Study of tidal effect on water mass stratification in Mahakam estuary using 3D hydrodynamic model

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Abstract. Mahakam Delta is a delta with unique characteristic. As a result of the continuous sedimentation process, the delta can be said as a complex delta because it has dozens of tributaries that are interconnected and flow into the sea to their estuaries. Mahakam Delta estuary is a meeting place for mixing masses of water from freshwater rivers and high salinity rivers. The aim of this study is to determine the water column stratification seen from the salinity and temperature parameters in the Mahakam Delta estuary. This study uses the ECOMSED model which is run for 40 days (July 7 to August 16, 2018) with tides and river discharge as the generating force. The simulation results show that stratification is predominantly influenced by differences in salinity between the layers. The strongest stratification is located in the northern Mahakam Delta line with a difference in salinity is 8 psu from surface to bottom layer.

1. Introduction
Mahakam Delta is one of watershed area in East Kalimantan and formed through sedimentation process. This region is divided into four vegetation zones, namely: perennial tree of low land tropical forest, palm tree and mixed lowland forest, Nypa magrove, and swamp forest. Since from tertiary period, rivers in East Kalimantan have developed to from delta system and this process still continue, Delta has been formed in many varieties starting from prograding deltas (such as Mahakam Delta) up to delta with domination of tidal areas such as Berau Delta. The formation of many ecosystems with abundant biodiversity (including coral reefs, seagrass, mangrove, and fish) is strongly influenced by the abiotic condition such as the presence of suspended sedimentation (turbidity), nutrient availability, current and tidal dynamic [1].

In Mahakam Delta, tidal processes control the sediment distribution in the delta mouth and are responsible for the flaring estuarine-type inlets and numerous tidal flats. The Mahakam estuary is influenced by tides and tidal currents from Makassar Strait [2]. The Mahakam Delta has three distinct area of channels distribution. The southern area has more distributaries than estuaries, the central area has no distributaries and is only occupied by estuaries, while in the northern area both types of channel are equal in number [3] (figure 1).
Figure 1. Map of Mahakam Delta Estuary (study area). There are 34 stations, station 1 to station 7 are located in main area rivers, and 27 other station, located on three area of channels distribution. Marker stars 1 through 4 show the stations for open boundary, which are shown in Table 1 and Table 2. While marker star 5 show station of verification.

In running model, the authors determine 34 observation stations, These stations aim to find out the changes that occur in each parameter so that it is easier to analyze. The first seven are the main Mahakam river where there is no branching flow from upstream to downstream. While a1 to a9 are station located in northern area, t1 to t9 are station located in central area, and station of southern area are station of b1 to b9.

The objective of this study is to determine the water column stratification seen from the salinity and temperature parameters using the numerical model. The model used in this study is the Estuarine Coastal and Ocean Modeling System with Sediment (ECOMSED) which is a development of the Princeton Ocean Model (POM). It is version for shallow aquatic environment such rivers, bays, estuaries and coastal ocean and lakes – named ECOM [4]. This module has a long history sucessful applications to oceanic, coastal, and estuarine marine [5]. Some recent applications of the module inlude Chesapeake Bay [6], the Gulf Stream Region [7], and the Oregon Continental Shelf [8].

2. Materials and Methods
Bathymetry data of the model domain were obtained from DISHIDROS (Indonesian Navy Hydrographic Department) of Indonesia (figure 1). This study was conducted in Mahakam delta estuary, East Kalimantan, the model domain in this study is in between $0^\circ 10'00''$S – $1^\circ 03'00''$S and $116^\circ 59'00''$E – $117^\circ 49'14''$E.

2.1. Governing equation
The momentum equations using the Boussinesq approximations and the assumption of vertical hydrostatic equilibrium in Cartesian coordinates are given :

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} - fV = - \frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z}(K_m \frac{\partial U}{\partial z}) + F_x$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} + fU = - \frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{\partial}{\partial z}(K_m \frac{\partial V}{\partial z}) + F_y$$

$$\rho g = - \frac{\partial P}{\partial z}$$

the continuity equation :

$$\nabla \cdot \mathbf{V} + \frac{\partial W}{\partial z} = 0$$
and, the conservation equation for temperature and salinity:

\[
\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T + W \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} \left( K_H \frac{\partial T}{\partial z} \right) + F_T \tag{5}
\]

\[
\frac{\partial S}{\partial t} + \vec{V} \cdot \nabla S + W \frac{\partial S}{\partial z} = \frac{\partial}{\partial z} \left( K_H \frac{\partial S}{\partial z} \right) + F_S \tag{6}
\]

