Modelling baroclinic circulation and particle tracking in Inner Ambon Bay

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Abstract; Generally in Inner Ambon Bay (IAB) the sedimentation problem generate revamp of waters base configuration that influence IAB circulation process. We use model tool of MIKE 3 FM in this research to modeling three-dimensional hydrodynamics of process circulation and modeling of particle tracking. The purposes of the research are to analysis pattern of water mass circulation which is considering the baroclinic mode, to estimate the movement and pattern of cohesive sediment from every river inflow and to estimate the flushing as well as residence time of IAB. Simulation result of models is to represent circulation and particle movement in rainy season and dry season in IAB. In baroclinic mode the vertical eddy dominant happen in middle of IAB and in front of Poka-Galala sill. This vertical eddy is influenced by topography configuration and stratification water mass due to the rivers inflow. In model simulation of particle tracking the pattern of particle movement is dominant in middle of bay and along coastal of Lateri and Halong. The average of residence time and flushing time are 5 days and 9 days in rainy season, respectively while those in dry season are 2 days and 5 days respectively.

I. Introduction

Research about modeling of water mass circulation in several decades is growing rapidly, including the simulation modeling of coastal circulation. Several research of modeling circulation such as: in waters of an elongated shelf-adjacent seamount [1], circulation in the deep canyon [2], circulation on the shelf and the upper slope of the Bay [3], Coastal water circulation response to radiational and gravitational tides within the Bay [4], and barotropic circulation on Inner Ambon Bay [5]. Ambon Bay is semi enclosed bay that divided into Outer Ambon Bay (OAB) and Inner Ambon Bay (IAB), between both parts there is narrow and shallow strait named Poka-Galala sill. Circulation in IAB is depends on basic water configuration and water mass stratification [5]. The base configuration or topography is depending on substrate of sediment in environment. Generally in IAB the sedimentation problem generate revamp of waters base configuration that influence IAB circulation process, flushing time, and residence time of water mass or particles in water column. The dominant sediment of IAB is sand, silt, and clay [6, 7]. Impact of sedimentation is increase the turbidity of IAB in rainy season [8, 9]. Sources of sediments probably came from permanent rivers that ended in IAB. Moreover around the Poka-Galala sill there is Wairuhu river which is appreciable supply of cohesive sediment into IAB [6, 7, 10]. Rivers inflow that enters into IAB influences water mass stratification and the circulation process.

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The circulation of IAB can be easily explained by using modeling water environment. We use model tool of MIKE 3 FM in this research to modeling three-dimensional hydrodynamics of process circulation and modeling of particle tracking. The purposes of the research are to analysis pattern of water mass circulation which is considering the baroclinic mode, to estimate the movement and pattern of cohesive sediment from every river inflow and to estimate the flushing as well as residence time of IAB. Result of simulation models can represent circulation and particle movement in rainy season and dry season in IAB.

2. Material and Method

2.1. Study sites
Study site of this research is Inner Ambon Bay (IAB) which is part of Ambon Bay in Ambon Island, Moluccas province, Indonesia (Figure 1). IAB have shallow and narrow sill with maximum depth around 12 m and width about 800 m [5]. Overall the average depth of IAB is between 25 and 30 m, wherein there eight permanent rivers which is flowing all year namely Wailata, Waiguru-guru, Waihunut, Waiheru, Waisala, Waitonahitu, Waireka, and Air besar. Also there are two temporal rivers that flowing in rainy season i.e. Wainini and Waigurita rivers. In east side of IAB from Poka-Galala sill until head bay is sub area Halong until Lateri, otherwise in west side is sub area of Poka until Waiheru. Wherein head bay is sub area of Passo.

2.2. Design and boundary conditions

2.2.1. Baroclinic model. This research is considering the baroclinic mode of waters modeling which is allowing the stratification of density on three-dimensional hydrodynamics modeling. For mesh design we used MIKE Zero to generate study sites into three segments i.e. IAB, the sill, and OAB [5]. The main parameter force of hydrodynamics is tidal force, wherein the tide harmonic component are M2, S2, K1 and O1 that we switch on MIKE 3 FM menu as potential input on model causes the component was dominant component of tides in Indonesia waters [11]. Horizontal eddy viscosity type is
Smagorinsky formulation and vertical eddy viscosity type is Log law formulation and also the bed resistance is using Quadratic drag coefficient [12].

