Numerical Modeling of Currents Circulation in Balikpapan Bay during Oil Spill Event on March 31, 2018

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Abstract. The coastal area in Balikpapan Bay and its surrounding area has been devastated after the burst of an underwater oil pipe at the bay on March 31st, 2018, and the crude oil still continues spreading for a few days later. A three-dimensional hydrodynamic model is used to simulate the currents dynamic and investigate the influence of the current circulation on the spreading of the oil spill in Balikpapan Bay from March 31th to April 15th, 2018, to cover the event i.e. several weeks after the oil spill incident. Model results are validated by calculating the RMSE, MAPE and model skill using water level between available observation data at Semayang Port, Balikpapan station and numerical model from October 1st, 2012 to January 1st, 2013. Verification result of tidal elevation data from observation and model prediction shows a good agreement with RMSE = 7.8 cm, MAPE = 14.3% and model skill = 0.995. Surface currents circulation in Balikpapan Bay can be distinguished by the currents pattern on the spring tide and neap tide condition. During the spring tide condition, the surface currents mostly move to the east after coming out from the bay. However, the surface currents are strongly going southward after come out from the bay on the neap tide condition. Based on the satellite images captured for the next days after the event, the spreading pattern of the oil spill seems to be matched to the pattern of surface currents circulation on the spring tide condition. From the analysis of the model result, it shows that the currents circulation playing the main role to disperse the oil spill in Balikpapan Bay towards the Makassar Strait.

1. Introduction

Balikpapan Bay is located in the eastern part of Kalimantan island and slightly southern part of the Mahakam Delta. This bay has become the most important and strategic area to the local government of East Kalimantan Province and the central government of Indonesia. This area has a vital role for transportation, business, industries, and responsible for the economic growth of the nearest cities including the Balikpapan city. The bay also becomes the main shipping lane for oil and gas industries and is one of the busiest routes in central Indonesian waters.

Up until now, there is already some research conducted [1][2] to know the probability from the oil spill incident that could turn into many serious problems in the Balikpapan bay. The oil spills disaster could happen at any time without warning, so the precise and quick responses are very important to reduce the
impact that will be caused by this incident. Some methods can be applied for the study about the oil spill such as numerical method, observational data analysis and also Digital Image Processing (DIP). But lately, the numerical method and DIP have become more widely used because it is much easier rather than to collect in-situ data and also takes less effort to work on it. One of the latest events that took place in Balikpapan Bay was oil spill that polluted almost the entire bay area due to the broken of one of the subsea oil pipes when the Panamian bulk-carrier is carrying out anchoring procedures in the restricted zone. According to the report of KNKT (National Transportation Safety Committee), the oil spills were first discovered in the jetties of Pertamina Refinery Unit V that located in the eastern side of the bay on the March 31st, at about 02.30 of local time [3].

Based on its morphology as a semi-enclosed bay that has been known dominantly affected by the tidal currents [4], the circulation inside the bay was highly possible to carry the oil and moves it from the source of the spill to its surrounding area. The leaked oil seems to spread very fast according to the satellite images released by LAPAN (National Institute of Aeronautics and Space) the days after the incident. In just the next 24-hours, the spills already move outside of the bay then going eastward and polluting Makassar Strait. Balikpapan city was suffered the most because of this tragedy when the oil stranded almost on the whole coastline area, but surprisingly the Penajam coastline which located across of the western Balikpapan has dealt with the opposite impact.

In order to have a better understanding about the incident, this study having the aim to simulate the currents circulation during the oil spill that happens in Balikpapan Bay and then only focus to investigate the relationship between the currents condition and the spreading pattern of the oil on that area based on satellite images which have been captured after the oil leaked.

2. Material and Methods

2.1. Model Description

Known as the three-dimensional, free-surface and terrain-following model [5][6], ROMS (Regional Ocean Modeling System) is used in this study to simulating the currents circulation in the Balikpapan coastal area (inside and outside of the bay) including some parts of the Makassar Strait. This ocean model uses Arakawa-C grid horizontally and terrain-following coordinates system vertically. The model also has many options...
of the configuration can be chosen, such as advection schemes, pressure-gradient algorithms, turbulence closure, and types of boundary condition [7]. The Eqs. (1-5) are the governing equation of the ROMS in flux form which represents on Cartesian and sigma coordinates. The full description of variables of those equations is completely described by [8].

