the mouth of the estuary which results in flooding there such as in the Rawa Makmur Village area (Ramawijaya *et al*., 2012).

Supiyati *et al*. (2016) previously discussed an in-situ sediment transport study based on empirical calculations at Teluk Segara District Beach which includes Pasar Bengkulu Beach, Zakat Beach, and Pondok Besi Beach. The results showed that the sediment transport at Pasar Bengkulu, Zakat, and Pondok Besi Beach were 110.959, 289.52, and 16.026 $m^3.day^{-1}$, respectively. While sediment transport with tidal flow generators at the Port of Pulau Baai Bengkulu studied by Supiyati *et al*. (2011) showed that the area of erosion occurred in the northeast and sedimentation in the port happened in the southwest to the southeast. At the channel, it is generally eroded at the mouth of the outer channel. In the west it is sedimented, and in the eastern part, it is eroded. Hutari *et al.* (2018) also conducted a

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sedimentation study at the Port of Pulau Baai Bengkulu. The results show that the sedimentation occurred in Pulau Baai Port with sedimentation rates ranging from 680.60 to 49,363.82 mg.cm^{-1} per year.

Another related study was the hydrodynamics of waters carried out by Alifdini *et al*. (2016) regarding wave energy in Pulau Baai waters calculated using the Floating Oscillating Water Column (OWC) method and Sverdrup, Munk, and Bretschneider (SMB). The results showed that the highest significant wave height in the period of 2000-2016 was 5.33 m and the average significant wave height was 2.01 meters, while the average power was 0.02 J.s^{-1}, and the average energy was 7.53 x 105 watts. Furthermore, Supiyati and Ekawita (2019) conducted a study of ocean currents and wave energy based on field measurements using ultrasonic sensors in the waters of Tapak Paderi Beach. The results showed that the average current velocity was 0.51 m.s^{-1}, the wave height was 0.86 meters and the wave energy was 382.84 Joules.

According to previous research, it is still necessary to conduct comprehensive research on how the direction and magnitude of sediment transport that results in changes in the coastal morphology of Bengkulu City. It is thought to be due to sediment transport generated by ocean wave currents on the Bengkulu City Coast. Previous research that has been carried out has only reviewed certain in situ areas but has not thoroughly studied Bengkulu City's marine waters. Whereas hydrodynamics in sea waters in the form of ocean currents and waves is an important aspect of the coastal control process related to its function as a medium for transporting sediment. The direction and magnitude of sediment transport greatly determine the process of changing the morphology of a coastal area, *i.e.* sedimentation or abrasion (Suwarsono *et al*., 2009; Davidson *et al*., 2010; Suresh and Sundar, 2011; Gede and Koji, 2014; Witantono and Khomsin, 2015; Jara *et al*, 2015; Kermani *et al*., 2016; Pérez-Ortiz *et al*., 2017; Reeve *et al*., 2019). Therefore, this research aimed to determine and analyze the changes in coastal morphology caused by sediment transport generated by currents due to sea waves in the Coastal waters of Bengkulu City.

The study of coastal changes due to sediment transport caused by the direct dynamics of seawater movement is very difficult to carry out because of the complexity of the processes involved and requires a relatively long time. Along with the development of the ability of computers to calculate, making numerical models become an economical alternative to solve this problem. The modeling used in this study is the one previously done by several scientists (Chapman, 1985; Koutitas, 1988; Van Rijn, 1990; Kowalik and Murty, 1993; Yang, 1996; Yanagi, 1999; Koutitas and Scarlatos, 2016; Setiawan, 2018; 2021). The verification of model simulation results is based on field measurement data. This study covers the sea waters of Bengkulu City, Indonesia. Geographically, the area of the model covers 3° 45' S to 3° 59' S and 102°14' E to 102°22' E (Figure 1.).

Materials and Methods

Field measurement

The tools and materials that are used in this study are a drifter, current meter, ultrasonic pitometer, Global Positioning System (GPS), and Bengkulu City bathymetry map with a resolution of 0.25 minutes (462.5 meters) x 0.25 minutes (462.5 meters) (Hydrography and Oceanography Center, Indonesian Navy, 2014 https://www.pushidrosal.id/buletin/50/peta-elektronik/), 10 years of wind speed data from Meteorological, Climatological, and Geophysical Agency Bengkulu City (2010 to 2019), and ships.

The data acquisition has been done during the east season, which was September 2, 2020, at Zakat Beach at the location 3° 46' S 102° 13' E and Pulau Baai at the location 3° 51' S and 102° 11' E. Measurement of the direction and speed of ocean currents were conducted using drifters and current meters, while the height of sea waves was measured using a pitometer based on ultrasonic sensors. Current velocity and sea wave data were also collected for one hour with interval monitoring for one minute. Wave data from field measurements are processed to determine significant waves (US Army Corps of Engineers, 2006; Triatmodjo, 2012). The field measurement data then were used to verify the model simulation results.

Hydrodynamic model

The hydrodynamic equation of current due to waves using the equation of conservation of momentum and conservation of mass integrated with depth is written as follows:

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = -g\frac{\partial \zeta}{\partial x} - \frac{C_f \bar{u}\sqrt{\bar{u}^2 + \bar{v}^2}}{(h+\zeta)} + R_x + M_x$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} = -g\frac{\partial \zeta}{\partial y} - \frac{C_f \bar{v}\sqrt{\bar{u}^2 + \bar{v}^2}}{(h+\zeta)} + R_y + M_y$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial(\bar{u}(h+\zeta))}{\partial x} + \frac{\partial(\bar{v}(h+\zeta))}{\partial y} = 0$$

Note: t = time; (*x,y*) = Cartesian coordinates in a horizontal plane; $(\bar{u},\bar{v})$ = current velocity component;

(C_f) = basic friction coefficient; (R_x, R_y) = radiation stress in the x and y directions; g = gravity acceleration; h = water depth; ζ = the water level. For lateral mixing, the following equation is used (Horikawa, 1988):

$$M_x = \frac{\partial}{\partial x}\left(\varepsilon \frac{\partial \bar{u}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon \frac{\partial \bar{u}}{\partial y}\right) \text{ and } M_y = \frac{\partial}{\partial x}\left(\varepsilon \frac{\partial \bar{v}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon \frac{\partial \bar{v}}{\partial y}\right)$$

Note : $\varepsilon = N l \sqrt{g(h+\zeta)}$ (Longuet-Higgins, 1970), N < 0.016, l = distance to offshore $= (h+\zeta)/\tan\beta$, $\tan\beta$ = mean of slope base Irregular base slope, lateral mixing is indicated:

$$M_x = A_H\left(\frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2}\right) \text{ and } M_y = A_H\left(\frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2}\right)$$

Note: A_H = the horizontal viscosity coefficient.

