Numerical models of hydrodynamics and marine debris in the Malacca Strait

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Abstract. The Malacca Strait is a very strategic world trade route and the potential for environmental pollution is also very large, especially pollution from ship and people activities. This study aims to perform numerical simulations to determine the movement of marine debris particles around the waters of Rupat Island, Malacca Strait. The modelling was carried out from June to December 2020 using a modelling application with the basic principles of mesh discretization and the Lagrangian method. The results showed maximum current velocity during the simulation around the distribution area of debris is a maximum of 0.92 m/s. Marine debris around the waters of Rupat Island, the Malacca Strait has the potential to be stranded on the mainland of Rupat Island, mainland Riau, Bengkalis Island and also mainland Malaysia.

1. Introduction

Marine debris that pollutes the environment has now become a global issue. Marine debris is not only bad for marine biota and the aquatic environment, but in the long term will affect the quality of the coastal and terrestrial environment. The impact of marine debris will not only decrease the quality of the waters, but will also have an impact on the economic and social conditions of the community. The Strait of Malacca is a very strategic world trade route which the majority of foreign ships crossing the Malacca Strait transit at the port of Singapore. The potential for environmental pollution in the Malacca Strait area is also very large, apart from coastal activities, as well as pollution from ship waste generated from ship operations in the form of liquid waste and debris that is disposed of carelessly and illegally washing ships. One of the main issues with floating marine debris is the distribution route [1]. This needs to be known to handle marine debris so as not to disturb the life of the ecosystem of living things.

Marine research using Flow Model FM software has developed rapidly, this is due to the complexity of the sea as a medium that is always dynamic. Marine modelling is designed at a boundary condition to approach the state/process that occurs in nature. The numerical model is a model with an approximation method, so it only gets the answer to the differential equation approach [2]. Modelling of marine debris particles has been carried out in Banten [3], Jakarta Bay [4, 5], Indramayu waters [6] and Pelabuhan Ratu [7]. The method that is most often used in numerical models to solve the problem of flow and transportation of rivers, estuaries, and beaches is the finite difference method because its formulation is relatively easy and efficient, and gives better results.
The numerical modelling used is a fluid flow based on mathematical equations that describe the principles of hydrodynamics [8], or which describe the physical phenomena of the flow and the equation numerically. The basic equations used in this numerical modelling are continuity and momentum equations for fluid flow [9], namely:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{xx}}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{yx}}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_{zx}}{\partial z} + g_x
\]

\[
\frac{\partial v}{\partial t} + \frac{\partial vu}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial vw}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{yy}}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_{zy}}{\partial z} + g_y
\]

\[
\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial vw}{\partial y} + \frac{\partial ww}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{1}{\rho} \frac{\partial \tau_{xz}}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{yx}}{\partial y} + \frac{1}{\rho} \frac{\partial \tau_{zz}}{\partial z} + g_z
\]

Equations 2, 3 and 4, t is time and x, y, z are the coordinate axes of the longitudinal, transverse, and vertical directions. u, v, w are the instantaneous velocity of flow in the x, y, and z directions. p is the pressure, ij (i,j = x,y,z) is the shear stress (which is a function of velocity and water viscosity). gx, gy, and gz are the acceleration due to gravity in the x, y, z directions. The above equations, the continuity equation (Eq. 1) and the momentum equation (Eq. 2, 3 and 4), are known as the Navier-Stokes equations.

The purpose of this study was to identify the characteristics and distribution of marine debris particles on the coast of the Malacca Strait and to examine the hydrodynamic conditions of the waters. The results of this study are expected to provide input/recommendations for the government and related institutions in the management of the coastal and marine areas of the Malacca Strait.

2. Material and Methods

2.1. Location and time

Primary data collection activities are carried out from August to October 2020 at Rupat Island. The field data that will be carried out is tides, bathymetry and sample of floating particle marine debris size.

![Figure 1. Research area in the Malacca Strait, Indonesia](image)

2.2. Bathymetry Data

Bathymetry data was obtained by direct measurement using a single beam echosounder. The spatial resolution is 500 meters using the MSL datum. The depth obtained is the real time depth which is connected to the GPS antenna to determine the position of the measured depth. The depth reference used is the Mean Sea Level (MSL) of the sea waters of the North Rupat waters which is processed based on observations for 30 days [10]. The measurement distance of the generalization of each space is in the range of 500 meters due to current conditions and because the generalization area is a ship route so that the planned path is slightly different from the actual measurement conditions in the field. However, the recording points obtained are still represented by each recorded path. Secondary water depth data from
Batnas [11] is used to complement the lack of bathymetry data in the waters of the Malacca Strait. National Bathymetry is formed from the inversion of gravity anomaly data resulting from altimetric data processing by adding sounding data. The spatial resolution of Batnas data is 6arc-second using the MSL datum.

