Water mass dynamics in Balikpapan Bay, Eastern Kalimantan Indonesia

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Abstract. Balikpapan Bay (BB) located 90 km southwest of Delta Mahakam is one of estuarine systems in eastern Kalimantan directly flows into Makassar Strait. Dimension of BB is about 36 km length and between 1-14 km width, with mouth is wider than head of the bay. Water depth is much deeper (18 m) at the middle part of the bay. More than 10 secondary rivers flow into the bay to contribute large amount of freshwater mass flux. To understand physical properties and water mass dynamics, field measurement during high and low tides were conducted. The results shows that the warmer and saltier water mass are dominant at the entrance of the bay at flood period. Warmer and less salty water mass remain in the inner bay. However, during ebb, salinity is slightly decreased near the entrance and freshwater are observed in the inner bay. During both high and low tides condition, vertical stratification of water mass is very weak. The model demonstrates that this is related to large seawater flux brought by flood current from coastal waters, as well as small freshwater influx from river runoffs. Hence, the tidal dynamics significantly controls stratification and dynamics of water mass in the bay.

1. Introduction
Balikpapan bay is a semi-enclosed bay where the exchange of water masses within the bay with the mass of water outside the bay still occurs, mainly generated by tidal forcing. At high tide the flow of water that comes out of the bay is retained by the tidal masses even most of the water mass is pushed into the bay upstream [1]. In the upper reaches there are many freshwater inputs through small rivers so the salinity of the bay water at the head of the bay is lower than the salinity of the water masses at the mouth of the bay.

Well known that main function of bay is as transportation media, recreation and potential area for fishing ground, spawning ground and feeding ground for several kinds of fish [2], [3]. On the contrary, bay often undergoes sedimentation due to relatively sheltered [4], contaminated area from pollutant [5]. Freshwater from the river flow into the bay and mix with water mass from the Makassar Strait, formed salinity gradient (vertically or horizontally) from the mouth to the head of bay, on the contrary. Mixing type of water mass within bay depends on bay depth, opening of the bay’s mouth, freshwater volume flow into the bay and tidal range [6], [7], [8], [9]. Several studies have been conducted in Balikpapan Bay, for example related to the heat distribution pattern of Pertamina UP V activities in Kampung Baru [10]; mangrove vegetation [11]. Study on erosion and sedimentation in Balikpapan Bay waters of East Borneo. The bathymetry of Balikpapan Bay can be seen in figure 1. In the vicinity of bay mouth the depth can reach 22 m, the further down into the bay the depth decreases to 9.6 m in front of the Wain River, when closer to the shore the depth diminishes Up to less than 2 m [12]. [13] said that the propagation of the tidal currents from the waters of the Strait of Makassar
enters through the mouth of the bay and then moves into the head of the bay during flood and oppositely the water mass moves toward the mouth of the bay with the flow of freshwater mass coming from the tributaries that empty into the bay during ebb.

There are still many things that have not been studied in Balikpapan Bay related to some fundamental issues that must be answered in order to be able to manage the bay well. Why are some parts of the Bay more contaminated than others? What is the capacity of the Bay to assimilate watershed and in-Bay sources of contaminants and attain water quality objectives? [14]. Knowledge of the fundamental physical processes governing hydrological structures is necessary for a better understanding of complex physical-biological interactions [15]. On this paper water mass dynamics processes within Balikpapan Bay will be described. The objective of this study is to understand water mass dynamics within the Balikpapan Bay by analysing temperature, salinity and density structure as well as its currents pattern.

2. Data and data analysis

2.1. Study area

Study area is situated in the Balikpapan estuarine eastern Kalimantan Indonesia (figure 1).

![Figure 1. Bathymetry condition of Balikpapan Bay.](image)

2.2. Material and methods

Field measurement of sea level fluctuation (tide) and water circulation by tidal gauge and current meter at mooring point (figure 2) was used to calibrate the model. Salinity and water temperature were measured by CTD sensor lowered at 12 stations located along the bay (figure 2). Three stations in front of the bay mouth are obtained from INDESO (Infrastructure Development of Space Oceanography) managed by the Agency for Marine and Fisheries Research & Development under the Ministry of Marine Affairs and Fisheries of Indonesian Government.
The hydrodynamics model has been performed by using the MIKE Version 2005 software developed by Danish Hydraulics Institute (DHI) Water and Environment, Denmark. The equations used in this model are the continuity equation and the momentum equation with the average depth. This model uses a different method approach to (finite difference method) to solve the equations used. The following description of the equations used in the above model [16]. Details formulation described on [17].