Where \( U, V, W \) : the current velocity component of each (x, y, z) direction (ms\(^{-1}\))
\( t \) : time (s)
\( f \) : the coriolis parameter (s\(^{-1}\))
\( \rho_0 \) : reference density (kgm\(^{-3}\))
\( \rho \) : density (kgm\(^{-3}\))
\( P \) : pressure
\( K_m \) : vertical eddy diffusivity of turbulent momentum mixing (m\(^2\)s\(^{-1}\))
\( g \) : the gravitational acceleration (ms\(^{-2}\))
\( F_x \) and \( F_y \) : the term of horizontal mixing processes (m\(^2\)s\(^{-1}\))
\( \eta \) : the surface elevation (m)
\( D \) : the total deep (= \( H + \eta \))
\( H \) : the depth (m)
\( \vec{V} \) : horizontal velocity vector with component (U,V)
\( \nabla \) : horizontal gradient operator
\( T \) : temperature
\( S \) : salinity
\( K_H \) : vertical eddy diffusivity of turbulent momentum mixing (m\(^2\)s\(^{-1}\))
\( F_T \) and \( F_S \) : the term of horizontal mixing processes (m\(^2\)s\(^{-1}\))

### 2.2 Boundary and initial condition

The boundary condition along the open boundary and considered constant with time, it was given as the salinity, temperature, and tidal elevation refer to the [9]. Tidal elevation used harmonic constant given by ORI.96 model are shown in table 1. The salinity and temperature are shown in table 2.

**Table 1.** The amplitude and phase of the dominant harmonic constituents along open boundary

| Constituent | Station 1 | Station 2 | Station 3 | Station 4 |
|-------------|-----------|-----------|-----------|-----------|
|             | Amplitude (m) | Phase (°) | Amplitude (m) | Phase (°) | Amplitude (m) | Phase (°) | Amplitude (m) | Phase (°) |
| M\(_2\)     | 0.647     | 278.37    | 0.646     | 278.38    | 0.699     | 276.04    | 0.729     | 276.88    |
| S\(_2\)     | 0.478     | 322.50    | 0.478     | 322.57    | 0.468     | 322.54    | 0.565     | 322.57    |
| N\(_2\)     | 0.075     | 257.25    | 0.075     | 257.22    | 0.066     | 251.94    | 0.166     | 253.53    |
| K\(_1\)     | 0.211     | 156.4     | 0.211     | 156.66    | 0.224     | 160.27    | 0.321     | 159.02    |
| O\(_1\)     | 0.159     | 137.03    | 0.159     | 137.22    | 0.165     | 140.45    | 0.234     | 139.36    |
| P\(_1\)     | 0.068     | 154.48    | 0.068     | 154.75    | 0.073     | 158.46    | 0.122     | 157.18    |

River discharger data is needed as an input model because it is a very influential parameter to determine the tidal current pattern, distribution of salinity, and temperature. The river discharge at upstream boundary in July to August, 2018 of 2040 m\(^3\)s\(^{-1}\). While for temperature and salinity were
29°C and 0.1 psu. The initial conditions of temperature and salinity are necessary for the start of the simulation.

| Station | Salinity (psu) | Temperature (°C) |
|---------|---------------|-----------------|
|         | $\Delta \sigma_1$ | $\Delta \sigma_2$ | $\Delta \sigma_3$ | $\Delta \sigma_1$ | $\Delta \sigma_2$ | $\Delta \sigma_3$ |
| Sta. 1  | 21.01          | 21.01            | 21.02            | 28.16            | 27.05            | 23.88 |
| Sta. 2  | 33.25          | 33.61            | 33.97            | 28.06            | 27.12            | 24.20 |
| Sta. 3  | 32.04          | 32.05            | 33.50            | 28.04            | 27.21            | 23.64 |
| Sta. 4  | 33.55          | 33.94            | 35.00            | 28.14            | 27.03            | 24.11 |

### 2.3 Numerical experiment
In this model, the water body is discretized by 3 equal layers over the depth. The horizontal grid size is 200 m, resulting in 468×490 grids. The surface wind stress is neglected. The external time step is 4 s and the internal time step is 40 s. The model was simulated for 40 days, from July 7 to August 16, 2018 and verified using water surface elevation data that obtained from observation using Compact TD (Temperature Depth) in Pangempong Muara Badak, Kutai Kartanegara.

### 3. Result

#### 3.1. Verification of elevation
The comparison of the observed water elevation data at Pangempong Muara Badak with model results for corresponding Januari – Februari 2017 is shown in figure 2. The result of model validation shows the value of RMS 0.193 m and the value of RRE 8.48%.

![Figure 2. Verification of elevation between the observation data and the simulation result](image-url)
Based on water lever output it can be show that tide in the Mahakam delta estuary has a semidiurnal type where there are two high and two low water in a day with different heights.

3.2. Surface current and distribution salinity

Figure 3. Surface current (m/s) in Mahakam delta estuary during 4 different spring tides conditions (a) flood, (b) high water, (c) ebb, (d) low water.

The current velocity in Mahakam delta waters has a value 0 – 1.2 m/s (figure 3). In flood condition, the current flow from south of Makassar strait and the velocity increase when coming to coastal area. Then during high water, the movement of current changes from north to south, occurs uniformity when coming coastal area and the current velocity are relatively low. In ebb condition, flow moved out to offshore area with the velocity is higher. And during low water, the direction is same with ebb condition but the velocity is lower.