2.3. Tides
Tidal data using predict a time series of water level based on tidal constituents using the IOS Method. The IOS method chosen when height (water level) time series should be inferred directly from the constituents. This method is potentially the most detailed description of the tide at a specific location, and is therefore typically used for locations where the tide is monitored continuously through several years [12]. Verification of tidal data using BIG data to obtained RMSE value [13]

2.4. Particle Tracking Modelling
Identification of marine debris particles tracking using numerical simulation modelling with the help of software, was carried out for 6 months from 1 June 2020 to 30 December 2020. Particle tracking simulations were carried out to determine the pattern of distribution and distribution of debris in coastal areas. The modelling is carried out using the help of a modelling application, namely Flow Model FM that using the basic principles of mesh discretization and the Lagrangian method method [14].

| Parameter     | Identification                                                      |
|---------------|----------------------------------------------------------------------|
| Time          | Number of time step = 5100                                         |
|               | Time step Interval = 3600                                          |
|               | period = 01/06/2020 00:00:00 - 30/12/2020 12:00:00                  |
| Mesh Boundary | National Bathymetry 2020                                           |
|               | Field bathymetry data, August 2020                                 |
|               | Tidal data forecasting                                             |
| Flood and Dry | Drying depth = 0.0005 m                                             |
|               | Flooding depth = 0.05 m                                            |
|               | Wetting depth = 0.1 m                                              |
| Boundary condition | Tides Verification           |
|               | Long : E 101.391183 Lat : N 2.364831                                |

The initial conditions of the simulation are by assuming there are 4 sources of marine debris particles located in the Malacca Strait. The following are the coordinates of the source of the marine debris particles:

| Coordinates of marine debris source |
|-------------------------------------|
| Longitude | Latitude |
|-----------|----------|
| 1         | E 101.22003050 N 2.1970712166236 |
| 2         | E 101.62390076 N 2.5883859234736 |
| 3         | E 102.21401171 N 2.1384786401969 |
| 4         | E 101.89593772 N 1.6278861884783 |

Consideration of choosing the location of marine debris sources based on areas that have the potential as a source of distribution, population activities, residential areas and representing each area in the Malacca Strait.
3. Result and Discussion

3.1. Tide
Using the least square method [15] it was found that the highest tide was 1.68 meters; the lowest tide is -1.67 meters, mean high water spring 1.41 meters, mean high water level 0.9 meters, mean low water level -0.9 meters and mean low water spring -1.42 meters. The tides used for model are the IOS tides. The verification results of the BIG tides obtained a RMSE value of 0.37. The verification value states that the IoT tides are suitable for modelling [16].

![Figure 2. Graph of water level elevation in the waters of the Malacca Strait](image)

3.2. Bathymetry
On the west side of Rupat Island, the water depth is at a depth of 0-24 meters. In the western part of the estuary of the Dumai Strait, the depth is increasingly gentle with a depth of 0-18 meters. Meanwhile, the southern part of the Dumai Strait estuary has deeper waters between 0-36 meters. This section is the main transportation route for ships entering the Dumai Strait. In the eastern part of Rupat Island, the depth is between 0-84 meters and will be shallower towards the mainland of Malaysia. The northern part of Rupat Island to the mainland of Malaysia is between 0-72 meters deep and seems to have a lot of steep bottom areas.

3.3. Current Condition
To observe the current velocity around the waters of Rupat Island, 4 coordinates (Figure 4) are determined which are considered to represent the waters of the West, East, South and North (Figure 5). Coordinates to the north: long 101.5956741866, lat 2.12755956685; east: long 101.8049466973, lat 1.914247960836; south: long 101.5895077458, lat 1.673696493503; west: long 101.3555648352, lat 1.924821651708.

When the spring tide on December 13, 2020 at 00.00 WIB, the current coming from the southeast of the Malacca Strait towards the northwest. The direction of the parallel coast current in the eastern part of Rupat Island, then turn west when it begins to enter the mainland of North Rupat Island. The currents around the northern part of the island will experience a deflection according to the morphology of the island, most of the currents will move to the west (Figure 4) after experiencing the deflection and some of the currents will be towards the east until they weaken. The maximum current speed in the northern part of Rupat Island is 0.5 m/s. The current direction in the northern part of the Rupat Strait will enter the strait area (towards the South) and in the southern part of the strait, the current will enter through the mouth of the strait towards the East and then turn towards the Northwest. The meeting of these currents will occur in the waters of Dumai City. The maximum current speed in the Rupat Strait is 0.51 m/s with
an average speed of 0.2 m/s. The coastal area of Sumatra Island in Riau waters tends to move parallel
to the coast towards the Northwest and will experience a deflection towards the West and East when
heading towards the southern part of Rupat Island.

Figure 3. Bathymetry map of the Malacca Strait waters

Figure 4. The condition of the Rupat Strait waters at spring tide
Figure 5. Graph of current velocity at spring tide

When the spring tide, the maximum speed in the North is 0.53 m/s, at the East is 0.39 m/s, at the South is 0.81 m/s and at the West is 0.35 m/s. In general, the current velocity in the southern part of the Rupat Island waters, namely the area around the mouth of the strait, has a higher current velocity compared to other water areas (Figure 5). The results of this modelling are in accordance with the conditions in the field when taking water quality data. Based on visual observations, when taking water quality data at the station located in the western part of Rupat Island, the current was lower and calmer than when at the station near the mouth of the estuary in the southern part of Rupat Island.

