Freshwater intrusion during ebb and flood tide in the Balikpapan Bay

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Abstract. The Balikpapan Bay waters is influenced by freshwater discharge from many rivers and its distribution is affected by tidal current. This study aims to estimate seawater intrusion during flood and ebb tides, using the box model and freshwater fraction methods. The data used in this study for calculating freshwater fraction and its transport volume were 45 conductivity-temperature-depth CTD casts and single moored ADCP current measurement, carried out between 17 and 25 May 2018. The budget of the box model system is calculated using evaporation and precipitation data. The results show that estimated freshwater fraction and transport volume during flood tide vary between 16.92 and 36.26%, and between 2.048 and 9.661x10^9 m^3/day^-1, respectively. Near the entrance of the bay, seawater flux urges freshwater westward with surface salinity budget of -95.352x10^6 psu.m^3.day^-1. Furthermore, during ebb tide, freshwater fraction and transport volume are estimated to be 19.33 – 34.5% and 2.048–9.661x10^9 m^3/day^-1, respectively. Near the mouth of estuary, freshwater pushes seawater toward east side of the bay with salinity budget of -186.187x10^6 psu.m^3.day^-1. During flood tide (ebb tide) estimated surface salinity budget in transect 5 that came out from the system is about -135.512x10^6 psu.m^3.day^-1 (-143.794x10^6 psu.m^3.day^-1) toward the southern bay.

1. Introduction
Balikpapan Bay is located between Balikpapan City and Penajam Paser Utara District. The hydrodynamics in Balikpapan Bay waters is influenced by rivers discharge and tidal forcing that control distribution of salinity, circulation patterns, and sedimentation. The tide forcing cause different input of seawater. On tidal cycle, salinity near estuary varies greatly following the tidal condition [1].

Freshwater intrusion near estuary causes the difference in the composition, chemical properties, and physical properties of salinity [2]. Freshwater intrusion in estuarine is affected by tides that interact with wind pressure, deep friction, and bottom friction. This interaction affects the density distribution in the water column [3].

Previous study using the box model method in Indonesian seas has been developed in the Delta Mahakam by Hadikusumah and Marojahan [4], in Ciliwung Estuary by Suryono and Moersidik [5], and in Matasiri Waters by Nasution [6]. The study of freshwater fraction method has been conducted in Tokyo Bay by Nurjaya [7] and in Balikpapan Bay by Sulardi [8]. The relatively closed water system and the large number of estuaries that flow along the bay need to be further studied. The objectives of this paper is to estimate the amount of freshwater intrusion during ebb tide and flood tide using freshwater fraction method and box model.
2. Data and method

2.1. Study area
The study area is located in the Balikpapan Bay, eastern part of Kalimantan, Indonesia (Figure 1). There are four transects crossing the bay (TR1 – TR4) and one transect along the bay (TR5). The field observations were conducted from 18 to 25 May 2018, as part of joint collaboration between Oceanography Division of IPB and PT Pertamina.

Figure 1. Location of study area in Balikpapan Bay.

2.2. Datasets
The ADCP current profiler, CTD, and tide datasets were obtained from field measurement. Besides that, we used air temperature and rainfall data, downloaded from Meteorological, Climatological, Geophysical Agency (BMKG) website and bathymetry data from Geospatial Information Agency (BIG) website. The datasets and its sources are presented in Table 1.

| Datasets             | Sources of the data                                      |
|----------------------|---------------------------------------------------------|
| Air temperature      | BMKG (http://dataonline.bmkg.go.id)                    |
| Rainfall data        | BMKG (http://dataonline.bmkg.go.id)                    |
| Spatial currents     | Marine Copernicus (http://www.marine.copernicus.eu)    |
| Salinity reference   | P2O-LIPI                                                |
| Bathymetry           | BIG (http://tides.big.go.id/DEMNAS/index.html)          |
| Tides                | BIG (http://tides.big.go.id/pasut/index.html)           |

Moored Argonaut-XR ADCP for current measurement was deployed for 6 day (18-25 May 2018) with frequency of 0.75 MHz, bin interval of 3m, and sampling interval time every 5 minutes. The CTD
Minos X version 1.87 were used during field measurement. Number of 47 CTD casts which consist of 4 cross-sections and 1 along-section of the bay have been measured. The tidal sea level elevation was recorded by Moritide with sampling time every 5 minutes at the same time with the CTD observations. Finally, we used 2003 archived-data of CTD SBE 911 plus offshore Balikpapan Bay for a reference of salinity representing the Makassar Strait. The data was obtained from Research Center for Oceanography, Indonesian Institutes of Sciences (P2O-LIPI).