Figure 4. Surface distribution of salinity in Mahakam delta estuary during 4 different spring tides conditions (a) flood, (b) high water, (c) ebb, (d) low water.
For all these conditions, salinity in the Makassar strait has a value of 33 psu. During flood condition, salinity in delta waters range from 10 - 25 psu. Then when high water salinity increase, but when condition of ebb the salinity decreases and decreases more during low water condition (figure 4). Not much during neap condition, salinity decrease due to the movement of currents that encourage freshwater to flow towards offshore when ebb and low water conditions (figure 5).

3.3. Water level elevation
The water level shows how far tidal effect the water column in the Mahakam river which will cause stratification of the mass of water. The biggest tidal effect occurs in the northern area, while for central area and southern area has tidal effect is almost the same. Topography of northern area which have river mouth lead to the north affects tidal flow that entire the delta area is deeper, because the sea water in the Makassar strait moves from Pasific ocean to the Indian ocean, or can be said that the sea water moves from north to south. If it is assumed that tidal range at a9 station is tidal energy of 100%, that means tidal energy at 2 station is 10.36%. This show that there are still tidal effects on the main river, although not so large.

Figure 5. Surface distribution of salinity in Mahakam delta estuary during 4 different neap tides conditions (a) flood, (b) high water, (c) ebb, (d) low water.

Figure 6. Water level at each station from upstream to downstream
3.4. Vertical profile with time

(a) temperature, (b) salinity, (c) velocity of V tidal current, (d) tidal height

Figure 7. Vertical profile with time at a7 station
Tides are the major forcing in an estuary and, along with freshwater inflows, control the vertical and horizontal distributions of salinity. Vertically, high tides lead to strong vertical mixing and little stratification, whereas low tides are insufficient to break up the vertical stratification. Tides are produced as the result of the gravitational attraction of the moon and the sun, while tidal currents are produced in response to the differences in tidal elevation [10].

Vertical profile of salinity with time at a7 station (figure 7), t9 station (figure 8), and b7 station (figure 9) are chosen to present points that have the greatest salinity stratification and located at the mouth of the river. The result are, salinity is relatively same from surface to the bottom because at the mouth of river a small discharge the tidal effect is greater.

Water density increases with increasing salinity and decreasing temperature. This relationship can be seen where the mass of water that has a greater salinity will be in the lower layer while the temperature of the water in the layer is cooler than the layer above it. At neap tide, the tide level is not maximum position which is the tidal range is low. Sea water mass that has high salinity can not flow far from this and also in this condition, mixing process is weak produces strong stratification. Although changes of temperature and salinity over look similar to the tidal cycle, there is a time difference. The greatest salinity occurs at the time of neap tide but when seen in figure 8, where the salinity reaches the peak when the tide has entered the spring tide. This time delay is usual called the age of the tide.

For see how tidal current affect the mass movement of water, then is shown tidal current profiles at a7 station (figure 7), t9 station (figure 8), and b7 station (figure 9). These current are divided in 2 categories namely U current and V current. U current represent the movements of currents in the east and west directions while V current indicate currents moving in the north and south direction. Tidal flow representation will be compared with temperature and salinity are adjusted according to river coordinates.
Based on figure 8 that present the condition at t9 station, it can be seen the tidal current that occurs is strong enough to make the body of water mixed so that stratification from surface to bottom is almost non-existent (or weak stratification). Temperature and salinity change with time, though not too much.
Figure 9. Vertical profile with time at b7 station
(a) temperature, (b) salinity, (c) velocity of V tidal current, (d) tidal height
With a river discharge that maybe stronger than in the northern and center area, the change in salinity at b7 station (figure 9) is quite significant from the surface to the bottom. Although not as strong as in the northern area, but effect of the tidal cycle is influential on change in salinity to time.

Station of b7 represent a change in temperature with stratification that is stronger than the others, even in some stations there is no stratification.

The most obvious changes occur when the tide enters the spring tide where the water column gets colder, here also have a phase delay. Although there is a tidal cycle, it does not have a large effect on changes in temperature, especially changes in temperature from the surface to the bottom. During spring tide conditions, tidal current at b7 station is strongest than at a7 station. Even though at neap tides condition the velocity is almost non-existent. Besides that the tidal period is also more visible at b7 station.

However, the current velocity at the a7 station is more stable, both at neap and spring tide conditions. When compared between salinity and tidal current movement, when neap tides the current velocity is small but salinity is high. This is relates, when there is no movement of tidal current or tidal current is very small the water mass will be quiter. So that, the material in the body of water mass will be more stable or in a higher condition.

4. Conclusions
Salinity is the most important parameter for stratification of the water mass in the Mahakam delta estuary. The movement of the salinity in the estuary is strongly influenced by the tidal cycle where the highest salinity occurs when neap. Tides do not have a significant effect on changes in temperature. Areas with a high level of stratification occur in the northern channel, at station a7.

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