The boundary condition of hydrodynamics model is head boundary condition or sea level elevation and flow-rate boundary condition as discharge inflow. The flow-rate from eight permanent river i.e. river of Wailata (Poka), Waiguru-guru (Batu.Komeng), Waihunut (Hunut), Waitheru (Waiheru), Waisala (Waiheru), Waitonaihiti (Passo), Waireka (Lateri), dan Air besar (Halong). We used the permanent river due to the constant flow and influences to IAB circulation system. The boundary condition of sea surface elevation is basic on mean sea level. For open boundary condition we use ocean as OAB and closed boundary condition is costal line of study sites or land boundary.

2.2.2. Particle tracking model. The trajectory of particle tracking model is only for cohesive sediment in assumption that the cohesive sediment will stay still in water column. The design of this model is to observe movement pattern of particle cohesive sediment in every river inflow that entering to IAB until it exit of IAB. We use modification of river inflow as open boundary in each scenario model as of eight river inflow. In each scenario we just allow one open river inflow and one open ocean boundary (OAB), so we have eight scenarios for particle tracking model.

2.3. Hydrodynamics equations
This research using three-dimensional equations of Reynolds averaged Navier-Stokes. Considering the incompressible waters, as of the density is not depend on pressure \((\rho)\) but only depend on temperature \((T)\) and salinity\((S)\):

\[
\rho = \rho(T, S) \tag{1}
\]

The transport of temperature \((T)\) and salinity\((S)\), the general equation of transport-diffuse [12]:

\[
\frac{\partial T}{\partial t} + \frac{\partial u T}{\partial x} + \frac{\partial v T}{\partial y} + \frac{\partial w T}{\partial z} = F_T + \frac{\partial}{\partial z} \left( D_v \frac{\partial T}{\partial z} \right) + \hat{R} + T_s \ S \tag{2}
\]

\[
\frac{\partial S}{\partial t} + \frac{\partial u S}{\partial x} + \frac{\partial v S}{\partial y} + \frac{\partial w S}{\partial z} = F_S + \frac{\partial}{\partial z} \left( D_v \frac{\partial S}{\partial z} \right) + S_s \ S \tag{3}
\]

where: \(D_v\) is the vertical turbulent (eddy) diffusion coefficient, \(\hat{R}\) is source term due to heat exchange with the atmosphere, \(T_s\) and \(S_s\) are the temperature of the source and \(F\) is the horizontal diffusion terms defined by:

\[
(F_T, F_S) = \left[ \frac{\partial}{\partial z} \left( D_h \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial z} \left( D_h \frac{\partial S}{\partial z} \right) \right] (T, S) \tag{4}
\]

where: \(D_h\) is the horizontal diffusion coefficient and related to the eddy viscosity;

\[
D_h = \frac{A}{\sigma_T} \quad \text{dan} \quad D_v = \frac{\nu}{\sigma_T} \tag{5}
\]

where \(\sigma_T\) is the Prandtl number [12]

2.4. Particle Tracking Equations.
This research use particle tracking model for cohesive sediment in which silt and clay particle are assumed will stay on waters column. The method of particle tracking to describe pattern transport and particle dispersion by using Langevin equations [12]:

\[
dX_t = a(t, X_t)dt + b(t, X_t)\xi_t dt \tag{6}
\]
Where: \(a\) is drift term; \(b\) is diffusion term; \(\xi\) is random number.

The applied random walk method is simple numerical solution to the Langevin equations. The stochastic differential equation is solved with an explicit Euler scheme:

\[
\Delta x = x_n - x_{n-1} = A(x_{n-1}, t_{n-1}).\Delta t + \sigma_L . N(0,1) \quad \ldots \ldots \quad (7)
\]

Where: \(N(0,1)\) is standard normal distribution \((\mu = 0, \sigma^2 = 1)\), \(\sigma_L\) is standard deviation of turbulent dispersion \(\sqrt{2.\Delta t. D_L}\) and \(D\) is dispersion coefficient.

3. Result and Discussion

3.1. Verification model

The tidal currents pattern of rainy season is dominant in north – south (Figure 2a). Direction of \(v\)-velocity dominant on south while in \(u\)-velocity dominant to southwest. In dry season the tide current pattern more dominant in east – west direction (Figure 2b). For \(v\)-velocity the direction dominant to south and direction of \(u\)-velocity are between southeast until southwest. Hamsah and Wenno (1987) [13] expressing the current direction of IAB is between southeast and southwest. The model result of current pattern in IAB (blue dot) show the same direction in measurement result. However the magnitude of current in models is smaller than measurement result because of initial condition range in the models [14, 15].