2.3. Procedure of data analysis

2.3.1 Tide. Ten years (1 January 2009 to 1 January 2019) of BIG’s tidal data were analysed to obtain the type of tides and its tidal datum in Balikpapan Bay. Reanalysis data were used to validate the tide data from observation. The Root Mean Square Error (RMSE) is used to check the accuracy of both data.

2.3.2 Current. Copernicus model current data and u (zonal) and v (meridional) component from ADCP were analysed using pyferret 7.1. Copernicus current data have a spatial resolution of 1/12° with an interval of 1 hour in the surface layer. Spatial distribution currents were analysed on May 23, 2018 when heading the flood tide and May 20, 2018 when heading ebb tide. Temporal currents were analysed from 19 to 24 May 2018.

2.3.3 Box model. Determination of box model layer based on salinity stratification and topography of the Balikpapan Bay waters. The upper layer when heading flood and ebb tide in Transect 4 is analysed at a depth of 0-2 m and the lower layer at a depth of 2-4 m. The upper layer and lower layer in Transect 5 when heading flood and ebb tide are analysed at a depth of 0-3 m and 3-6 m.

Box model analysis follows Gordon et al. [10] as shown in the equation below:

\[ 0 = \sum \text{input} - \sum \text{output} \]  

(1)

At the upper layer there will be input from freshwater (\( V_R \)) flowing into the sea. The surface water (\( V_{\text{surf}} \)) budget equation is as follows:

\[ V_{\text{surf}} = V_R - V_{\text{deep}} \]  

(2)

with freshwater input according to Swaney and Giordani [11]:

\[ V_R = -(V_Q + V_p + V_g + V_O + V_E) \]  

(3)

In this study several assumptions are applied to simplify the calculation of freshwater input, such as the system is in a steady state, input is positive, output is negative. In addition, the value of the river discharge budget, the groundwater budget, and the budget from other influences sources are not included in the calculation. Then substitute \( V_R \) to equation 3. The water balance in the surface layer is:

\[ V_{\text{surf}} + V_Q + V_p + V_g + V_O + V_E + V_{\text{deep}} = 0 \]  

(4)

Assuming that there is no freshwater budget that brings salinity, the salinity balance on the surface layer is:

\[ V_{\text{surf}} S_{\text{sys-s}} + V_{\text{deep}} S_{\text{sys-d}} + V_s (S_{\text{sys-d}} - S_{\text{sys-s}}) = 0 \]  

(5)

Then to balance the salinity of the lower layer:
Seawater from the lower layer replaces the water budget on surface layer:

\[
V_{\text{deep}}S_{\text{ocn-d}} - V_{\text{deep}}S_{\text{sys-d}} - V_{\text{surf}}(S_{\text{sys-d}} - S_{\text{sys-s}}) = 0 \tag{6}
\]

In order for the system to remain balance, the water in the upper layer and the lower layer must experience mixing. Vertical water budget equation which experiences mixing (Vz) as follows:

\[
V_{\text{z}} = V_{\text{deep}} \frac{(S_{\text{ocn-d}} - S_{\text{sys-d}})}{(S_{\text{sys-d}} - S_{\text{sys-s}})} \tag{7}
\]

The freshwater salinity budget (VQSQ) enters and exits from the upper layer and become surface salinity budget (Vsurf Ssurf−s). The ocean salinity budget (Vdeep Socn-d) will intrude through the lower layer and mix with the upper layer Vz(Ssurf−s − Ssurf−s).