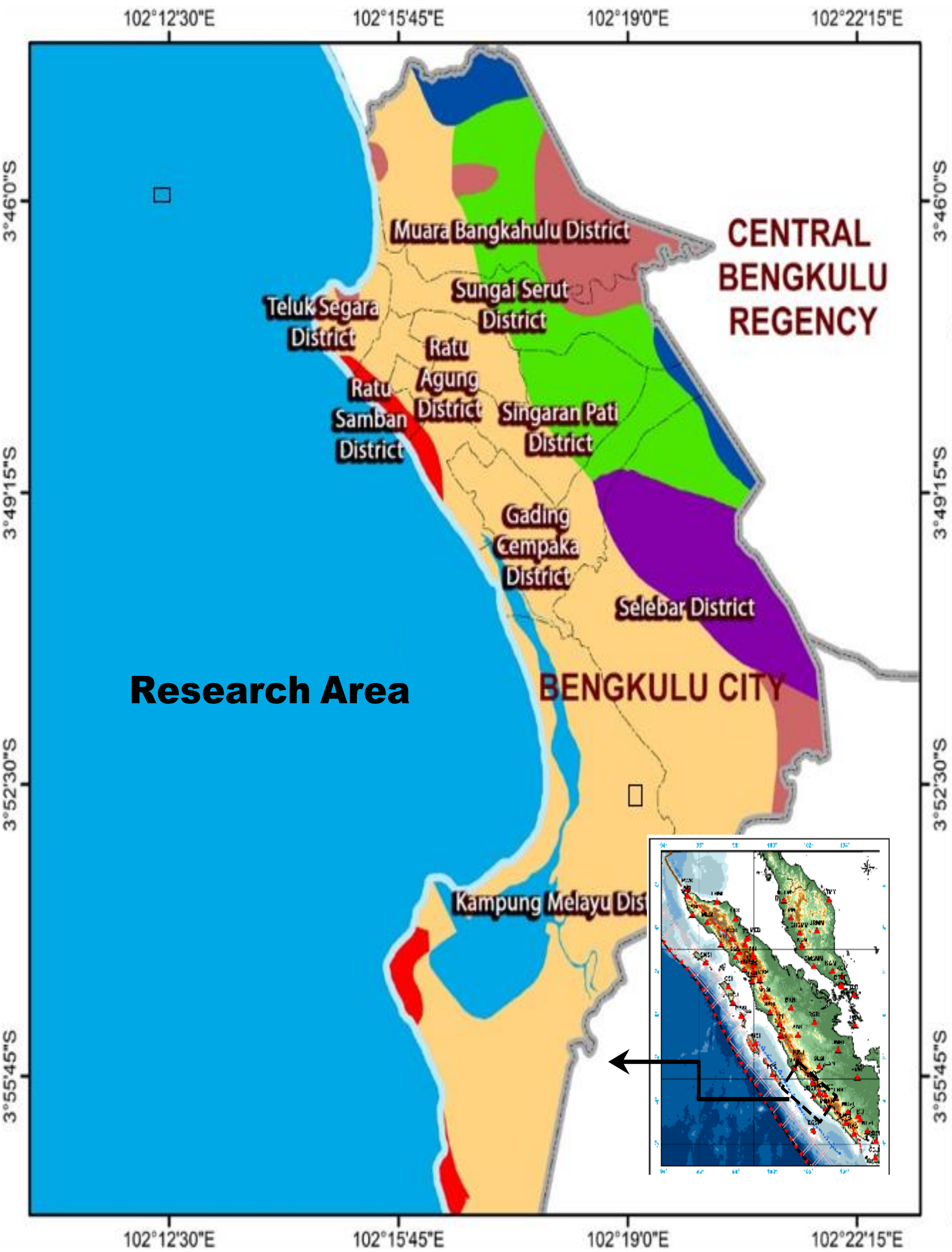

Figure 1. Map of research location at Bengkulu City waters

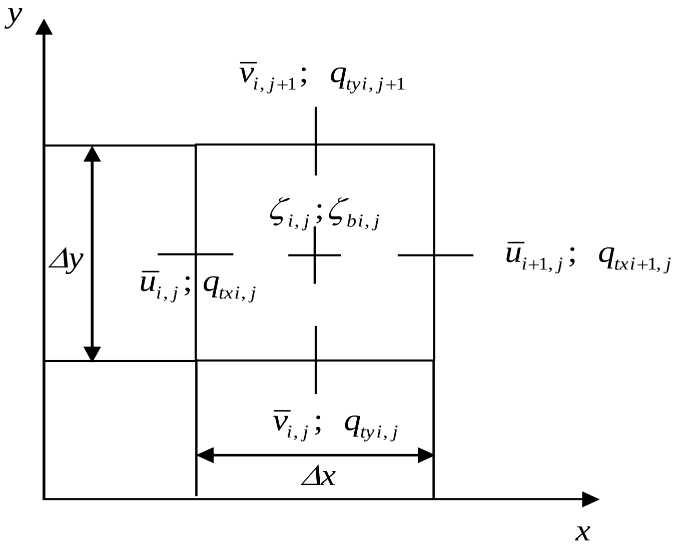

Figure 2. Discretization Scheme $\bar{u}_{i,j}$, $\bar{v}_{i,j}$, $\zeta_{i,j}$, $q_{txi,j}$, $q_{tyi,j}$, and $\zeta_{bi,j}$