Domain models are created in 4 stages, ranging from large, medium and small domains (figure 3). Models with broader domains are intended to look at external influences such as tidal propagation and wind forces.

2.3. Model verification
Verifierification of hydrodynamics model has been done by comparing the current model and field measurement. The result of verification between the model data and the measurement data is depicted on the scatter diagram on figure 4.

In figure 4 shows that the pattern of measurement current movement (blue triangle mark) is northwest-southeast direction. The pattern of current movement of the hydrodynamic model (orange quadrilateral mark) also shows the same direction, but the magnitude between the two results is still different. The measurement current data is measured at 5 m depth layer, while the model flow data is the result of the average of the depth, so that the measurement current velocity tend to be larger.
3. Results and discussion

3.1. Properties of seawater within the bay

The temperature and salinity of seawater are two parameters of oceanography that are relatively easy to measure and important in studying the dynamics of water masses. The range of temperature and salinity of certain seawater is also indispensable for marine organisms to live. Significant temperature differences within a certain area can be used to identify the upwelling phenomenon or the increase of cooled water mass from the deeper to the upper layer. Generally characterized by low temperatures compared to around it. Figure 5 is a plot of temperature and salinity data along Balikpapan Bay during tidal conditions, the color scale on the right shows the temperature and salinity values, the right-hand side image representing the transect line connecting stations as measured by their temperature and salinity values to CTD sensor (Conductivity Temperature Depth). On the left side the drawing draws toward the mouth of the bay, while the right side describes the condition toward the head of the bay.

The temperature of the seawater in the bay toward the bay head is relatively warmer than >30 °C compared to the water mass temperature around the bay mouth (<30 °C). Conversely, the salinity of the water mass around the bay mouth is higher (>29.75 psu) than the salinity of the water mass around the head of the bay (<27.75 psu).

The temperature and salinity at ebb conditions are presented in Figure 6. The bay water temperature is higher in the bay waters (30.4-30.6 °C) than in the bay mouth (30.2 °C) and bay head (<30.2 °C). Compared to the tide (>29.75 psu), the salinity of water masses within the bay at low tide is smaller, i.e. <29 psu, and its value decreases towards the head of the bay (figure 5, bottom panel). There appears to be a Low Salinity Water (LSW) trapped upstream bay with a salinity value of 27.75 psu at flood time and < 26 psu at ebb time.

The distribution of water density within Balikpapan Bay is more controlled by the salinity of seawater than temperature one. At flood tide there is a mass of water with a higher water density flow into the middle part of the bay, this can be understood because at flood tide, higher density of water mass pushed towards the middle of the bay (figure 7, above panel). At ebb period there is a color degradation that indicates that the salinity decreases towards the head of the bay.
Figure 5. Longitudinal section of temperature and salinity along Balikpapan Bay at flood period.

Figure 6. Cross section of temperature and salinity along Balikpapan Bay at ebb period.

Figure 7. Cross section of Water Density along Balikpapan Bay at flood period (upper panel) and ebb period (lower panel) calculated from temperature and salinity data at the same.

3.2. Tidal Condition
One of the waves that has a long period is tidal or tidal wave. The phenomenon of the rise and fall of the sea surface periodically caused by the attraction between space objects, especially the moon and the sun against the surface of water on the surface of the earth. The existence of the tensile force
causes the sea level towards the moon and/or the sun to rise higher, with the earth’s rotation and the gravitational force of the disturbance to the sea surface can generate long-period waves of the ups and downs. The tidal waves that propagate into the bay come from the propagation of the tidal waves that spread from the Pacific Ocean and parts of the Java Sea through the Sulawesi Sea and Makassar Strait.