Momentum equation:

\[
\begin{align*}
\frac{\partial (H_z u)}{\partial t} + \frac{\partial (u H_z u)}{\partial x} + \frac{\partial (v H_z u)}{\partial y} + \frac{\partial (\Omega H_z u)}{\partial s} - f H_z v &= - \frac{H_z}{\rho_0} \frac{\partial p}{\partial x} \\
- H_z g \frac{\partial \eta}{\partial x} &= \frac{\partial}{\partial s} (u' w') - \frac{\nu}{H_z} \frac{\partial (H_z S_{xx})}{\partial x} - \frac{\partial (H_z S_{xy})}{\partial y} + \frac{\partial S_{px}}{\partial s} \\
\frac{\partial (H_z v)}{\partial t} + \frac{\partial (u H_z v)}{\partial x} + \frac{\partial (v H_z v)}{\partial y} + \frac{\partial (\Omega H_z v)}{\partial s} + f H_z u &= - \frac{H_z}{\rho_0} \frac{\partial p}{\partial y} \\
- H_z g \frac{\partial \eta}{\partial y} &= \frac{\partial}{\partial s} (v' w') - \frac{\nu}{H_z} \frac{\partial (H_z S_{yy})}{\partial y} + \frac{\partial (H_z S_{xy})}{\partial x} + \frac{\partial S_{py}}{\partial s} \\
0 &= - \frac{1}{\rho_0} \frac{\partial p}{\partial s} - \frac{g}{\rho_0} H_z \xi 
\end{align*}
\]  

Continuity equation:

\[
\frac{\partial \eta}{\partial t} + \frac{\partial (H_z u)}{\partial x} + \frac{\partial (H_z v)}{\partial y} + \frac{\partial (H_z H)}{\partial s} = 0
\]  

Scalar transport equation:

\[
\frac{\partial (H_z C)}{\partial t} + \frac{\partial (u H_z C)}{\partial x} + \frac{\partial (v H_z C)}{\partial y} + \frac{\partial (\Omega H_z C)}{\partial s} = - \frac{\partial}{\partial s} \left( \frac{v_0}{H_z} \frac{\partial C}{\partial s} \right) + C_{source}
\]

Reynolds/Turbulent stresses terms:

\[
\begin{align*}
\overline{u' w'} &= -K_M \frac{\partial u}{\partial z} \\
\overline{v' w'} &= -K_M \frac{\partial v}{\partial z} \\
\overline{c' w'} &= -K_M \frac{\partial c}{\partial z}
\end{align*}
\]  

2.2. Model Input

2.2.1. Bathymetry and Coastline

Bathymetry and coastline of Balikpapan bay are needed for the realistic simulation in this area. In this study, bathymetry obtained from SRTM15 PLUS (Shuttle Radar Topography Mission) which has resolution ~450m and then interpolated to the model domain (donor and main model) (Figure 1). The coastline data was extracted from the GADM (Global Administrative Areas) database and become the better option rather than GSHHS (Global Self-consistent Hierarchical High-resolution Shoreline) data for the accuracy in this area. The coastline data is useful for the pre-processing of the model grid to make the masked area. The mask variable is used by the model internally to distinguish between wet (ocean) and dry (land) area.

2.2.2. Initial and Boundary Condition

The initial and boundary condition for the donor model has extracted from HYCOM (Hybrid Coordinate Ocean Model) global dataset which applied onto the model domain area and at specific times. The initial condition does not vary with time because it was only used at the start of the model run. These data input consists of five variables: free-surface (zeta), depth-integrated velocities (\(\bar{u}, \bar{v}\)), velocities (\(u, v\)), salinity (salt), and temperature (temp) [9]. The data input for the boundary condition is alike as the initial condition,
but have a different shape which is vertically spatial and vary with time. This data also needs to have all the information on the whole sides of the boundary.

Furthermore, the initial and boundary condition for the main model was obtained from the donor model results. The initial condition was interpolated spatially at the time of the model is going to run. The reason why the main model does not obtain the data input directly from the HYCOM is because of the resolution gap between them. It turns out the data for boundary condition from the global dataset is losing its characteristics after interpolating process to the main model resolution and causes the main model to become unstable or not having good results. Therefore, the easiest way but could be taking much effort is just to make another model that can fill the gap resolution between the global dataset and the main model (Figure 2).