The radiation force according to Van Rijn (1990) was calculated using the following equation:

$$S_{xx} = \frac{\bar{E}}{2}(2n-1) + \bar{E}n\cos^2\theta$$
$$S_{yy} = \frac{\bar{E}}{2}(2n-1) + \bar{E}n\sin^2\theta$$
$$S_{xy} = \frac{\bar{E}}{2}n\sin 2\theta$$

Note: $\bar{E} = \frac{1}{8}\rho g H^2$

The force that causes the longshore current is proportional to the radiation stress gradient which can be written as:

$$R_x = \frac{1}{\rho(d+\bar{\eta})}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right)$$
$$R_y = \frac{1}{\rho(d+\bar{\eta})}\left(\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y}\right)$$

Sediment transport models and bed morphological change

Total sediment transport due to waves and currents is defined as the sum of baseline sediment transport and floating sediment transport, with a simple approximation of total sediment transport expressed in the following equation:

$$q_t = 0.05U \frac{\tau_c^2 C}{\rho^2 g^{5/2}\left[\frac{(\rho_s-\rho_w)}{\rho_w}\right]^2 D_{50}}$$

Note : ρ_w = water density, ρ_s = sediment density, D_{50} = sediment grain diameter,

$\tau_c = \rho g U^2 / C^2 + \frac{1}{2}\left(\xi \frac{\hat{u}_b}{U}\right)^2$ = shear stress,

$\hat{u}_b = (\pi H / T)(\sinh kh)^{-1}$ = wave velocity amplitude

$\xi = \frac{c}{\sqrt{(2g)}}\sqrt{(f_w)}$ = bottom roughness parameters, (f_w) = the bottom wave friction coefficient.

Sediment equilibrium is approximated by equation (Koutitas, 1988):

$$\frac{\partial \zeta_b}{\partial t} + \frac{\partial q_{tx}}{\partial x} + \frac{\partial q_{ty}}{\partial y} = 0$$

Note: q_t = represents the total sediment transport; ζ_b = bed level change.

Numerical solutions for hydrodynamic models, sediment transport, and bed morphological changes

Discretization of hydrodynamic equations ends bed morphological changes using an explicit method of middle difference for derivatives with respect to space and forward differences for derivatives with respect to time. The numerical stability of this method is determined by the stability criteria (Koutitas, 1988).

$$\frac{\Delta x}{\Delta t} = \frac{\Delta y}{\Delta t} > \left\{|U| + \sqrt{g(h+\zeta)}\right\}_{\max}$$

Sediment transport caused by currents and waves was calculated using the total sediment transport equation, and the basic morphological changes were solved using the sediment equilibrium equation (Koutitas, 1988), whose numerical solution was based on the discretization scheme (Figure 2) for the velocity component $\bar{u}_{i,j}, \bar{v}_{i,j}$ *dan* $\zeta_{i,j}$.

Model design

In this research, the model was built using the Fortran programming language. The design of the hydrodynamic model for the wave model simulation uses H_o and T_p which are predicted based on wind speed and direction at an altitude of 10 meters for 10 years (2010–2019). It was obtained from an empirical formula approach (Setiawan *et al*., 2021) which obtained H_o is 2.5 meters and T_p is 7.2 s. The wave model simulation produces wave rays and steady wave field vectors from H_o and T_p inputs from wind data for 10 years. The wind friction coefficient is $C_D=0.001*(1.1+0.035*U_{10})$. The horizontal viscosity coefficient (A_H) is 10 m.s^{-1}. The basic friction coefficient with respect to the wave (F_w) is 0.1, and $C_f=F_w$., while the grain diameter of the sediment (D_{50}) is 0.0001 m. C^2 = 45 m.s^{-2}, where C is the Chezy coefficient (m$^{1/2}$.s^{-1}). The difference in density ($\frac{\rho_s-\rho_w}{\rho_w}$) is 150 and Δt is 1 s, and the grid size (Δx and y) in the model is 462.5 m x 462.5 m.

The initial condition used in this simulation is t = 0, this states that the condition of the waters is assumed to be calm without any vertical or horizontal movement which is mathematically formulated: $u=v=\varsigma=0$, and it is assumed that there is no sediment transport and changes in bed morphology that have occurred so that, $q_{tx} = q_{ty} = 0$, and $\varsigma_b = 0$. The boundary conditions used are open boundary conditions that use radiation boundary conditions and normal direction gradients and closed boundary conditions that use wall boundary conditions.

Result and Discussion

Simulation of the hydrodynamic model of Bengkulu City Waters

The greatest annual average wind speed of Bengkulu city for 10 years is 10.567 m.s^{-1}. It comes from the west direction. Wind speeds were obtained from the wind rose diagram analysis of wind data from 2010 to 2019. Based on wind data processed by using the Sverdrup-Munk-Bretschneider (SMB) method (US Army Corps of Engineers, 2006), the significant wave height is H_o = 2.5 m, the peak wave period is 7.2 seconds with the direction θ_o = 240^o (west direction). The simulation results of the hydrodynamic model can be seen in the propagation of the wave rays, the wave height, and the vector of the wave direction as shown in Figure 3. The propagation of these wave rays causes divergence and convergence zones. Usually, the convergence zone occurs in a headland that has greater energy than in the bay area (divergence zone).

The pattern of the height and direction of the wave propagation of the model simulation is shown in Figures 4 and 5. It can be seen that the average wave height of 2.5 m (Figure 4.). The direction of propagation of the waves from the west (240^0) can be seen from the arrow shown in Figure 5. The closer to the beach, the wave height decreases, and shrinks. The incoming waves toward the beach can cause nearshore currents. However, there are two current systems that dominate the movement of seawater, namely rip currents and longshore currents. These two currents play a role in sediment transport along the coast and the formation of sedimentation on the coast.

