Variation of water mass exchange on tidal scale in Balikpapan Bay

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Abstract. Balikpapan Bay is enclosed water influenced by freshwater from river runoff and saline water from Makassar Strait. The exchange of water mass was examined by 3D numerical model simulation-Hamburg Shelf Ocean Model (HAMSOM) with horizontal resolutions approx. 150 m and 10 vertical layers applied in Balikpapan Bay. The thirteen tidal components, daily river runoff, atmospheric forcing, subsurface temperature, and Salinity in 3D used for model input. The tidal elevation from Geospatial Information Agency (BIG) model fits with this result from 01/03/2020 to 31/03/2020. It has coefficient correlation 0.99 with a significant level of 95% and Root Mean Square Error (RMSE) is 0.1 m. The volume and salt transport in the mouth (Line-A) and middle (Line-B) of bay was examined. The maximum transport in Line-A during spring (neap) high to low tide and low to high tide is -18364.72 m$^3$/s (-1717.57 m$^3$/s) and -17532.27 m$^3$/s (4258.86 m$^3$/s) for volume. Then, 531,947,898.90 kg.psu./s (-45,127,135.38 kg.psu./s) and -536,410,944.50 kg.psu./s (140,700,437.97 kg.psu./s) for salinity. Positive (negative) of water transport is inflow (outflow) to Balikpapan Bay. The net transport in a day during the spring (neap) is -832.45 m$^3$/s (5976.43 m$^3$/s) for volume and -4,463,045.58 kg.psu./s (185,827,573.35 kg.pau./s) for salt. The vertical structure of net volume and salt transport bot in Line-A and Line-B shows the water goes to outer bay in surface and inner bay in subsurface. While in the spring tide the surface deeper than neap tide. It indicated that water mass exchange dominantly influenced by river in surface and tidal in subsurface. It also shows that water mass from inner bay more easy flushing during spring tide than neap tide and vice versa.
1. Introduction
Indonesia national capital city will be moved to East Kalimanta [1]. Some area in Penajam Paseur Utara and Kutai Kartanegara, East Kalimatan will be the new national capital city candidate [2][3]. It located in Balikpapan Bay coastal area. The occupation area for central zone planed 2000-3000 ha [4]. It around three till five times the capital city of Jakarta area.

The infrastructure development regarding to supply national capital needs has started in 2020. The development of Sepaku-Semoi water dam is one of these projects [5]. It will be reduced and change the seasonal pattern of river run off. The natural river flow influenced by seasonal precipitation. In Kalimantan the precipitation pattern changing by following Intertropical Convergence Zone [6].

Balikpapan bay is semi enclosed water affected by ocean and land area [8][9]. Saline water moves to inner bay dominantly generated by tide and freshwater flow to bay following the river. The tidal and river flow has driven the dynamic in water column of Balikpapan Bay [2][8][9]. Thus, the changing of river run off in future will be affected to the dynamic system in Balikpapan Bay.

The 3D and hourly model output from Hamburg Shelf Ocean Model (HAMSOM) have been analyse. It reveals preliminary result of water mass exchange in Balikpapan Bay before Capital City established in Penajam Paseur Utara. It will be focusing to investigate the water mass exchange by using volume and salt transport approach [10]. The 3D and time series of volume and salt transport in Balikpapan Bay could represent the water mass exchange.

2. Methods

2.1. Numerical model and verification

HAMSOM is acronym from Hamburg Shelf Ocean Model. The early version of HAMSOM was built by Beckhaus in 1984. Then, it developed by [11]. The latest version of the source code was provided by [12]. HAMSOM has been successfully to describe the ocean process in Indonesia and its surrounding waters. Such as studied water mass transport in Karimata Strait [10], examine the oil spill in Pari Island waters [13], explain the dynamic process of upwelling in Southern part of Java [14], found the Makassar jet [11], and revealing the coastal upwelling mechanism in Arafuru Sea [15]. The model used Arakawa-C for horizontal and z-coordinate for vertical. In this time, the model run by using 3-dimensional baroclinic mode. It applied to examine the physic and dynamic of ocean circulation in Balikpapan Bay with focusing on water mass exchange.

The model in Balikpapan Bay consists of 4,58’ x 4,58’ (~150 m) for horizontal resolution and 10 vertical layer. The thick of vertical layers are 4 m, 4 m, 5 m, 5 m, 5 m, 5 m, 5 m, 5 m, 10 m, and 10 m. The source of bathymetry data retrieved from Naval Chart [16] and National Bathymetry Data (BATNAS) [17]. The model area shows in Figure 1. The model input consists of tides, meteorological forcing including wind speed, river discharge, temperature, and salinity in whole area also in open boundary.