2.2.3. Data Forcing

Data forcing for the model specifically on this case includes surface, tidal and river forcing. Surface or atmospheric forcing is acted as a boundary condition on the upper layer of the model. The forcing data used in this study was taken from the ECMWF (European Centre for Medium-Range Weather Forecasts) dataset [10]. All of the atmospheric data have a three-hourly frequency to have better dynamics of the air-sea boundary layer. Unlike the initial condition, the surface data does not have to be interpolated to the model because of ROMS internally will do spatial and temporal interpolation during the computational process.

For the tides, nine major tidal constituents were used as the tidal forcing into the model, such as $M_2$, $S_2$, $N_2$, $K_2$, $K_1$, $O_1$, $P_1$, $Q_1$, and $M_4$. ROMS explicitly required the data consist of the angular period, elevation amplitude, elevation phase angle, currents phase angle, currents inclination angle, maximum tidal currents (ellipse major axis) and minimum tidal currents (ellipse minor axis) [9][11]. For this study, the data is acquired from the output of the global ocean tides model TPXO8-ATLAS. However, the tidal forcing data actually can also be taken from other sources as long as the required variables that already described before are fulfilled.

Balikpapan Bay periodically have freshwater inputs beside precipitation that come from the rivers which always flows into the bay. But because of the lacks of data, only four rivers discharges (Table 1) are available to be used and just only a month-averaged data. It makes the data need to be set to a constant value during the computational process because of no real-time measurements for these rivers input. The things that also missing are the values of salinity and temperature which is required by the model. To avoid the instability on the river grids during simulation, the salinity and temperature were set to proper values even though it might seem unrealistic.

| Table 1. River discharges dataa. |
|River | Discharges (m³s⁻¹) |
|------|-------------------|
|Wain  | 2.477             |
|Semoi | 83.496            |
|Sepaku| 42.189            |
|Riko  | 16.852            |

a Kelompok Kerja Erosi dan Sedimentasi (2002)

2.3. Model Scenario

Larger domain (donor model) is needed to compensate the gap resolution between the HYCOM (~1/12º) and the main model. The donor model has ~750m horizontal resolution with 16 layers in the vertical direction. Donor model domain covering the eastern coast of Kalimantan island from the northern of Mahakam delta to southern of Apar Bay. The domain also slightly rotated in the clockwise direction from its vertical axis with the pivot point on the low left edge and have a purpose to maximize the wet area of the donor model grid. The main model that covers the whole area of Balikpapan bay is represented by
~150m horizontal resolution and 20 vertical layers. The spatial and vertical discretization producing the grid by the size of 168x320x16 and 360x400x20 for the donor and main model respectively.

Bathymetry for both models must have the \( r_x_0 \) (topographic stiffness ratio) and \( r_x_1 \) (hydrostatic instability) number less than 0.2 \[12\] and 10 \[13\] respectively by doing the smoothing process. In this step, the ocean depth will have positive values because ROMS not allowing the depth values equal to or less than zero on the whole grid domain even the grid is located inland. The reason is the ocean depth which denoted by \( h \) represents the water column thickness from the free-surface to the seafloor and will be used for computing vertical level thickness \( H_z \). So, if \( H_z \) is divided by zero, the numerical computation for the equations (1-5) will have results of Inf or NaN. The minimum depth \( h_{min} \) also need to be determined to limit the model vertical time-step due to CFL condition \[8\].

![Figure 2. Model domain (left) and the comparative map between donor model and main model (right)](image_url)

Surface forcing for donor model have a different approach than the main model. For the donor, the surface boundary condition applied using bulk-fluxes formulation, so for the wind, heat, and moisture flux would be computed using Monin-Obukhov theory \[14\]. On the other hand, the main model does not follow the same step as the donor model because it turns out the result became unrealistic.

Simulation of donor model performed for 43 days from March 5 to April 16, 2018. Meanwhile, the simulation of the main model was performed between the simulation period of the donor model. Because the results of the donor model providing the initial and boundary condition for the main model, so the initial time of the main model would be selected after several days of simulation of the donor model until the results became stable. As a result, the main model starts running from March 12 to April 15, 2018.