2.3.3 Salinity anomaly. Salinity anomaly analysis is used to explain the mass of seawater that mixes with freshwater mass. According to Nurjaya [7], salinity anomaly value is defined as follows:

\[
S'(x, z) = S(x, z) - S_{\text{ref}}(z) \tag{9}
\]

where \(S'(x, z)\) is the salinity anomaly value (psu) at station \(x\) with depth \(z\) (m), \(S(x, z)\) is the salinity value (psu) at station \(x\) with depth \(z\) (m), and \(S_{\text{ref}}\) is the reference salinity value (psu) at each \(z\) depth (m). The reference station is located offshore the Balikpapan Bay in the Makassar Strait with coordinates of 117.525 E and -1.599 S. The reference salinity value is 34.625 psu at 34 m depth.

2.3.3 Freshwater fraction. Freshwater fraction analysis explains quantitatively the freshwater which has an intrusion into seawaters which will then experience mixing. This analysis uses reference salinity values that are assumed to be far from freshwater sources [12]. According to Nurjaya [7] and Pettigrew et al. [12], freshwater fraction values are defined as follows:

\[
F(x, z) = \frac{S_{\text{ref}}(z) - S(x, z)}{S_{\text{ref}}(z)} \tag{10}
\]

where \(F\) is value of freshwater fraction, \(S_{\text{ref}}\) is the reference salinity value (psu) at each \(z\) depth (m), and \(S(x, z)\) is the salinity value (psu) at station \(x\) with depth \(z\) (m). Average value of freshwater fraction is defined as follows:

\[
F_{\text{r}} = \frac{1}{h} \int_{-h}^{0} \frac{S_{\text{ref}} - S}{S_{\text{ref}}} \, dz \tag{11}
\]

where \(F_{\text{r}}\) is the average value of freshwater fraction in a transect, \(h\) is the water depth of each station (m) and \(S_{\text{ref}}\) is the reference salinity value. The reference salinity value is 34.625 psu.

2.3.3 Transport volume of freshwater mass. Transport volume of freshwater mass analysis is performed to calculate the mass of fresh water flowing out of the bay. The value of transport volume of freshwater mass is calculated following Blanton et al. [13], Fang et al. [14], and Nurjaya [7] which is defined as follows:

\[
V_{\text{fw}} = \int_{A} F_{\text{r}} \, u \, dA \tag{12}
\]
V_{fw} is the transport volume of freshwater mass (m$^3$s$^{-1}$), $F_r$ is freshwater fraction, $u$ is the average current velocity along the transect (ms$^{-1}$), and $A$ is the area of freshwater mass (m$^2$). The area of freshwater mass is determined from the cross-section of salinity anomalies with values less than zero.

3. Results and discussion

3.1. Dynamics of Balikpapan Bay

Tidal elevation and its tidal current in the Balikpapan Bay during CTD observations is shown in Figure 2. In order to get a more detail of tides condition in Balikpapan Bay, we reanalyzed tidal data from January 2009 – January 2019. Validation (the RMSE value = 0.093) shows a high accuracy between observation and re-analyzed data of BIG [15]. From 10 years tidal data, we analyzed the type of tide in Balikpapan Bay is mixed tide prevailing semidiurnal (Formzahl number = 0.44), the MSL is $-4.65 \times 10^{-5}$ m, HW and LW is 1.59 m and -1.27 m, respectively. These results agreed well with Soeyanto and Arifiyana [16] and Sinaga et al. [17]. They reported that the tidal type in Balikpapan Bay is a mixed tide prevailing semi-diurnal with Formzahl numbers of 0.37 and 0.54. The tides indicate twice floods and ebbs in one day, and sometimes occur one flood and ebb tide with a different height and time of occurrence. The tidal period in Balikpapan Bay ranges from 6-7 hours per day [8].

Figure 2b is temporal of tidal current velocity and Figure 2c is a tidal current at a depth of 0-3 meters in Balikpapan Bay. Current velocity at a depth of 0-3 meters of 0.018-0.647 ms$^{-1}$. The average of current velocity at a depth of 0-3 meters of 0.199 ms$^{-1}$. Temporal of current velocity and tidal current patterns are almost similar that means these results are in good agreement [18], where water circulation within the Balikpapan Bay is dominated by currents generated by the tides. When flood tide, the current moves northwestward and when ebb the current moves southeast.