The tides use 13 tidal components. They are Q1, O1, P1, K1, N2, M2, S2, K2, Mf, MM, M4, MS4, and MN4. It derived from Oregon State University (OSU) - TOPEX/Poseidon global tidal model (TPXO) 9.1 [18]. Then the meteorological forcing is wind speed, precipitation, evaporation, temperature, and solar radiation. They are change periodically in 6 hour or 4 data per day. They retrieved from The National Centers for Environmental Prediction (NCEP) reanalysis 2 [19]. Then, the river discharge flow in four river mouths. They are Riko, Wain, Sepaku and Semoi rivers. The daily mean of river discharge derived from Global Flood Awareness System (GloFAS). It is an operational system of the European Commission’s Copernicus Emergency Management Service [20]. The initial value of horizontal and vertical temperature and salinity used monthly climatological mean from World Ocean Atlas (WOA) v.2 [21]. Then the open boundary of temperature and salinity with 6 hourly data supply.
by The Max Planck Institute Ocean model (MPI-OM) prepared by [11]. Then, the model was run for two years (2019-2020) with time step 60 second.

![Figure 1. Map of Balikpapan Bay and Its surrounding water. The red triangle is location of tidal elevation verification between BIG model and HAMSOM model. The black line is a transect to calculate water mass transport. The blue rounds are river main mouth.](image)

In this research focusing to tidal time scale thus we analyse the hourly data in one month of 1-31 March 2020. For verification of water level will used hourly data model from BIG [22]. Then for temperature and salinity will use the data survey from [2]. The verification of water level will be applied Root Mean Square Error (RMSE) for investigate the differences of water level. Then for check the phase of the HAMSOM model and BIG mode will be applied coefficient correlation. The equation of RMSE and correlation shows in equation 1 and 2.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (x_i - y_i)^2}{n}}$$  

(1)

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$  

(2)

With,
- $r$ is coefficient correlation ($-1 \leq r \leq 1$)
- $n$ is quantity of data
- $x$ is variable of data observation/trusted model output
- $y$ is variable of model output
If the correlation more than 0.3 with significant 95%. It means both of HAMSOM and BIG is clearly in similar pattern. Then for RMSE could understand the HAMSOM model was underestimate overestimate to BIG model. The BIG model is a tidal model derived from the station data all around Indonesia seas. Thus, the output of water level from BIG model could be trusted as like as observation.

2.2 Water mass transport
Calculation of water mass exchange will be approached by using water mass transport. This research will be employed the volume transport and salt transport [10][23][24]. The volume and salt transport will be calculated following equation 3 and 4.

\[ F_v = \int_A u \, dA \]  
(3)

\[ F_s = \rho \int_A S \, u \, dA \]  
(4)

With,
- \( F_v \) is volume transport (m³/s)
- \( F_s \) is salt transport (kg.psu. /s)
- \( \rho \) is water density (kg/m³)
- \( S \) is salinity (psu)
- \( A \) is cross-section transect area (m²)
- \( u \) is perpendicular of current vector with cross-section transect area (m/s)

The orientation of water mass transport in Line-A and Line-B (see Figure 1.) is north – south. Thus, the positive (negative) of transport refers to northward/inflow (southward/outflow) in Balikpapan Bay.

3. Results and discussion
3.1 Model verification
Hourly data of sea surface high from HAMSOM and BIG on 1-31 March 2020 shows in Figure 1. The correlation both is 0.99 of significant level 95%. It means the model has a similar pattern in time series data. Then the RMSE shows almost 0.1 m. The HAMSOM model was overestimate than BIG model. It caused the HAMSOM model was run in baroclinic mode. It also adding river discharge. It will be significant impact to sea surface high. In other condition, the RMSE is only 0.004 m. It happens when the input of model only tides and run in barotropic mode.

Figure 2. Sea surface high at red triangle in Figure 1. on 1-31 March 2020. The blue is derived from BIG, and the orange is output of HAMSOM.
The tidal range is almost 2.5 m in spring tide and 1 m in neap tides. While the daily tide has a semi diurnal [2][8][9]. It appears two peaks of high tides and low tides in a day. During spring tide, the sea level high differences between high tide first and second is almost zero. But in neap tide the differences is around 0.2-0.3 m with the second high tide is lower than first high tide. In this case, it caused the effect of baroclinic forcing and river discharge. It will be impact to the water mass transport in Balikpapan Bay.

3.2. **Time series water mass transport**

The tidal condition will be figuring the dynamic of Balikpapan Bay. Thus, the hourly data of water level, total volume and salt transport shows in Figure 2. The water level retrieved from the red triangle in Figure 1. The total volume and salt transport calculated by sum up from bottom to surface in line-A and line-B. Both of volume and salt transport reveal twice a day on high and low tide in lunar day. It correlates with the water level [2][8].