The pattern of flow in the simulation model results in a steady state as can be seen in Figures 6 and 7, where the pattern of water level elevation is evenly distributed in the coastal waters of Bengkulu City of about 0.5 m. In the area near the coast, it can be seen that after the waves break, the water level increases up to the coastline. The maximum current occurs shortly after the wave breaks, then its speed decreases towards the shoreline and zeroes at the shoreline, except in the northeast direction, the sea level elevation decreases about 0.3 m as can be seen in Figure 6. Whereas, in Figure 7, you can see that the current moves from the west from the deep waters, and when it approaches the coast, there is a change in the direction of the current. Some are perpendicular to the beach, along the coast, and some turn away from the beach and get closer to the beach. It is seen that the current accumulates on the beach indicated by the direction and size of the arrows with a top speed of 2.5 m.s^{-1} and the lowest speed of 0.5 m.s^{-1}.

Verification of model results against field measurement

Verification between the field measurement and the model simulation results of the error calculation approach model is determined by using Mean Absolute Percent Error (MAPE) calculated using the following equation (Bowerman and O'Connell, 1987):

$$MAPE = \frac{1}{n}\sum \frac{|actual - forecast|}{|actual|}\ x\ 100$$

Note: actual = data from field measurements; forecast = data from model simulation results, N = the amount of data.

The calculation of the model simulation and the field measurement data taken from Zakat Beach and Pulau Baai waters using the MAPE equation can be seen in Table 1. The verification of significant wave height and ocean current velocity between model simulation results and field measurement show the

Table 1. Verification of model simulation with field measurement data

Results from	Significant wave height (m)		Current velocity (m.s^{-1})	
	Zakat Beach	Pulau Baai	Zakat Beach	Pulau Baai
Model Simulation	2.3	2.47	0.16	0.32
Field measurement	2.7	3.12	0.19	0.39
MAPE	1.5%	2.1%	1.9%	2.2%

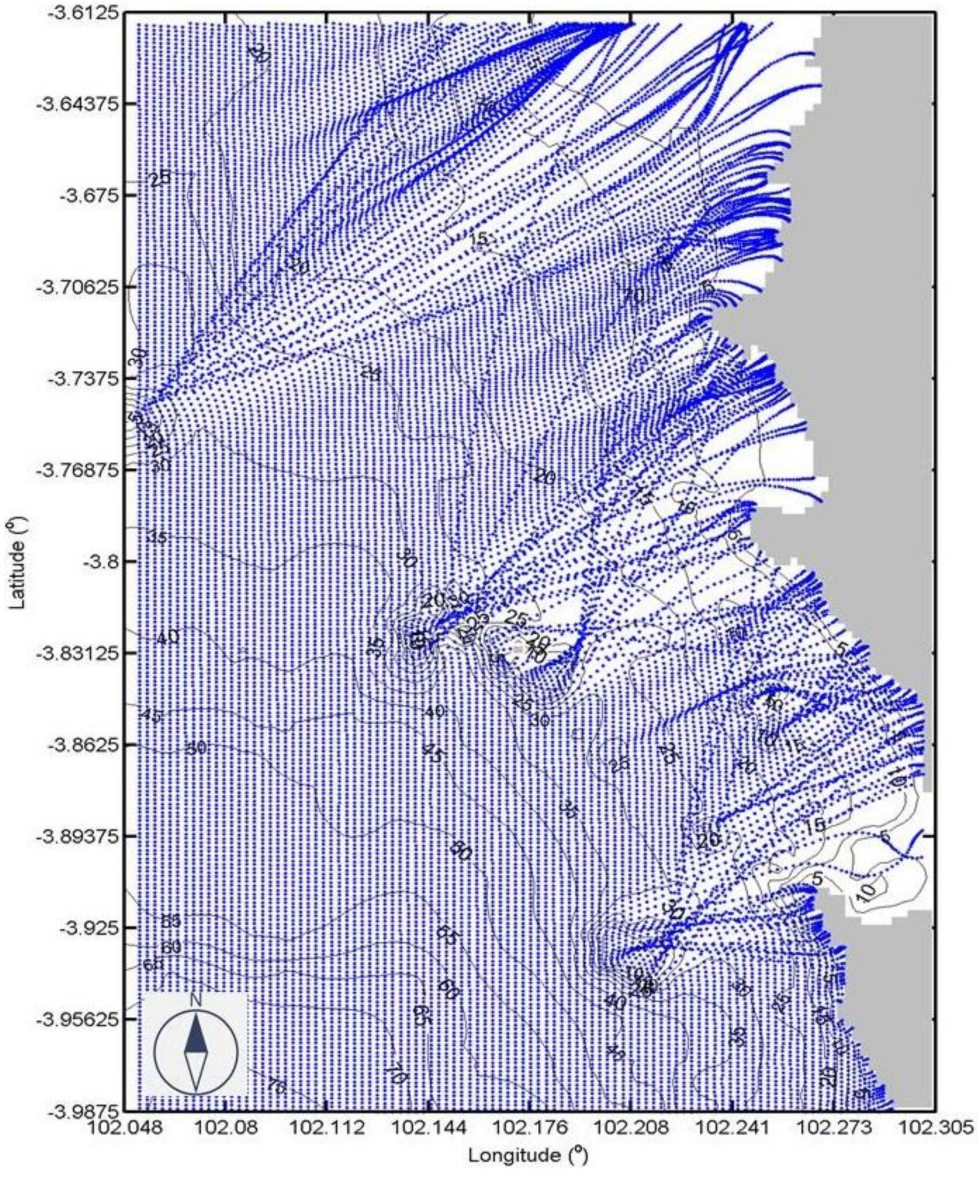

Figure 3. Wave rays (dots) with input Ho = 2.5 m and Tp = 7.2 s from the West direction. Contour lines (strips) represent bathymetry in meters. The gray palette shows coastal or land.

suitability quite good, with MAPE for significant wave height at Zakat Beach is 1.5% and Pulau Baai Beach is 2.1%. As for the speed of ocean currents, the error is 1.9% on Zakat Beach and 2.2% on Pulau Baai Beach.

