A numerical study of mixing and sediment transport caused by tidal in the Bontang waters

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Abstract. Freshwater and sediment that carried by the river then flow into the bay will cause sediment transport and mixing in the bay, in this case the Bontang Waters. The three-dimensional finite difference baroclinic model system (ECOMSED) is used to do numerical studies of the mixing and sediment transport process, this model was simulated for 40 days and verified using tidal data that taken using CTD. The values of sediment concentration ranged from $1 \times 10^{-6}$ to $1 \times 10^{-5}$ gr/cm$^3$ on the surface, with sediment transport ranging between 0 – 12 (gr/m$^2$)/s. Salinity on the surface is 0 - 35 ppm, and the temperature is 25 - 40 $^\circ$C. Mixing occurred at one river mouth with a salinity profile of 25 ppm on the surface and 32 ppm at the bottom, the sediment concentration value was in the range of $1.2 \times 10^{-5}$ gr/cm$^3$ on the surface and decreased to $4 \times 10^{-6}$ gr/cm$^3$ at the bottom.

1. Introduction

Makassar Strait is one of the Indonesian throughflow that has been known has major Impact to the global ocean circulation. Pacific and Indian Ocean heat and freshwater budget have depended on the Indonesia sea throughflow [1]. In the Makassar Strait, there are two areas on Borneo Island which are the main sources of freshwater, sedimen, and heat flux that empties into the strait. The first one is Mahakam Delta, Mahakam Delta is an active delta system which has been formed in humid tropical environment under condition of relatively large tidal amplitude, low wave-energy, and large fluvial input, tidal processes control the sediment distribustion in the delta mouth and are responsible for the flaring estuarine-type inlets and numerous tidal flats [2]. The second one is Balikpapan Bay, Balikpapan Bay is semi-enclosed bay and strongly affected by waves distribution in the southern part of the bay, the hydrological condition in the bay was strongly affected by the Makassar Strait [3].

Bontang waters is located in the East Borneo Province, Indonesia, and it in the north of Mahakam Delta, and it is has several rivers that empty into these waters, the Bontang Waters is same as the Balikpapan Bay and Mahakam Delta which borders the Makassar Strait. This means the rivers that empties into the Bontang Waters is affected by Makassar Strait, and there are 5 small river that lead to the Bontang Waters (figure 1).
Figure 1. Map of Bontang Waters (study area). There are 7 stations, station 1 to station 5 are located in river mouth, and station 6 to station 7 located little far from the river mouth.

Station 1 is located in Sekangat, station 2 in Muara Sekambing, station 3 in Baltim, station 4 is in Nyerakat, and Station 5 is in Selangan. Station 6 and station 7 located to see how far the distribution of the freshwater, heat, and sediment.

The objective of this study is to elucidate the spatial tidal current and the effect to the sediment transport and mixing using the numerical model. The model that used in this study is ECOMSED (Estuarine Coastal and Ocean Modelling System with Sediment) sediment transport module, it is HydroQual’s state-of-the-art-three-dimensional sediment transport model [4]. This module has been successfully applied to the coastal and estuarine waters, including Pawtuxet River in Rhode Island [5], Tannery Bay in Michigan [6], Green Bay in Wisconsin [7], and Mahakam Estuary in East Kalimantan [8]. The development of ECOMSED was originated in the mid 1980’s with the creation of the Princeton Ocean Model [9].

2. Materials and Methods

2.1. Model Description

Ecomsed model is a three-dimentional hydrodynamic and sediment transport model. The governing equations of the hydrodynamic component in the model are the continuity equation, momentum equation, and heat and salt transport equation. The simulation of cohesive sediment transport processes is performed solving the 3D-conservative advection-dispersion equation. The hydrodynamic governing equation are solved using a mode-splitting technique. The external mode that contains fast moving gravity wave is solved with small time step to ensure stability, whereas the internal mode uses large time step to save the computation time. Finite difference of the differential equation is applied on a staggered C grid in space, and the three-time-level leap-frog scheme is applied for the time stepping. Three schemes, including central difference, upwind difference, and the multidimensional positive definite advection scheme are provided in the model to solve the advection term in the transport equation the sediment transport component uses the same grid, structure, and computational framework as the hydrodynamic component to simulate the settling, deposition, and resuspension of sediment.