To get spatially distribution of current around Balikpapan Bay, we presented Marine Copernicus model data on May 23, 2018 during flood tide and May 20, 2018 during ebb tide (Figure 3a and 3c) and MIKE model in July [7] (Figure 3b and 3d). The results of the spatial distribution of currents in figures 3b and 3d were analyzed by using wind, tidal, water density difference, and hydrostatic pressure of waters as forcing forces [18].

Current patterns when heading the flood tide in the East Kalimantan waters are directed to the southwest with an average speed of 0.484 ms$^{-1}$ (Figure 3a). Current movements when heading the ebb tide are directed to the northeast with an average speed of 0.371 ms$^{-1}$ (Figure 3c). The current patterns that analyzed from Marine Copernicus data is in accordance with the results of previous research [18] in Balikpapan Bay Waters, when heading the flood tide, the current moves into the bay and when heading the ebb tide, the current flows from inside the bay to the east of the bay (Figures 3b and 3d).
**Figure 2.** Tidal height for 6 days of field observations when heading flood tides (●) and ebb tides (○) (a), temporal of current velocity (b) and tidal current (c) at a depth of 0-3 meters in Balikpapan Bay.
3.2. Box model

The results of the freshwater budget are presented in Table 2 while the box model when heading flood tide in the Balikpapan Bay is shown in Figure 4. The surface salinity budget (Vsurf.Ssys-s) when heading the flood tide flows to the West of Balikpapan Bay is $-95.352 \times 10^6$ psu.m$^3$/day$^{-1}$ (Figure 4), while the surface salinity budget when heading for ebb flows to the east of Balikpapan Bay for $-134.785 \times 10^6$ psu.m$^3$/day$^{-1}$ (Figure 6). When heading the ebb tide in the mouth area of the bay, freshwater flows to the east of the bay as far as 12.22 km, whereas when the waters head to flood tide, sea water from the east flows into the bay and pushes the mass of fresh water as far as 7.44 km to the west of the bay. This is consistent with the direction of the current in the region at the time (Figures 3a and 3b) and with the cross section of salinity (Figures 5a and 5b) when heading the flood and ebb tides.

Table 2. Water budget in Balikpapan Bay.

| Water Budget             | Value      | Unit             |
|--------------------------|------------|------------------|
| Precipitation Budget ($V_p$) | 0.401      | $x \ 10^6$ m$^3$/day$^{-1}$ |
| Evaporation Budget ($V_e$)    | 0.015      | $x \ 10^6$ m$^3$/day$^{-1}$ |
| Freshwater Budget ($V_R$)     | -0.386     | $x \ 10^6$ m$^3$/day$^{-1}$ |

The surface salinity budget is getting smaller with the increasing distance of the station from the bay head. The surface salinity budget when heading to flood and ebb tide in the bay area (Transect 5) shows that freshwater is still found along the bay but has increased at a distance of 26.97 km when heading to the flood tide, which is $-116.331 \times 10^6$ psu.m$^3$/day$^{-1}$ with a salinity value of 28.662 psu, while during the
ebb, freshwater pile up at a distance of 28.42 km with a salinity value of 29.328 psu and a surface salinity budget of -125.484 x 10^6 psu.m^3.day^{-1}. The surface salinity budget that flows out towards the south of the bay during the tide is -135.512 x 10^6 psu.m^3.day^{-1}, while during the ebb tide is -143.794 x 10^6 psu.m^3.day^{-1}.

Waters that have varying salinity values and form stratification will have a smaller value of mixed salinity sea water (V_{s}(S_{z})) compared to waters that tend to be homogeneous. The seawater salinity budget value is mixed when the waters are receding in the head to mouth bay area having a greater value than when the waters are heading for the tide. This is in accordance with the cross-section of salinity which tends to be homogeneous during the ebb (Figure 5). The existence of stratification of water mass affects the stability of the water mass [19]. Waters with strong stratification require a large force to have a mixing process [20].