![Comparison result of measurement (red) and modeling (blue) of current tide](image)

Figure 2. Comparison result of measurement (red) and modeling (blue) of current tide

Measurement of temperature (red dot) in surface waters until 10 m depth on rainy season is between 26.7 – 27.5 \(^\circ\)C. In this layer the temperature pattern is changing in station 3 and quite significant because this station near to head of the bay and influenced by rivers of Waiheru, Waisala, Waitonahitu and Waireka. In 11 – 25 m depth the temperature profile relatively constant between 26.6 – 26.7 \(^\circ\)C while in depth > 30 m the temperature drop until 25.3 \(^\circ\)C i.e. in station 1 (Figure 3a). Model
result (blue dot line) in rainy season shows same pattern with measurement. Nonetheless the temperature profile in station 1 decline at 25 m depth in range 26.5 – 25.3 °C.

In dry season the measurement of temperature in surface layer to 10 m depth is around 29.5 – 30.6 °C. The temperatures profile decline at 11 – 26 m depth on 29.4 – 29.6 °C while in at depth > 26 m (at station 1) temperature is between 29.1 – 28.8 °C (Figure 3b). The model result in dry season show similar pattern with measurements result. These results parallel to the previous research about sea surface temperature in IAB i.e. between 25 – 27 °C on rainy season whereas in dry season just around 29 – 30 °C [16, 17]. The variation of temperature on seasons due to peak rainfall in rainy season and inflict decline of temperature, whereas in dry season the solar intensity increase and induce warmer temperature [17].

![Figure 3. Comparison result of measurement (red) and modeling (blue) of temperature](image)

![Figure 4. Comparison result of measurement (red) and modeling (blue) of salinity](image)
Result of salinity measurement (red dot line) in rainy season at surface layer until 5 m depth is 29.6 – 33.7 PSU and at 5 – 35 m the salinity is between 33.7 and 34 PSU (Figure 4a). On dry season the result of salinity measurement is between 32.8 – 33.9 PSU in surface layer until 10 m depth while in 11 – 35 m the salinity is relatively constant at 33.9 – 34 PSU. Result modeling of salinity (blue dot line) in rainy season and dry season has same pattern with measurement (Figure 4b). Variability of salinity in previous study on IAB shows in rainy season the salinity is 25 – 30 PSU [17], and in dry season the surface salinity is between 31.7 – 33.4 PSU [18]. This means verification of the model is well match with the measurement.

3.2. Model baroclinic circulation

3.2.1. The circulation of IAB on rainy season. Model results of current inflow in rainy season at phase ebb tide and low tide is shown in Figure 5. Result show the inflow in surface layer (0.25 – 15 m) exit from IAB with current speed in around the Poka-Galala sill is about 0.12 – 0.35 m/s. Current inflow that pass through the sill is dominant fringe at coastal of Poka to OAB in 0.25 – 5 m depth (Figure 5a, 5b). The current speed in OAB is between 0.03 – 0.09 m/s in surface layer and > 15 m depth the speed decline to < 0.01 m/s. Current inflow in OAB to ocean boundary are split into two direction; the dominant inflow through of west OAB (around Wayame), and another inflow passes through the middle bay directly to ocean boundary. Current speed in surface layer of IAB is around 0.01 – 0.12 m/s and inflow directly exit from IAB. However in 25 – 30 m the water mass inflows turn over to head bay (Passo area) with current speed is around 0.01 – 0.06 m/s (Figure 5e, 5f). This is show that turn over inflow to head bay conduce the vertical eddy.

Figure 5. Model result of baroclinic circulation in rainy season at ebb tide phase
Result of cross section model in ebb tide and low tide phase shows vertical eddy (anticlockwise) is happen in front of Poka-Galala sill at OAB side (Figure 5g). Double vertical eddy happens in ebb tide phase at IAB, while in low tide phase the vertical eddy occur on middle of IAB. Probably occurrences of the double vertical eddy due to the mass inflow in surface layer still moving with maximum speed along exit of IAB.