The boundary of both models using the same boundary condition type. For the three-dimensional momentum component like velocity, used mixed radiation-nudging (RadNud) boundary condition \[15\]. The two-dimensional component such as free-surface used the Chapman boundary condition \[16\] and for the depth-integrated velocity used the Shchepetkin boundary condition type \[17\]. The reason for this boundary configuration has been already explained by \[11\]. The difference between both models can be seen in Figure 2 shows that the donor model has three open boundaries (north-south-east), while the main model only has two open boundaries (south-east).
2.4. Model Validation

The result from the model is validated using the observational data that also used in the previous research [11] to compensate lacks of the data for the time period in this study. Hourly time-series of water elevation that were conducted by BIG (Indonesian Geospatial Agency) on the period of October 1st, 2012 – January 1st, 2013 was the only option for the model validation. The measurement of tides by tide gauge instrument is located in the Semayang Port of Balikpapan (Figure 2).

After comparing visually by overlay the data between the observation and the model like in Figure 3, both datasets are clearly showed not so much different. The elevation from the model very well reproduces the amplitude and pattern of the observation data. However, the model data showing underestimate pattern than the observation during spring tide condition that might be caused by the constant value of the rivers input or the other factors which still unknown.

Statistically, the model validation is done by calculating RMSE (Root Mean Square Error), MAPE (Mean Absolute Percentage Error), and model skill which is described by [18]. The calculation of (Eq. 7) produces the RMSE value about 7.8 cm and when calculating the MAPE using (Eq. 8) gives the result about 14.3%. On the other hand, the value obtained from the model skill (Eq. 9) for this simulation was about 0.995, while the perfect model would have the value of one (perfect skill).

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (M_i - O_i)^2} \tag{7}
\]

\[
\text{MAPE} = \left(1 - \frac{1}{n} \sum_{i=1}^{n} \frac{|M_i - O_i|}{|M_i| + |O_i|}\right) \times 100% \tag{8}
\]

\[
\text{skill} = 1 - \frac{\sum_{i=1}^{n} (|M_i - O_i|)^2}{\sum_{i=1}^{n} (|M_i| + |O_i|)^2} \tag{9}
\]

3. Model Results and Discussion

3.1. Time Series of Currents (Depth-integrated velocity)

Figure 4 shows the currents condition in the Sta.1 located in the mouth of the bay is strongly influenced by the meridional component. The maximum range of the $u$-velocity (Figure 4b) in this location is only about -0.12 to 0.09 m/s when the $v$-velocity have a range of values between -0.39 and 0.44 m/s. (Figure 4c). If
the window time is focused on the period of the spill until the next day, \( \bar{u} \)-velocity on Sta.1 have values from \(-0.11\) to \(0.04\) m/s while the \( \bar{v} \)-velocity is range from \(-0.3\) to \(0.36\) m/s.

Figure 4. Water level (A), depth-integrated velocity in the x-direction (B), and depth-integrated velocity in the y-direction (C) at the Station 1. 24-hours window time (March 31, 03.00 – April 1, 03.00) denoted by the red patch.

However, the velocity of the currents on the Sta.2 that located on the offshore area of Balikpapan coastline showing the very different pattern and completely on the opposite term from the Sta. 1 which can be seen in Figure 5. The \( \bar{u} \)-velocity is stronger than its counterpart on this area. Minimum \( \bar{u} \)-velocity is about \(-0.28\) m/s and maximum \( \bar{u} \)-velocity reaching \(0.38\) m/s. At the same time, the \( \bar{v} \)-velocity only ranges between \(-0.13\) and \(0.12\) m/s. And also during the window time of the spill, this meridional velocity component is much weaker with the values ranges from \(-0.05\) to \(0.03\) m/s. Meanwhile, the \( \bar{u} \)-component have the minimum value of velocity about \(-0.25\) m/s and the maximum velocity about \(0.19\) m/s.

3.2. Sea Surface Currents Circulation (0-24 hours after the incident)

The spatial pattern of the circulation is divided by four tidal conditions from the start of the oil spill happen (around 03.00 o’clock) until the next 24 hours. The first low tide occurring at the time around 04.00 of local time which is showed in Figure 6a. The currents speed in this period is reached about 0.6 m/s inside of the bay but on the outside, the currents have the speed that only ranges between 0-0.2 m/s. Flood tide takes place on the three hours after the low tide happened. From Figure 6b, showing that the currents are moving into the bay with the maximum speed around 0.8 m/s. The area with the higher currents speed is distributed from the upstream to the downstream of Balikpapan bay. Around 10.00 o’clock, the high tide occurs and the currents speed is going weaker on the whole domain. The currents speed has magnitude from 0 to 0.3 m/s and evenly distributed inside and outside of the bay. On 13.00 o’clock, the currents speed gets much stronger when coincides with the ebb tide condition. The currents which moving out from the bay almost reaching 1 m/s and gradually decreasing when already on the Makassar strait (Figure 6d).