The peak of water level during high and low is slack water. Thus, the volume and salt transport almost zero. But, when the water level move from high to low or vice versa. It generates the transport southward/outflow or northward/inflow to the inner bay [2][8][9]. The nett of total volume transport in Line-A (Line-B) is -309,057.433 m$^3$/s (-246,504.732 m$^3$/s) on a month. Meanwhile, the net of total salt is -5,704,533.930 kg.psu./s (-2,485,688.920 kg.psu./s). It reveals that the net of water mass exchange goes to southward or outgoing to Makassar Strait.

In the other hand, the daily water mass transport during spring and neap tide has a unique characteristic. It correlates to the tidal dynamic. The yellow (red) box in Figure 3 shows a lunar day during neap (spring) tides. The peak of inflow(outflow) volume transport is 4258.863 m$^3$/s (-1717.568 m$^3$/s) in Line-A and 2169.648 m$^3$/s (-988,508 m$^3$/s) in Line-B during neap tide. While, in spring tide is 17,532.266 m$^3$/s (-18,364.720 m$^3$/s) in Line-A and 9,179.935 m$^3$/s (-9,574.993 m$^3$/s). Then, the net of the total volume transport during neap (spring) tide in Line-A is 5,976.431 m$^3$/s (-832.454 m$^3$/s) and 3,158.156 m$^3$/s (-395.058 m$^3$/s) in Line-B.

The net total volume transport during neap tide is positive. It means that the water volume ‘trapped’ in inner bay. Although, it happened in few hours during a day. Then, the spring tide reveal the negative and small value. It means that the water mass exchange ‘flush’ in a day. It going to outer of bay.

Figure 3. Sea Surface high at red triangle in Figure 1. (a), volume transport in Line-A and Line-B (b), and Salt transport in Line-A and Line-B (c) on 17-31 March 2020. The yellow box shows the neap tide while the red ones during spring tide. The positive(negative) transport is northward(southward)
Both of net total volume transport in Line-A and Line-B on spring tide shows the small number than the neap tide. It indicated that water mass exchange in Balikpapan Bay during spring tide is easy to flush. Otherwise, the neap tide gives an affect to ‘trap’ the water mass in inner bay. This fact reveals that the dynamic of Balikpapan Bay in the total depth generate by tidal forcing. The investigation of vertical characteristic explained in the next section. It admits the generate forcing in the dynamic of Balikpapan Bay and Its surrounding waters.

3.3. Vertical structure of water mass transport

The total transport during neap tide admits the water mass ‘trap’ in inner bay for several time. While the spring tide, it goes to Makassar Strait or outer bay. Then, to investigate the role of every layer, the transport should plot on vertical structure. Here the Figure 4 and Figure 5 appear to explain it. The volume transport shows in Figure 4 while the Figure 5 present the salt transport.

The vertical variation of volume transport during neap tide shows the opposite direction from surface to near bottom (Figure 4). It appears both Line-A and Line-B. The magnitude and direction on vertical transport during neap tide more vary than spring tide. But the net volume transport in neap and spring tide vertical variation has similar pattern. However, the volume transport in the spring tide more goes to outer bay than in neap tide and vice versa. This phenomenon detected that the water mass exchange in surface deriver by river discharge. Then the tidal push and pull the water mass dominantly in subsurface. It indicated the tide and river run off in Balikpapan Bay has an important role to generate tidal mixing [10].

![Figure 4](image-url). Volume transport on neap tide during peak inflow (a), outflow (b) and the differences both (c) in Line-A. (d), (e), and (f) in Line-B. While the spring tide during peak inflow (g), outflow (h) and the differences both (i) in Line-A. (j), (k), and (l) in Line-B.
The water level move from low to high tide generate the water transport from Makassar Strait to Balikpapan Bay. Figure 4a, 4d, 4d, and 4j show the vertical transport during neap tide in Line-A, Line-B, Spring tide in Line-A, and Line-B respectively. The vertical structure of water mass transport during neap tide has different direction from surface to bottom. The transport volume goes to southward or outer bay in surface whit magnitude less than -50 m$^3$/s in Line-A and 30 m$^3$/s in Line-B. Then it goes to inner bay in subsurface till bottom with maximum magnitude 150 m$^3$/s and 120 m$^3$/s in Line-A and Line-B respectively. The spring tide condition generate volume transport to northward or inner bay with magnitude 150 m$^3$/s - 300 m$^3$/s both Line-A and Line-B.