Table 1 is the main tidal constant values calculated from sea level observation data within 30 days in Balikpapan Bay. If the main constants are included in the formula Formzhall \( F = \frac{(K + O)}{(M + S)} \), then the value of \( F = 0.39 \) means that the type of tide that occurs in Balikpapan Bay is mixed tide prevailing semi-diurnal type (type mixed coupling tends to double daily). In 4 hours there are times the tide and two times the tide, but the amplitude is not the same. The range of tidal range in Balikpapan Bay can reach 2.7 m [13].

Table 1. Tidal Constant at Balikpapan Bay.

| Tidal Component | M2 | S2 | N2 | K2 | K1 | O1 | Q1 | MS4 |
|-----------------|----|----|----|----|----|----|----|-----|
| Amplitude       | 3.1| 600.1| 40.3| 5.8| 10.9| 22.3| 17.2| 7.4 |
| Degree          | 244.3| 127.6| 176.8| 141.3| 176.8| 258.2| 239.3| 258.2 |

3.3. Sea current pattern

The movement of water masses (currents) in a waters is generated by various forces of current generation such as wind, tidal, water density difference, and hydrostatic pressure of waters [6]; [18]; [19]. The magnitude of the influence of each force on the strength and direction of the current flow it generates depends on the type of water (beach, bay or sea off) and its geographic state.

Water circulation within the Balikpapan Bay is dominated by currents generated by the tides. Wind is the next important factor, especially in open water. The effect of the difference in density, hydrostatic pressure is generally small so it can be ignored. In the north-east monsoon from November to February the direction of the current is relatively small due to the dominant wind direction from the north where the land of Borneo. In the southeast monsoon the influence of wind and tidal propagation can strengthen inflows into the bay.

The tidal current dominates the circulation within the bay at low tide the current velocity range from 0.5 to 0.8 m/s with the dominant direction to the south (to the mouth of the bay), while at the tide 0.4-0.8 m/s northward (to the head of the bay).

To understand the more intact current pattern, the simulation of hydrodynamic model using bathymetry data input. Tidal and wind as the current generator. Simulations are performed on two differences monsoon. The northeast monsoon and southeast monsoon. Figure 8-15 are the snapshot of current results at different sea level position. i.e.: at the MSL (Mean Sea Level) point towards the highest tide. At the highest tide, when the sea level at the MSL point towards the lowest tide and when the sea level at low tide Lowest. The current pattern on these four positions of sea level is performed both in the north and south seasons.

Figure 8 is the current pattern towards the flood tide. The water mass is pushed into Balikpapan Bay. The average current velocity at flood tide can reach 10-15 cm/s. Due to the geographic conditions of the bay where the mouth is wider than the body of the bay and the head of the bay the current velocity when entering the bay looks stronger. On the contrary at the time of ebb tide the pattern of current appears to be reversed where the water mass flowed out from the bay into the Makassar Strait (figure 9).

The current pattern at the highest tide and lowest tide is presented in figures 10 and 11. From these two patterns the stream looks calmer when the sea level is at its highest tide point and there is a difference of direction especially in the southern mouth of the bay. When the flood tide the current moves counter clockwise. On the contrary, at the lowest ebb the direction of the current moves in a clockwise direction. Figure 12 through figure 15 are the results of current simulations in Balikpapan Bay and surrounding areas for the Southeast Monsoon. Similar with the result of current simulation at the MSL lead to the highest tide point in the northeast monsoon that the water mass circulation in the north-western Makassar Strait moves northward and a small part of the water mass is seen entering the
bay of Balikpapan. The current velocity at the mouth of the bay ranges from 20-30 cm/s. the current is still strong and extending to the centre of the bay waters (figure 12).

Figure 8. The current pattern during the northeast monsoon, when the sea level at MSL leads to the highest tide (the top panel is the current pattern presented in vector form. the lower left panel is the sea level (tide) position. and the lower right panel is the wind vector (velocity and direction).

Figure 9. The current pattern during the northeast monsoon, when the sea level at MSL leads to the lowest tide (the top panel is the current pattern presented in vector form. the lower left panel is the sea level (tide) position. and the lower right panel is the wind vector (velocity and direction).

Figure 10. The current pattern during the northeast monsoon, when the sea level at the highest tide (the top panel is the current pattern presented in vector form. the lower left panel is the sea level (tide) position. and the lower right panel is the wind vector (velocity and direction).