2.1.1. Governing equation. The hydrodynamic model has been explained in the conservation law of momentum and water mass by following the general continuity equation:

\[
\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0
\]  

And the Reynolds momentum equation are:
\[
\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -\frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left[ K_M \frac{\partial U}{\partial z} \right] + F_x
\]
(2)

\[
\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} = -\frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{\partial}{\partial y} \left[ K_M \frac{\partial V}{\partial z} \right] + F_y
\]
(3)

\[
\rho g = -\frac{\partial P}{\partial z}
\]
(4)

Where \((U,V,W)\) are the velocity components of each \((x,y,z)\) direction, \(t\) is time, \(\rho_0\) is the reference density, \(\rho\) is density, \(g\) is gravitational acceleration, \(P\) the pressure, \(K_M\) the vertical eddy diffusivity of turbulent momentum mixing, \(f\) is the coriolis parameter, and both \((F_x\) and \(F_y\)) as term of horizontal mixing processes.

2.1.2. Sedimen Transport Model. The three dimensional advection-dispersion equation for sediment transport is;

\[
\frac{\partial C}{\partial t} + \frac{\partial U C}{\partial x} + \frac{\partial V C}{\partial y} + \frac{\partial (W - W_s) C}{\partial z} = \frac{\partial}{\partial x} \left( A_H \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_H \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_H \frac{\partial C}{\partial z} \right)
\]
(5)

Boundary conditions:

\[
K_H \frac{\partial C}{\partial z} = 0, z \to \eta
\]
(6)

\[
K_H \frac{\partial C}{\partial z} = E - D, z \to -H
\]
(7)

Where \(C\) denotes sediment concentration, \(W_s\) is settling velocity, \(A_H\) is horizontal diffusivity, \(K_H\) vertical eddy diffusivity, \(E\) and \(D\) is resuspension and deposition flux, \(\eta\) is water surface elevation above a specified datum, and \(H\) is bathymetric depth below the datum.

2.2. Model Input

This study was conducted in Bontang Waters, East Borneo, bathymetry data (figure 1) of the model domain in this study is in between 0º0’30”N-0º0’30’3”N and 117º28’00”E-117º36’00”E obtained from DISHIDROS (Indonesian Navy Hydrographic Departement). The boundary condition along the open boundary and considered constant with time, it was given as the salinity, temperature, sediment concentration, and tidal elevation. Tidal elevation used harmonic constant are given by nao99b that showed in Table 1. The river discharge data obtained from the [10], the data is shown in Table 2. Sediment concentration value in river is an assumption value and considered constant with time, because there is no data available.

| Constant | Amplitude (m) | Fase (°) |
|----------|--------------|----------|
| S2       | 0.387        | 323.46   |
| M2       | 0.570        | 279.51   |
| N2       | 0.082        | 259.47   |
| K1       | 0.206        | 158.52   |
| P1       | 0.069        | 156.04   |
| O1       | 0.160        | 135.50   |

| Station | River       | Discharge (m³/s) |
|---------|-------------|------------------|
| 1       | Sekangat    | 42               |
| 2       | Muara Sekambing | 1               |
| 3       | Baltim      | 1                |
| 4       | Nyerakat    | 1                |
| 5       | Selangan    | 1                |
2.3. Numerical experiment
In this model, the water body is discretized by 3 equal layers over depth. The horizontal grid is ~50 m, resulting this model divided into 297x240 grids. The surface wind stress is neglected, the external time step is 3 s and internal time step is 30 s. This model was simulated for 40 days, from June 7 to 17 July 2017, and this model verified using water surface elevation data, that obtained from observation using Compact TD (Temperature Depth) in Bontang Waters.

2.4. Model validation
The results of the model are then validated with RMSe (Root Mean Square Error), this value is obtained from the average difference in square between each observation data \((O_i)\) and the results of the model \((P)\) as much as the amount of data \((N)\).

\[
RMSe = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (O^n - P^n)^2}
\]  

(8)

Then proceed with calculating the value of RRE (relative RMS error), the value of RRE is the ratio of RMSe to changes in observation data \([11]\).

\[
RRE = \frac{RMSe}{\text{Observed Change}} = \frac{\sqrt{\frac{1}{N} \sum_{n=1}^{N} (O^n - P^n)^2}}{o_{\text{max}} - o_{\text{min}}} \times 100\%
\]  

(9)

RRE is useful for measuring the performance of a model on a river \([12]\), lake \([13]\), and estuary \([14]\).