**Figure 4.** Box model in the mouth of Balikpapan Bay when heading the flood tide. Inset: location of transect 4.

**Figure 5.** Cross section of salinity when heading flood (a) and ebb (b) tide in Mouth of Balikpapan Bay.
3.3. Freshwater fraction

The results of data analysis conducted at the time of the tide conditions indicate the highest value of the average freshwater fraction near the bay head (Figure 6). The decrease in the value of the freshwater fraction may be caused by intrusion of seawater that enters the waters of Balikpapan Bay at the time the tide conditions begin to occur. Freshwater fraction value is influenced by the process of mixing mass of water due to tidal oscillations and salinity solubility in estuary waters [21]. The freshwater fraction value in Transect 1 is greater when the water conditions are heading to the tide with the mass of fresh water flowing towards the bay. The mass of fresh water in Transect 2 flows in the direction of the bay, the Transect 3 value of the freshwater fraction is higher when the water conditions are receding with the direction of the flow of freshwater mass toward the bay exit. The freshwater fraction value in Transect 4 has almost the same value when heading the flood tide and low tide with the mass of fresh water flowing into the bay on the way to the tide and out of the bay when heading for ebb (Figure 6).

The average value of the highest freshwater fraction in Balikpapan Bay when heading flood and ebb tides was found in Transect 3, which was 36.26% and 36.26% (Figure 6). This may be related to the presence of freshwater input from a river near the transect location. The average freshwater fraction that infiltrates into Balikpapan Bay continues to increase until the Transect 3. The average size of the freshwater fraction at Transect 4 on the way to tides and ebb shows a decrease from the transect 3. When the CTD data conducted in Transect 3 is not far from the peak tide conditions on May 17, 2018 (Figure 2). Freshwater mass with lower salinity values only move up to Transect 3 and experience build up in the transect due to the influence of sea water masses from the East Kalimantan that are around the bay mouth. The seawater mass can be indicated from the salinity value in the area around the bay mouth which is higher than that of the transect within Balikpapan Bay. The characteristic of water mass dynamics in Balikpapan Bay is influenced by the tidal process where at the time of high tide the mass of water from the East Kalimantan Waters pushes the mass of water that is inside the Gulf. So that salinity during flood tide is measured higher than at ebb tide [22]. Sulardi [8] showed the value of freshwater fraction in Balikpapan Bay was high in May and the lowest freshwater fraction value was in October.

![Figure 6. Freshwater fraction when heading flood and ebb tides in Balikpapan Bay.](image-url)
3.4. Transport volume of freshwater mass
The transport volume of freshwater mass is calculated from the value of transect area, average current velocity, and fresh water fraction. It serves to describe the mass of freshwater that flows from the bay to the open sea.

Transport volume during flood and ebb tides continues to increase from the head of the bay to the mouth of the bay. In general, the transport volume value when heading ebb is higher than that during heading flood tide. The volume of fresh water flowing towards the bay mouth is slightly greater than the volume of fresh water entering the bay (Figure 7). Valle-Levinson [23] suggested that the flow in the mouth of the estuary is also controlled by the shape and the slope of the channel so that bathymetry is an important factor for understanding circulation in the estuary of the sea. Balikpapan Bay waters show shallow bathymetry. The shallow waters in Balikpapan Bay which are below 30 m with the influence of tidal currents which are more dominant will cause a variance values of transport volume in each transect [8].

![Figure 7. Transport volume of water mass in Balikpapan Bay.](image)

4. Conclusion
Based on estimates from the freshwater fraction method and box model, during flood tide freshwater intrusion revealed much greater than that during ebb tide. Freshwater intrusion fraction during flood tide is 16.92 - 36.26% with transport volume of $2.048 \times 10^9$ m$^3$day$^{-1}$. Estimated freshwater intrusion from box model method is $-95.352 \times 10^6$ psu.m$^3$day$^{-1}$ with a salinity value of 28.425 psu which is pushed towards west of the bay mouth as far as 7.4 km. During ebb tide the mass of freshwater intrusion is estimated to be 19.33 - 34.5% with transport volume of $1.084 \times 10^9$ m$^3$day$^{-1}$, while the estimated freshwater intrusion value from the box model method was $-135.512 \times 10^6$ psu.m$^3$day$^{-1}$ with a salinity value of 29.277 psu flowing out of the bay and heading east of the bay as far as 12.2 km.

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