In phase of flood tide the current inflow entering to IAB (Figure 6). Model result show in part of OAB at surface layer (0.25 m depth) partly of mass inflow entered to IAB in speed 0.03 – 0.06 m/s (Figure 6a) and a half of the inflow at OAB reversed to ocean boundary. This probably happen due to in 30 m depth mass inflow is increase about 0.06 – 0.09 m/s from west side of OAB and collide with shallow topography near the sill (Figure 6f). Movement of mass inflow will follow base topography and ascend to shallow sill (Poka-Galala sill). Mass inflow pass through sill to IAB in surface layer seen collide with mass inflow from head bay (Figure 6a, 6b). Current inflow increases at 10 – 15 m depth through sill to waters around Halong (Figure 6c, 6d). In 25 – 30 m depth current speed increase around 0.03 – 0.09 m/s (Figure 6e, 6f). This is showing the deep current inflow headed to head bay and induce the vertical eddy.

Cross section in phase of flood tide and high tide showing current inflow entered to IAB with speed around 0.15 – 0.45 m/s until reach the deepest point in IAB. The current vector as though reflected from base bay to surface layer. In high tide phase the vertical eddy (anticlockwise) occur in middle of bay to head bay. It probably happen cause when the high tide phase the mass inflow was entered to IAB with maximum speed.

![Figure 6. Model result of baroclinic circulation in rainy season at flood tide phase](image-url)
3.2.2. The circulation of IAB on dry season. Phase ebb tide and low tide in dry season shows current inflow at 0.25 – 15 m depth is exit from IAB to OAB (Figure 7). The current speed in surface layer (0.25 – 5 m) is between 0.03 – 0.09 m/s (Figure 7a, 7b) while in 10 – 15 m depth current speed decline to < 0.03 m/s especially around head bay (Passo area) (Figure 7b, 7c). In depth of 25 – 30 m the current vector towards to head bay with speed < 0.06 m/s (Figure 7e, 7f). The maximum current speed occur in Poka-Galala sill at ranges 0.25 – 0.45 m/s form surface layer until 15 m depth. Mass inflow in 15 m that exit of IAB and headed to OAB, it’s seen divided into two parts; each of it headed to coastal waters of Wayame and Tantui coastal. In 30 m depth mass inflow through coastal Tantui is inflow from IAB. This indicate the upwelling can be happen around coastal Tantui. At low tide phase current speed around OAB is between 0.09 – 0.2 m/s, while in IAB is around 0.01 – 0.06 m/s at surface layer (0.25 – 5 m). In Poka-Galala sill, the current inflow are emerge in two parts; half is the entering mass and others is the exit mass. This is probably occur causes in low tide phase, half of mass inflow in coastal Galala side was the first trail to flood tide phase.

In cross section at ebb tide phase the mass inflow exit from IAB with maximum speed at Poka-Galala sill. The vertical eddy (clockwise) that happen in this phase occur from head bay (Passo area) until middle of IAB (Figure 7g). When low tide phase, the vertical eddy coverage is along IAB from the sill until the head bay. In this phase appear of vertical eddy (anticlockwise) happen in sill side (afore OAB). This probably due to the mass inflow at base flowing opposite direction from OAB headed to IAB. Wherein mass inflow in base topography, when reach a surface layer will turn over to ocean boundary condition of OAB.

Figure 7. Model result of baroclinic circulation in dry season at ebb tide phase

Mass inflow in flood tide phase and high tide phase moves towards IAB (Figure 8). In flood tide phase current inflow from ocean boundary condition headed to Poka-Galala sill with speed around 0.06 – 0.09 m/s. however this mass inflow when reach middle IAB its seen to turn of direction to ocean boundary condition. Current speed at sill is between 0.23 – 0.35 m/s from surface until 15 m depth. In surface layer (0.25 m) the dominant mass inflow is from head bay around Waitonahitu outfall (Passo area). At 25 – 30 m depth around deepest point of IAB near to sill the current speed is between...
0.15 – 0.27 m/s (Figure 8e, 8f). This indicate the slightly strong vertical eddy (clockwise) that current vector in this point is stronger than others side in IAB. In high tide phase the current inflow is higher around coastal Wayame about > 0.5 m/s. This inflow turns over to coastal Tantui and return to ocean boundary condition. Current speed in sill is around 0.03 – 0.06 m/s at surface layer. In 0.25 – 15 m depth the mass inflow will enter to IAB and collide with mass inflow from middle bay. This accident inflicts the turbulent in front of the sill (on IAB side).

In cross section phase flood tide the mass inflow headed to IAB with current speed around 0.15 – 0.4 m/s and can reach deepest point of IAB. This makes surge of current vector that reflected to surface layer. The dominant vertical eddy (anticlockwise) occurs in middle bay to head of the bay. In high tide phase, the turbulent emerge in front of Poka-Galala sill and occur the double vertical eddy in front sill, also along the middle bay until head of the bay (Passo area).