When high water level move to low water level the transport on surface to -5 m goes to outer bay with magnitude reach 150 m$^3$/s for each grid. Then in -5 m to -20 m goes to inner bay with maximum magnitude 50 for each grid in Line-A. While in Line-B, the volume transport goes to outer bay more deeper 2 m than in Line-A with maximum magnitude around 140 m$^3$/s. Then, the volume transport goes to inner bay in subsurface reach the maximum -60 m$^3$/s in each grid. The size of line-A is longer than line-B but similar in depth. Thus, the volume transport keeps the continuity rules. The similar condition in spring tide shows the uniform direction both Line-A and Line-B. The magnitude increases from surface to bottom around -400 m$^3$/s to -100 m$^3$/s.

![Salt transport](image)

Figure 5. Salt transport on neap tide during peak inflow (a), outflow (b) and the differences both (c) in Line-A. (d), (e), and (f) in Line-B. While the spring tide during peak inflow (g), outflow (h) and the differences both (i) in Line-A. (j), (k), and (l) in Line-B.

The salt transport pattern follows the volume transport pattern. It causes the main driven of transport is volume transport. But in salt transport the salinity has adding as an indicate the salt. The vertical structure of salinity and current speed will be ruling the salt transport in general.
4. Conclusions
HAMSOM has successfully assessed the hydrodynamic condition in Balikpapan Bay on tidal time scale. Even though it applied the baroclinic model, the tidal cycle figure clearly with twice a day of high tide and low tide. The RMSE of tidal elevation between BIG model and HAMSOM model is 0.1 m. It means that the HAMSOM model overestimate around 0.1 m than the BIG model in water level. It signifies that the river runoff has an important role in the dynamic of surface Balikpapan Bay.

The water mass in Balikpapan Bay more flux in spring tide than in neap tide. The vertical structure of volume and salt transport shows the different direction in neap tide and similar direction in spring tide during tidal cycle. The river runoff shows influenced the vertical transport in the upper layer. Then the tidal generate in the subsurface. The river runoff effect not really clear during spring tide while in neap tide it exists.

The net transport in a day during the spring (neap) is -832.45 m$^3$/s (5,976.43 m$^3$/s) for volume and -4,463,045.58 kg.psu./s (185,827,573.35 kg.pau./s) for salt. Here we could see that more forty times salt transported from the ocean to inner Bay during neap tide than spring tide.

References
[1] Ihsanuddin 2019 Kompas (Jakarta) p.1
[2] Putri M R, Anwar I P, Sihotang Z, Bernawis L I, Setiawan A, Mandang I, Tatipatta W M. 2021 J. Depik 10(2).
[3] Putri M R, Sari T, Anwar I P, Mandang I, Setiawan A, Tatipatta W M. 2021 IOP Conf. Ser.: J. of Phy. 1763.
[4] Ramadhani Y 2019 Tirto (Jakarta) p.1
[5] Biro Komunikasi Publik 2019 Rilis PUPR SP.BIRKOM/XII/2019/587 (Jakarta) p.2
[6] Hendrizan M, Ningsih N S, Cahyarini S Y, Putri M R, Setiadi B, Anwar I P, Utami D A and Agusta V C 2020 Int. J. Ocean. Oceanogr. 14 197–220
[7] Dubois N, Oppo D W, Galy V V, Mohtadi M, van der Kaars S, Tierney J E, Rosenthal Y, Eglinton T I, Lückge A, and Linsley B K. 2014 Nature Geoscience 7 513-517.
[8] Nur A A, Mandang I, Mubarrok S, and Riza M 2018 IOP Conf. Ser.: Earth Environ. Sci. 162
[9] Hermansyah, H, Ningsih N S, Nabil, Tarya A and Syahruddin 2020 J. Ilmiah Perikanan dan Kelautan, 12(1) 9–20.
[10] Anwar I P, Putri M R, and Setiawan A 2018 IOP Conf. Sef.: Earth Environ. Sci. 162.
[11] Pohlmann T 1996 Continental Shelf Research 16(2), 131–146.
[12] Mayer B and Pohlmann T. 2017 J. Ilmu dan Teknologi Kelautan Tropis 9(2) 657-664.
[13] Egbert D E and Erofeeva S Y 2002 J. of Atm. Oce. Tech. 19 183-204.
[14] Lialalidiajwati 2016 Spektra: Jurnal Fisika dan Aplikasinya 1(1) 69-76
[15] Nurfitri S, Busit A, Putri M R, Patsch J, and Pohlmann T. 2020 IOP Conf. Sef.: Earth Environ. Sci. 618.
[16] Pushidros TNI-AL 2016 Naval Chart
[17] Pusat Pemetaan Laut dan Lingkungan Pantai-BIG 2019 BATNAS BIG
[18] Banyumati, M., W. Ebisuizaki, J Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002 Bull. Amer. Meteor. Soc. 83 1631-1643.
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