After the last ebb tide condition ended, the second low tide starts around 16.00 o’clock with the currents speed ranges from 0 to 0.6 m/s. By looking at Figure 7a, it is clearly shown that the area inside of the bay
has stronger currents than the outside. At 19.00, the tide condition changes to the flood tide when the currents entering the bay and have the speed between 0.2-0.8 m/s. The maximum speed of the currents occurs on the three different areas inside the bay, which is the mouth, middle, and northern part of the bay. After that, the high tide slowly begins at 22.00 o’clock with currents getting much slower on the whole domain which can be looked at Figure 7c. The area of the currents slightly faster is located inside of the bay with maximum speed is around 0.3 m/s. On the next day at 02.00 o’clock during ebb tide condition, the currents speed inside the bay reached over 1 m/s. It happens when the currents strongly going outside and leaving the Balikpapan bay into Makassar Strait.

![Figure 5. Water level (A), depth-integrated velocity in the x-direction (B), and depth-integrated velocity in the y-direction (C) at the Station 2. 24-hours window time (March 31, 03.00 – April 1, 03.00) denoted by the red patch.](image)

### 3.3. Influence of Currents Circulation on the Oil Spill

The characteristics of the currents between Sta.1 and Sta.2 clearly showing a very different pattern for the depth-integrated velocity component respectively. Sta.1 that located inside of the bay having the \( \bar{v} \)-velocity is more dominant than the \( \bar{u} \)-velocity. Contrarily, Sta.2 on the outside of the bay records that the \( \bar{u} \) velocity is much stronger to be compared of the \( \bar{v} \)-component. However, both stations have one thing in common which is the velocity component has a similar pattern with the tidal elevation. It is indicating that the currents circulation in Balikpapan bay is dominated by tidal currents.

The dominant of \( \bar{v} \)-velocity at the Sta.1 means that the currents in this area are responsible for the oil spill going upstream and downstream on the Balikpapan bay. Unlike the Sta.1, the area outside of the bay has dominant \( \bar{u} \)-velocity (Sta.2). Therefore, the oil which was already coming out from the mouth of the bay will be transport by the zonal velocity component and makes oil spill going much further to eastward. Even the \( \bar{v} \)-component have slower velocity than the \( \bar{u} \)-component, but it has the role to transport the oil to the Balikpapan coastline if flowing northward.

Based on Figure 6 and Figure 7 that captured the surface circulation in the Balikpapan bay during different tide condition, showing that currents inside the bay are just moving back and forth while the
currents outside the bays are constantly heading eastward. Moreover, when comparing it with the satellite images released on April 1, 2018 (Figure 8), it does make sense to explain why the spreading pattern of the spill would be like that. Currents can transport and also modify the oil spill at many different scales, especially at the larger scales (hundreds of meters to a few kilometers) the turbulence from the currents can strongly affect the oil on the surface and spreading it to the wider area [19].

Figure 6. Sea Surface Currents Circulation during tide condition I (time period from March 31, 03.00 – April 1, 03.00): low tides (A), flood tides (B), high tides (C), and ebb tides (D).
Figure 7. Sea Surface Currents Circulation during tide condition II (time period from March 31, 03.00 – April 1, 03.00): low tides (A), flood tides (B), high tides (C), and ebb tides (D).
Figure 8. Oil Spill Estimate. (Image by M. Agus Salim and David Gaveau).

4. Conclusions
The model has high accuracy based on water level estimation at the Semayang Port, Balikpapan and could represent the tidal dynamics very well for the time period of October-December, 2012. Using the donor model is proven to be an effective way in this study to avoid the unrealistic behavior of the model result if directly using HYCOM dataset. The only problem is the constant rivers input (discharges, temperature, and salinity) which seem unrealistic, but need to be done to avoiding instability during computational processes.

From the model results, surface current velocity has maximum values ranged between 0.8 m/s (northward) – 1 m/s (southward) on the following hours after the incident was responsible for transporting oil spill to the upstream and downstream areas in the Balikpapan Bay. On the other hand, the oil spill that already moves out from the bay is heading eastward after carried away by ocean current and spread to the Makassar Strait. It is clearly shown that the oil spill spreading pattern follows the movement direction of surface current. This incident was further aggravated due to coinciding with the spring tide condition so that the oil spill can travel farther and wider in the Balikpapan bay compared to the neap tide condition.

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