Figure 11. The current pattern during the northeast monsoon, when the sea level at the lowest tide (the top panel is the current pattern presented in vector form. the lower left panel is the sea level (tide) position. and the lower right panel is the wind vector (velocity and direction).
Figure 12. The current pattern during the Southeast monsoon, when the sea level at MSL leads to the highest tide (the top panel is the current pattern presented in vector form, the lower left panel is the sea level (tide) position, and the lower right panel is the wind vector (velocity and direction).

Figure 13. The current pattern during the Southeast monsoon, when the sea level at MSL leads to the lowest tide (the top panel is the current pattern presented in vector form, the lower left panel is the sea level (tide) position, and the lower right panel is the wind vector (velocity and direction).

Figure 14. The current pattern during the Southeast monsoon. When the sea level at the highest tide (the top panel is the current pattern presented in vector form, the lower left panel is the sea level (tide) position, and the lower right panel is the wind vector (velocity and direction).

Figure 15. The current pattern during the Southeast monsoon. When the sea level at the lowest tide (the top panel is the current pattern presented in vector form, the lower left panel is the sea level (tide) position, and the lower right panel is the wind vector (velocity and direction).
Figure 13 is the current pattern when the sea level at the MSL flow to the lowest ebb in the southeast monsoon. The water mass within the bay is pushed out at the speed of 0.15-0.20 cm/s, when it outside of the bay the water mass is pushed eastward to the southeast as it forms a frontal zone which is the boundary of current flowed from the bay and the coastal current of the Makassar Strait. Plume of coastal current pattern is clearly visible from the difference of current direction and magnitude (current vector).

When the tidal conditions are highest during the south season, the water mass is seen moving northward in the north and east of the bay's mouth, while in the south-southwest of the mouth the water bay moves to rotate counter-clockwise. Current velocity appears to be stronger offshore compared to areas located near the coast (figure 14).

The current pattern is seen changing at the lowest tide (figure 15), almost at all model domain current flowing toward the northeast along the coast of Balikpapan, only slightly seen turning southwards. A stronger current is seen in the transition zone, there is between the coast waters of Balikpapan and the offshore. In the south-eastern part of the bay especially at the offshore part the current velocity decrease to be 10 cm/s.

3.4. Stratification of water mass

The gravitational stability of an adiabatically displaced air parcel in the atmosphere depends on the vertical stratification of pressure and density [20]; effects of continental slope and variable Brunt-Vaisala frequency [21]. There are three parameters usually used to calculated Brunt-Vaisala Frequency i.e.: vertical profile of temperature, salinity and density [22].

Figure 16 and 17 are longitudinal section according to water depth and parallel to bay length, respectively in periods of high and low tides. Generally, the water mass at low tide looks more stable compared to the high tide. This is indicated by the higher Brunt-Vaisala value at low tide compared to the high tide. The maximum value of Brunt-Vaisala Frequency was 22.5 cycle/hour. In the ocean where salinity is important, or in fresh water lakes near freezing, where density is not a linear function of temperature. Brunt-Vaisala frequency depend on both temperature and salinity [23], [24], [25].

![Figure 16. Longitudinal Section of Brunt-Vaisala Frequency on Flood Period along the Balikpapan Bay.](image-url)
4. Conclusion

Water mass stratification was found. It looks stronger in the center of the bay compared with the area near by the head and mouth of bay. Salinity more dominant to control water density within the bay compared to the water temperature. Tide is one of forces to withhold water mass which flow into and flow out the bay. Stability of water mass at along Balikpapan Bay at low tide looks more stable than when high tide.