Sediment transport model simulation and coastal morphological change

Based on the bathymetry study, the conditions of the coastal waters of Bengkulu were shallow water

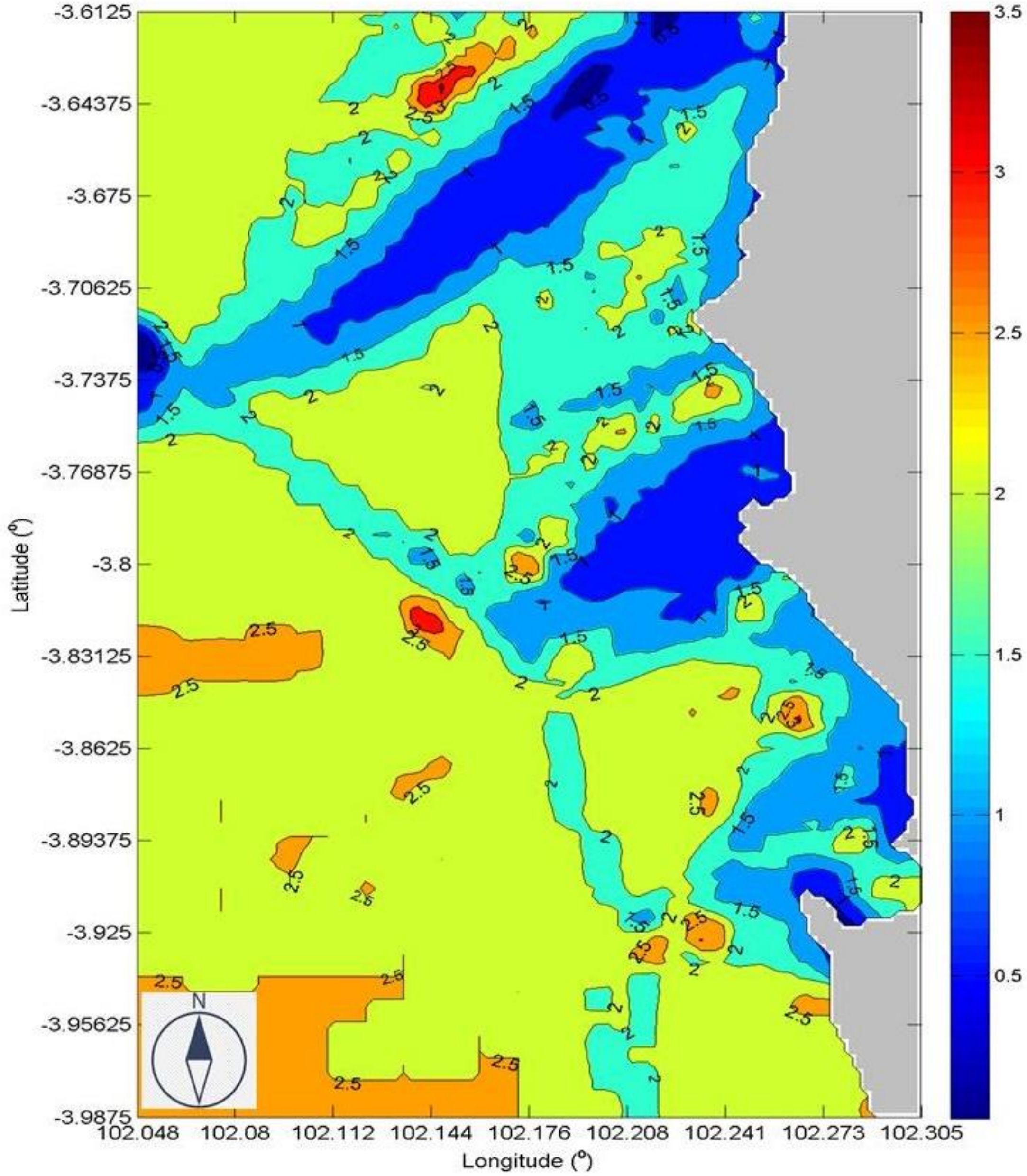

Figure 4. Hydrodynamic simulation of sea wave height with the same input as Figure 3. The color contour palette represents Sea wave height in meters.

with a depth ranging from 0 to 20 meters (Alifdini *et al*., 2018), except that the west of Pulau Baai has a maximum depth of around 75 m. In general, the bathymetry condition of the coastal waters of Bengkulu City is relatively flat with a slope of less than 1°.

The results of the sediment transport model with a year simulation can be seen in Figure 8, where the direction of changes in coastal morphology due to sedimentation and erosion occurred in the northeast direction of the waters of Bengkulu City. The area towards the northeast direction of the waters of Bengkulu City is around Sungai Suci Beach to Tapak Paderi Beach and Pulau Baai Beach. From these four different simulation times, it can be seen that the longer the simulation time causes the area, where sedimentation and erosion occur, to expand along the coast of Bengkulu City. Sedimentation and erosion occurred in the northeast of Bengkulu city and Pulau Baai waters because this area is a bay area, i.e. Sungai Serut Bay and Bay of Pulau Baai Port. Based on the rays of the waves (Figure 3), this area is a divergence area where the wave rays spread, and the area that experiences sedimentation is an area that is not traversed by the wave rays. Meanwhile, it can be seen from the ocean current that the water level is reduced in the northeast direction, and the speed of the current weakens. Accordingly, it is unable to bring the sediment back to the middle of the sea.

To determine the volume of sedimentation and erosion of the coastal waters of Bengkulu City, the calculation was done by assuming the initial net volume was zero. Then, the sedimented and eroded volume of each cell was calculated from the height of the base elevation multiplied by the unit area which is found by Supiyati *et al*. (2011) which was shown in the following equation:

$$V_{sedimentation} = \varsigma_b(t).\Delta x \Delta y \quad \text{for} \quad \varsigma_b(t) > 0$$

$$V_{erosion} = \varsigma_b(t).\Delta x \Delta y \quad \text{for} \quad \varsigma_b(t) < 0$$

The total net volume is obtained from the difference between the sum of each sedimented volume cell and the sum of each eroded volume cell. Based on the above approach, the volume of sedimentation and erosion in the coastal waters of Bengkulu City are shown in Table 2.