Figure 8. Model result of baroclinic circulation in dry season at flood tide phase

3.3 Model particle tracking in rainy season and dry season

3.3.1 Pattern of particle tracking in rainy season. Model result of particle tracking in rainy season shows in Wilata river reach the sill in 4 day but do not pass the sill. It turns over to IAB in west side around Waieru area and then move forwards back to sill straight exit to OAB in day 8th (Figure 9a). Probably change direction of the particle due to the strong flood tide phase in day 4th, it inflicts mass inflow drive the particle re-enter to IAB.

The particle pattern from Waiguru-guru rivers are move circling in middle of IAB (Figure 9b). This happened due to horizontal eddy that assumed occur in barotropic mode of IAB [5]. In other side,
the particle from Waihunut river is go straight to exit of IAB in 1 day and 19 hours (Figure 9c). Particle from Wailata river dominantly drift along coastal of Halong and shoved by ebb phase to exit IAB. The particle from Waieru river across coastal Passo and drift along Lateri coastal to Halong and exit IAB in 7 day (Figure 9d). The longest particle stay in IAB is from Waisala river which is more than 29 day. The particle move circling in middle of IAB to coastal Passo and exit of IAB (Figure 9e). This probably due to particle buoyancy and resistance of coagulation [10].

Generally the particle from Waitonahitu move along coastal Lateri then straight to Halong and finally exit IAB with dominant pattern drift across east OAB (Figure 9f). The particle from Waireka river started moving along Passo area to Waieru coastal and cross middle bay headed to Halong coastal then exit of IAB (Figure 9g). This particle movement similar with particle from Waitonahitu inclined across east side of OAB. The particle from Air-Besar move across middle bay to coastal hunut and eventually circling around Poka-Galala sill then exit of IAB. The circling movement around the sill it probably cause of turbulent and vertical eddy near the sill [5, 19]. In general the residence time of particle in IAB is about 3 – 10 day, and IAB need 9 – 18 day for flushing out the particle.

Figure 9. Model result of particle tracking in rainy season

3.3.2. Pattern of particle tracking in dry season. The result of simulation model in dry season shows the particle movement from Wailata river is straight exit from IAB in 1 day and 5 hours (Figure 10a). While the particle from Waiguru-guru rivers need 1 day and 8 hours to exit from IAB (Figure 10b). After exit of IAB the particle from Wailata river drift along west coastal of OAB and in east side is particle from Waiguru-guru river.

The particle movement from Waihunut river across middle bay and turn over coastal Halong until Lateri in generally the particle circling along bay for 20 day (Figure 10c). The particle from Wiheru river move along middle bay to exit of IAB in 4 day and this particle drift to east coastal of OAB (Figure 10d). The pattern of particle from Waisala river near to Waieru rivers need 9 day and 10
hours to exit the IAB (Figure 10e). While the particle from Waitonahitu rivers dominant drift to Lateri coastal until Halong and exit of IAB in 7 day (Figure 10f). The particles from Waireka river move circling in outfall and then drift around Halong coastal until exit of IAB (Figure 10g). Whereas the particle from Air-Besar river moves along middle bay to around Passo coastal then go to Waiheru waters and turn over to middle bay for exit of IAB (Figure 10h). Basically in dry season the residence time of particle in IAB is about 1 – 4 day and around 3 – 10 day for flushing it out of IAB.

4. Conclusion
The verification model of tide current, temperature, and salinity between the model and measurement result is well matched in pattern and magnitude. In baroclinic mode the vertical eddy dominant happen in the middle of IAB and in front of Poka-Galala sill. This vertical eddy conduce by topography configuration and stratification water mass due to the rivers inflow. The seasonal effect to water mass circulation in IAB is shown in current speed in Poka-Galala sill. Wherein Rainy season the current speed is higher than in dry season.

In model simulation of particle tracking in rainy season, the pattern of particle movement from rivers Wailata, Waiguru-guru, Waihunut, Waiheru, and Waisala occurs dominantly in the middle of the bay, while particle from Waitonahitu, Waireka, and Air-Besar rivers dominantly drift along coastal of Lateri and Halong with the average of residence time is 5 day and for flushing time is 9 day. In dry season the movement pattern of particle from rivers Waihunut, Waiheru, Waisala and Air Besar is dominantly drift in the middle of the bay. The average of residence time of particle in dry season is 2 day and IAB need 5 day for flushing out the particle.
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