When the low tide on August 24, 2020 at 00.00 WIB, the current coming from the south-eastern direction of the Malacca Strait is heading towards the Northwest. The direction of the parallel coast current in the eastern part of Rupat Island will then turn west when it begins to enter the mainland of Northern Rupat Island.

Figure 6. Conditions of the waters of the Rupat Strait at low tide

Currents around the northern part of the island will experience a deflection according to the morphology of the island [17], most of the currents will move to the west (Figure 6). When compared to at high tide, the direction of the current at low tide is more to the west and there is no deflection of
the current to the east. The direction of the current at the mouth of the strait in the northern Rupat Strait will turn towards the west and then up towards the south without entering the strait area (towards the south) and in the southern part of the strait, the direction of the current will enter through the mouth of the strait towards the east and then turn towards the northwest. The meeting of these currents will occur at the mouth of the strait in the western part of Rupat Island. At the time of low tide, the currents towards the north in the strait are more dominant, so that the current confluence occurs at the mouth of the estuary of the northern strait. The maximum current speed in the Rupat Strait is 0.341 m/s with an average speed of 0.2 m/s. The coastal areas of Sumatra Island in Riau waters tend to move parallel to the coast towards the west to the mouth of the estuary. The direction and speed of this current are still in the same range of values in the research conducted in the Malacca Strait in August [18].

When the low tide, the maximum speed in the north is 0.53 m/s, the east is 0.39 m/s, the south is 0.81 m/s and the west is 0.35 m/s (Figure 7). In general, the current velocity in the southern part of the waters of Rupat Island, namely in the area around the mouth of the strait, has a higher current velocity compared to other water areas. The results of this modelling are in accordance with the conditions in the field when collecting water quality data. Based on visual observations, when taking water quality data at the station located in the western part of Rupat Island, the current was lower and calmer than when at the station near the mouth of the estuary in the southern part of Rupat Island.

3.4 Marine debris
Marine debris particles that are in the open waters, it can be seen that at the end of the simulation on December 30, 2020, marine debris in 4 different sources was carried away by surface currents with a maximum speed of 1.35 m/s. Marine debris particles have different scattering patterns (Figure 8), influenced by the speed and direction of the current and wind direction [19]. The dynamics of the movement of marine debris particles at point 1 can be seen in Figure 8 and Figure 9.

The current velocity during the simulation time around the particle source area is a maximum of 0.53 m/s. Current movement is seen spreading in all directions and there are radial currents (Figure 9), this is due to changes in topography, wind conditions and morphology of the mainland. Marine debris particles originating at point 1 spread to the northeast and then back towards the mainland coast of Sumatra Island. Seen some particles trapped on the beach and some are still on the surface of the waters. If there are sources of marine debris around this area, the debris has the potential to be trapped on the beach.
Figure 8. Movement of marine debris particles in the Malacca Strait

Figure 9. Movement of marine debris at point 1 (a); point 2 (b); point 3 (c), point 4 (d)

The current velocity during the simulation time around the particle source area is a maximum of 0.52 m/s. The movement of currents is more dominant parallel to the coast and will weaken on the coast. Marine debris particles at point 2 will spread out following the movement of currents and it can be seen that the particles from June to December are around the coastal area and not towards the mainland (Figure 10). Marine debris that continues to be on the sea surface will decompose and be degraded into smaller sizes [20]. Marine debris, especially the type of plastic that is decomposed and degraded, has the potential to be harmful to marine biota and coastal ecosystems.

The current velocity during the simulation time around the particle source area is a maximum of 0.98 m/s. The current movement is more dominant parallel to the coast and will weaken in the coastal part (Figure 11). Marine debris particles at point 3 will spread out following the movement of currents and it can be seen that the particles from June to December are around the coastal area and not towards the mainland. Marine debris that continues to be on the sea surface will decompose and be degraded into...
smaller sizes. Marine debris, especially the type of plastic that is decomposed and degraded, has the potential to be harmful to marine biota and coastal ecosystems. The current direction around point 3 looks more varied due to the basic morphology of the waters and coastal contours consisting of straits, headlands and there are islands near the coast.

The maximum current velocity around the distribution of marine debris particles from the beginning of the simulation to completion is a maximum of 1.35 m/s. The particle source scenario is at the north-western of Bengkalis Island, assuming there is marine debris shipped from Bengkalis waters. The simulation results for 7 months show that the particles will be washed up on the Southeast coast of Rupat Island. Debris with 4 types of mass size does not appear to be going into the Rupat Strait, but will go to the mainland of Rupat Island. Some of the waste will be distributed towards the southeast towards the Bengkalis Strait (Figure 12). Marine debris particles that stranded around the coastal area of Rupat Island have the potential to damage the life of coastal biota [21] and anticipatory steps are needed to minimize this amount of marine debris.

4. Conclusion

Marine debris in coastal areas will tend to continue to be around the beach area and some will be stranded. The movement of marine debris particles will tend to move towards the north of the Malacca Strait. Marine debris particles located around the coastal areas of Riau province will tend to be trapped in the South of Rupat Island and some of the debris will be stranded in the eastern part of Rupat Island.

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