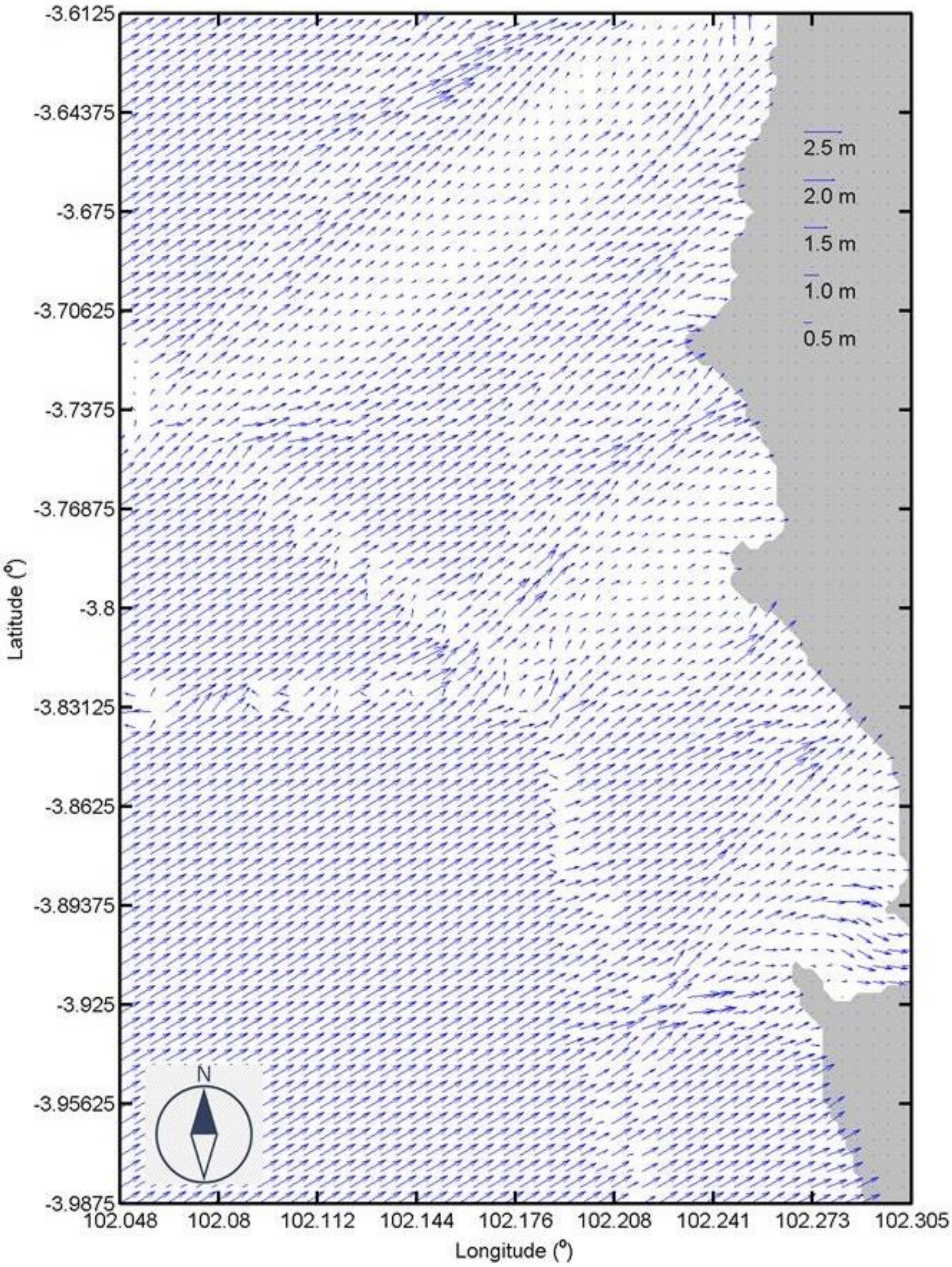

Figure 5. Hydrodynamic simulation of height (m) and direction in the vector of sea waves with input is the same as Figure 3.