3. Result
The result of model validation show the value of RMSe 0.198 m, the value of RRE 8.70 %, and the model has a value 0.918 from perfect score 1 in agreement. This indicate the model has a great success to correctly simulates the observed sea level.

![Figure 2. Comparison of observed and prediction time series of water level in Bontang Waters](image)

The water level output in model show that the tides in Bontang Waters has a semidiurnal type, this can be seen from two high and two low waters in a day with different heights.

3.1. Surface current and sediment transport
The current velocity in Bontang Waters has a value around 0 – 0.6 m/s (figure 3), in flood condition, the current flow from south and east and the velocity increase when coming to coastal area, and then during high water, the current velocity are relatively low, and the direction of the flow is going east and deflected to north, in ebb condition the direction is same with high water but the velocity is higher. And during low water current heading from south and east to coastal area.

Result from surface sediment transport are enlarged to see more detail, and different colorbar are used to see the value ranged of sediment concentration that transported. During flood and high water, sediment that transported are driven by tidal current and the concentration is higher in high water, and in ebb dan low water, the sediment is carried by ebb current, and the concentration that carried are not have much different (figure 4).
Figure 3. Surface current (m/s) in Bontang Waters during 4 different neap tides conditions (a) flood, (b) high water, (c) ebb, (d) low water.

Figure 4. Zoom surface sediment transport in Bontang Waters during 4 different neap tides conditions (a) flood, (b) high water, (c) ebb, (d) low water.

3.2. Vertical profile with time
Vertical profile of salinity with time at station 1 (figure 5), station 2 (figure 6) and staion 6 (figure 7) are chosen to represent points at the mouth of the river with small discharge, large discharge, and to see how far they affect. The result are, at the river mouth which has a small discharge the tidal effect is greater so that from surface to the bottom the salinity is relatively same, but the salinity changes with time as the tidal cycle occurs. salinity will decrease when low tide and increase during high tide.
Figure 5. Salinity vertical profile (ppm) with time in station 1, compared to tidal in station 1

Figure 6. Salinity vertical profile (ppm) with time in station 2, compared to tidal in station 2

At station 2 which has a large discharge, on the surface the salinity is around 25 ppm, and at the middle to the bottom the salinity is around 30 ppm. This salinity changes with time the salinity is from surface to the bottom is higher when in neap condition. Station 6 is affected a little by station 2 which contributes substantial fresh water, but from surface to the bottom of the salinity value at station 6 not have so much different, it ranged from 32.6 to 33.4 ppm.
3.3. Vertical profiles

This vertical profile will focus on station 2 (figure 8) by considering the value of the river discharge, so that the effect can be seen clearly. U velocity (x direction) in the surface have positive values, it means current on the surface tend to head eastward, this current is from freshwater river discharge that carried sediment, and in the middle (around 2m depth) the velocity have a negative values, it means the current in the 2m depth are heading westward. This current come from tidal current that carried saltwater, and the velocity almost zero at the bottom. This condition not have a significant different with time.

V velocity in station 2 have a small ranged values, on the surface the values are have negative values, in the middle the velocity direction heading southward in flood condition, and head northward in ebb condition.

Sediment concentration that carried by river discharge in the surface have values around $9 \times 10^{-6}$ – $1.5 \times 10^{-5}$ gr/cm$^3$, and it decrease with depth, the concentration values are around $3 \times 10^{-6}$ gr/cm$^3$ at the bottom, as well as salinity vertical profiles. In the surface, salinity values are in ranged 22-26 ppm, and it increase with depth and reach around 30 ppm at the bottom. This means eastward heading freshwater that carried sediment from the river discharge in in surface, and salt water which has a heavier density below.
4. Conclusion
Tidal current are have an effect on sediment transport, but this cannot be seen in more detail due to the small value of sediment concentrations in the river. The largest sediment transported occurs in high water spring tide, in other condition the value of sediment concentration that transported not are relatively same. Mixing is seen at station 2, which is has a large discharge value. Freswater that carried sediment is on surface and salt water below. At the other station (1, 3, 4, and 5) due to small discharge, then the tidal current is more dominant for surface to the bottom.

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