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References

[1] Kang X. Xia M. Pitula J S and Chigbu P 2017 Dynamics of water and salt exchange at Maryland Coastal Bays Estuarine. Coastal and Shelf Science 189 1-16
[2] French P W 1997 Coastal and Estuarine Management (London: Routledge)
[3] Mitra A and Zaman S 2016 Basics of Marine and Estuarine Ecology (India: Springer)
[4] Najamuddin. Prartono T. Sanusi H S and Nurjaya I W 2016 Seasonal distribution and geochemical fractionation of heavy metals from surface sediment in a tropical estuary of Jeneberang River. Indonesia Mar. Pollut. Bull. Elsevier 111 456-462
[5] Najamuddin. Prartono T. Sanusi H S and Nurjaya I W 2016 Distribution and behaviour of dissolved and particulate Pb. and Zn in Jeneberang Estuary. Makassar J. Ilmu dan Teknologi Kelautan Tropis 8(1) 11-28
[6] Dyer K R 1973 Estuaries: A Physical Introduction (Great Britain: John Wiley and Sons Ltd.)
[7] Liu W C. Chen W B. Kuo J T and Wu C 2008 Numerical determination of residence time and age in partially mixed estuary using a three-dimensional hydrodynamic model Continental Shelf Research 28(8) 1068-1088
[8] Casares-Salazar R and Marino-Tapia I 2016 Influence of remote Forcing and local winds on the barotropic hydrodynamics of an Elongated Coastal Lagoon J. Coast. Res. 32(1) 116-130
[9] Nurjaya I W 2016 Salinity structure within the estuary of Bintuni Bay. at the southern part of bird head of West Papua. Indonesia J. Segara 12(2) 73-80
[10] Rizkiyah D. Nugroho and Purwanto 2015 Studi pola sebaran buangan panas PT. Pertamina UP V Balikpapan. di Perairan Kampung Baru. Teluk Balikpapan Bull. Oseanigrafi Marina 6(1) 1-13
[11] Warsidi and Endayani 2017 Komposisi vegetasi mangrove di Teluk Balikpapan. Provinsi Kalimantan Timur J. Agrifor 16(1) 115-124
[12] Working Group of Erosion and Sedimentation 2002 *Kajian erosi dan Sedimentasi pada DAS Teluk Balikpapan. Kalimantan Timur* CRC/URI CRMP. Proyek Pesisir Kaltim Balikpapan p 51

[13] Sarwono, Mursidi, Abdunnur, Malik R and Audrie 1999 *Kondisi Hidroooceanografi Perairan Teluk Balikpapan. Proyek Pesisir technical Report TE-99/16-I* Coastal Resources Center. University of Rhode Island. Jakarta. Indonesia p 27

[14] Schoellhamer D H, Mumley T E and Leatherbarrow J E 2007 Suspended sediment and sediment-associated contaminants in San Fransisco Bay *Environment Research* 105 119-131

[15] Koutsikopoulos C and Cann B L 1999 Physical processes and hydrological structures realted to the Bay of Biscay *Scientia Marina* 60 9-19

[16] Abbott M B, Petersen H M and Skovgard O 1978 On the numerical modelling of short waves in Shallow Water *Journal of Hydraulic Research* 16(3)

[17] Nurjaya I W and Surbakti H 2010 Thermal dispersion model of cooling water of gas and steam power plants at Cilegon CCPP discharge into Margasari coastal waters at the western coast of Banten Bay *J. Ilmu dan Teknologi Kelautan Tropis* 2(1) 31-49

[18] Dyer K R 1977 *Lateral Circulation Effects in Estuaries. Estuaries. Geophysics and the Environment* (Washington D C: National Academy of Sciences) p 22-29

[19] Fischer H B, List E J, Koh R C Y, Imberger J and Brooks N H 1979 *Mixing in Inland and Coastal Waters* (New York: Academic Press) p 483

[20] Prandle D 2004 How tides and river flows determine estuarine bathymetries *Progress in Oceanography* 61 1-6

[21] Prinsenber J S and Rtrray J M 1975 Effects of continental slope and variable Brunt-Vaisala frequency on the coastal generation of internal tide *Deep-Sea Res.* 22 251-263

[22] Imberger J and Ivey GN 1991 On the nature of turbulence in a stratified fluid. Part II: application to lakes *Journal of Physical Oceanography* 21 659–680

[23] Imberger J 1998 *Physical Processes in Lakes and Oceans Coastal Estuarine Studies Vol. 54* (Washington DC: American Geophysical Union)

[24] Thorpe SA 2007 *An Introduction to Ocean Turbulence* (Cambridge: Cambridge University Press)

[25] Wolanski E 2007 *Estuarine Ecohydrology* (Amsterdam: Elsevier)