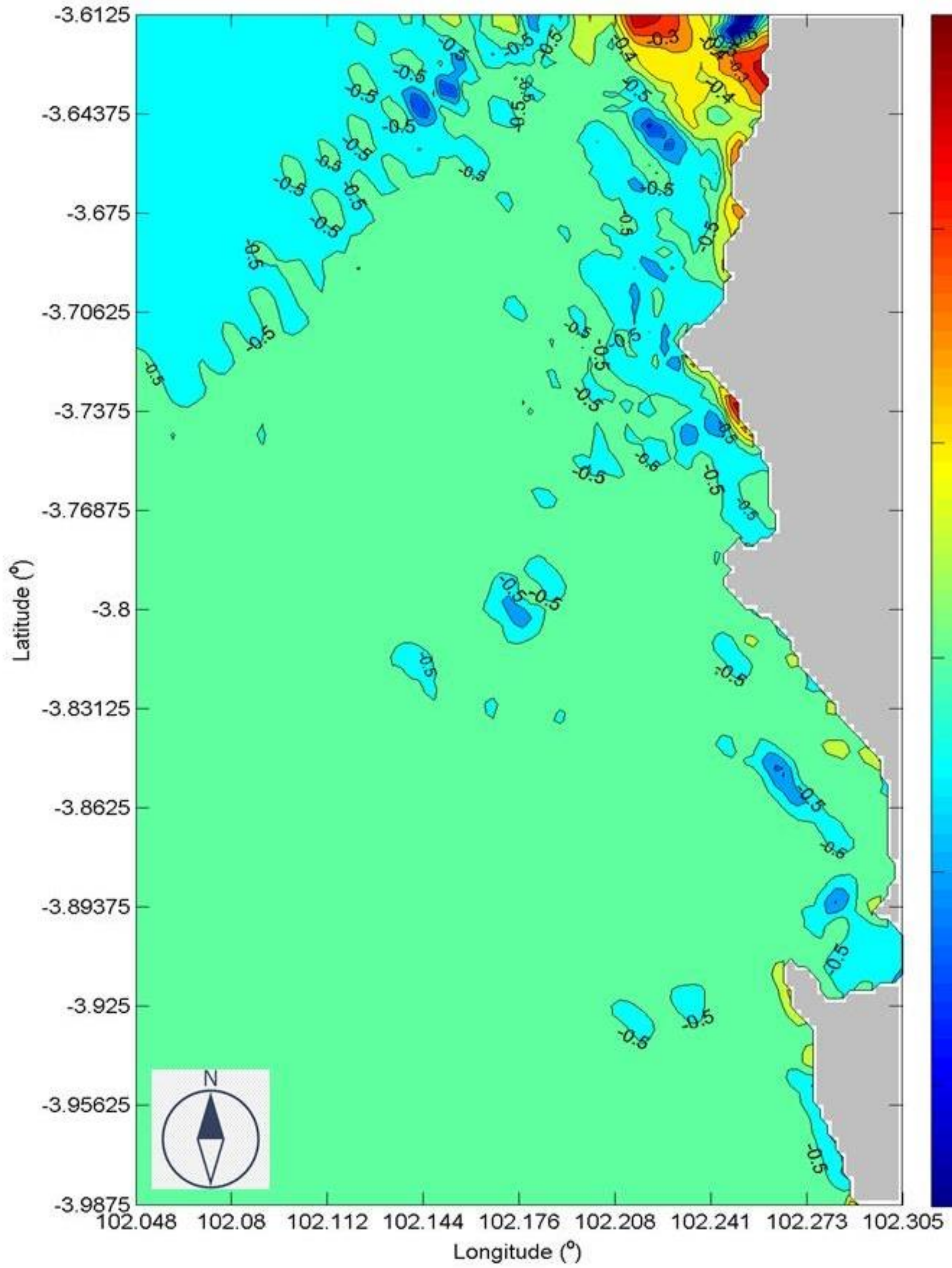

Figure 6. Hydrodynamic simulation of the water level due to sea waves with the same input as Figure 3. The color contour palette represents water level due to sea waves in meters. Positive values (+) indicate flood and negative values (-) indicate ebb.

Table 2. Sedimentation and erosion volume of Bengkulu City Beach

Simulation time (Month)	Sedimentation volume (m^3)	Erosion Volume (m^3)	Net (m^3)
1	2.97 x 10^6	2.87 x 10^6	0.1 (sedimented)
3	9.05 x 10^6	8.64 x 10^6	0.41 (sedimented)
6	22.47 x 10^{18}	2.23 x 10^{18}	20.24 (sedimented)
12	28.37 x 10^{18}	8.12 x 10^{18}	20.25 (sedimented)

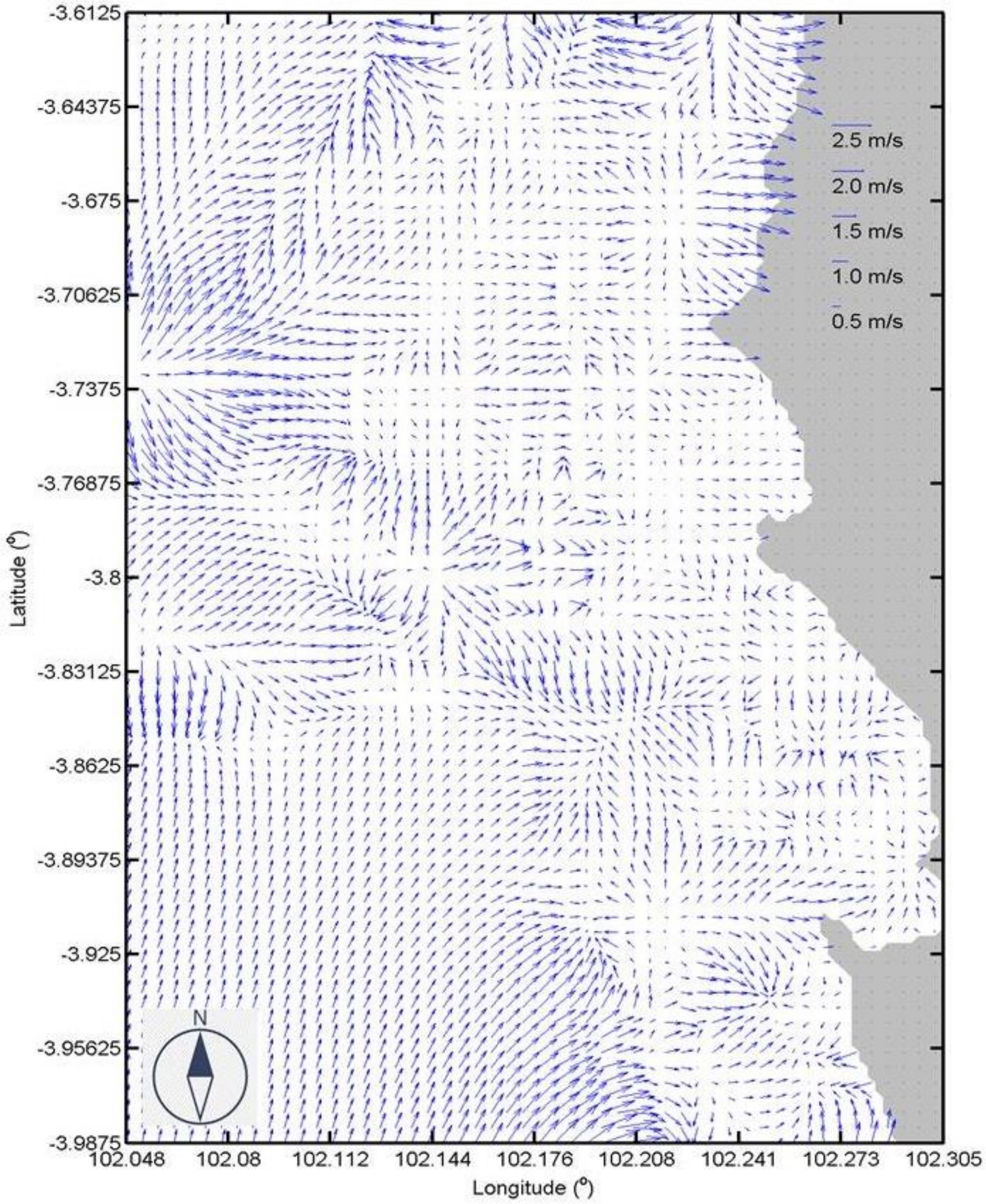

Figure 7. Hydrodynamic simulation of current velocity due to sea waves (m.s^{-1})

This sediment transport simulation model which produces 1, 3, 6, and 12 months use steady current input due to the wave field based on Ho and Tp calculated from 10 years of wind data. The sediment transport simulation model is simulated for 1 year.

Then the data on the results of basic morphological changes from the sediment transport model were sampled for 1 month, 3 months, 6 months, and 12 months (Table 2.).

The process of sedimentation and erosion in the coastal waters of Bengkulu City resulted in changes in the coastal morphology. Based on the net volume of sedimentation and erosion as shown in Table 2, it shows that the net volume as a whole is sedimented more predominantly in the coastal waters of Bengkulu City, with a simulation time of one month, the sedimentation volume is 0.1 m^3, 3 months simulation is 0.41 m^3, six months simulation is 20.24 m^3 and a year simulation is 20.25 m^3. This is 20.24 m^3 and a year simulation is 20.25 m^3. This shows that the longer sedimentation on the coast of Bengkulu City, the volume of sedimentation increases. Meanwhile, the changes in the volume of erosion vary and is not increase with the increase of simulation time.

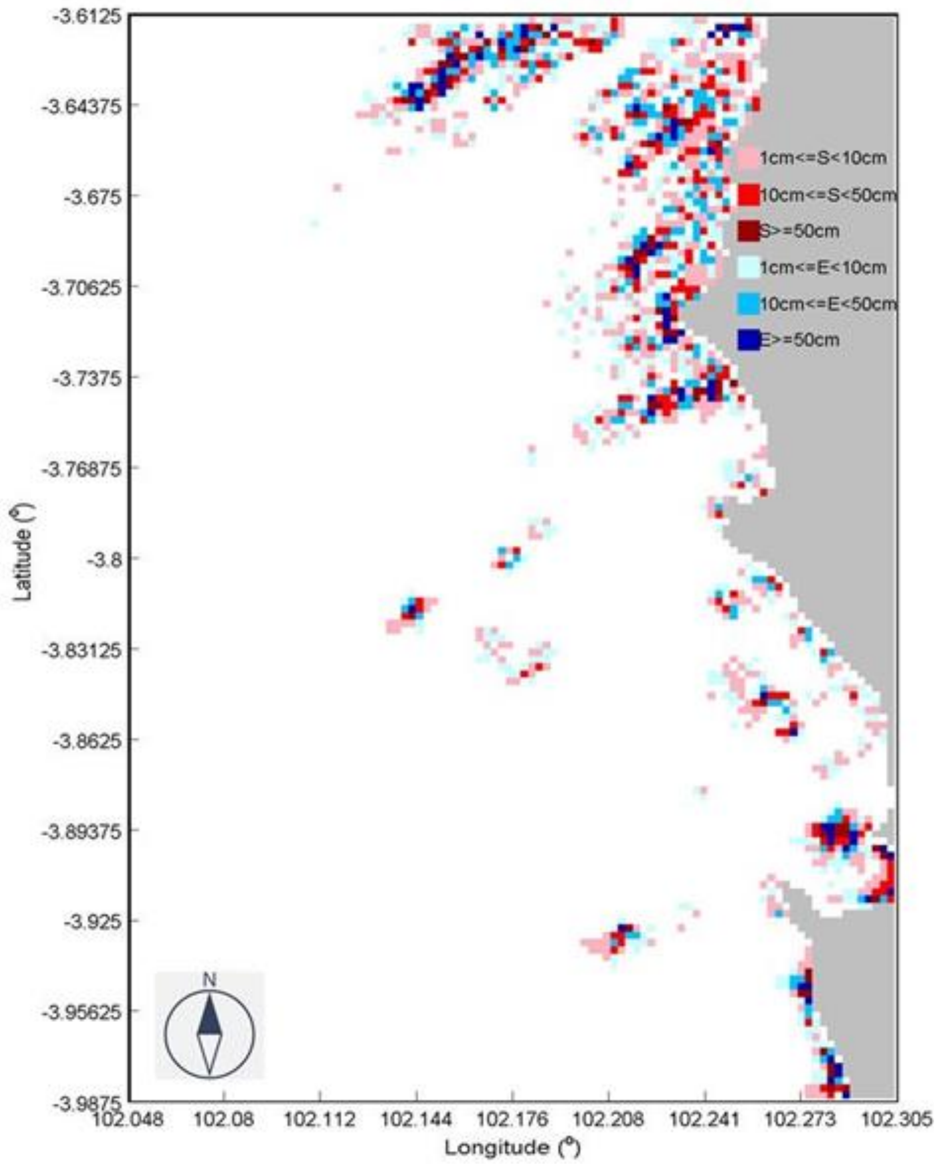

Figure 8. Simulation of the changes in coastal morphology generated by currents (Figure 7) due to waves (Figures 4 and 5) in the coastal waters of Bengkulu City a year simulation. Note that S (red palette from less red to bright red) indicates sedimentation and E (blue palette from less blue to bright blue) indicates erosion.

Conclusions

The changes in coastal morphology of Bengkulu City are caused by sediment transport generated by ocean wave currents with an overall net volume of 20.25 $m^3.y^{-1}$. Sedimentation occurs in the northeast direction of the coastal waters of Bengkulu City, which is around the coast of the Black River, the coast of Sungai Serut, Zakat Beach, Tapak Paderi Beach, and southeast of the coastal waters of the City of Bengkulu, which is around the Port of Pulau Baai. The verification of ocean wave height and current velocity between the simulation model and field measurement shows fair good compatibility, with MAPE at Zakat Beach being 1.5% for wave height and 1.9% for current velocity, while MAPE in Pulau Baai has 2.1% for wave height and 2.2% for current velocity.

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