Seasonally physical characteristics of ROFI zone (Region of Freshwater Influence) in Pelabuhan Ratu Bay

Z Zibar1*, I W Nurjaya2, N M N Natih2

1 Department of Marine Science, Graduate School of Bogor Agricultural University, Agatis Road, Bogor 16680, Indonesia
2 Departemen of Marine Science and Technology, Bogor Agricultural University, Agatis Road, Indonesia
*e-mail: zanzibar301@gmail.com

Abstract. Coastal waters have many oceanographic phenomena are still being studied. One such phenomenon is how the influence of freshwater to the water mass in coastal waters. This study aims to calculate freshwater fraction, volume transport of freshwater and water mass stability. Physical water characteristics were measured by CTD (Conductivity, Temperature and Depth) deployed in 15 locations for temperature, salinity and density. The results of freshwater fraction analysis show that the west season had a greater on water fraction than the east season with value ranging from 0.40 % - 0.70 % with the amount 18.07 %, while the east season had a value of 0.02 % - 0.28 % with the amount is 7.30 %. The transport of freshwater volume in west season is 1.429.244 m$^3$s$^{-1}$ while in the east season it is 1.066 m$^3$s$^{-1}$. Water mass stability of water column in the research location has static stability with its average N$^2$ in west and east monsoon are 0.008 cycl/s and 0.7 x 10$^3$ cycl/s, respectively. Those analyses above infer that freshwater input hugely influences physical water mass of ROFI zone in research location.

1. Introduction
Pelabuhan Pelabuhan Ratu Bay is located geographically at 6°-57'-7°07’S and 106°22'-106°-23’E and its coastal line is about 105 km length. It is also being the mouth for some big rivers such as Cimandiri and Cimaja [1]. The freshwater inputs influences on coastal water trough estuaries are verily important information to coastal areas. Predicted transport, distribution, total pollutants, suspended materials are very important matters for various coastal information because the dynamic mixing as a result of some physical process [2,3]. The importance of physical processes in coastal areas, caused by freshwater inputs from rivers that have been studied by several researchers, Some research such as the alongshore transport of freshwater in a surface-trapped river plume [4], A simple theory for the fate of buoyant coastal discharges [5], Relating river plume structure to vertical mixing [6], SST observations of upwelling induced by tidal straining in the Rhine ROFI [7], observation of coastal front and circulation in the northern Java, Indonesia [8].

Region of freshwater influence (ROFI) is a zone between sea exposure and estuary where as local freshwater buoyancy from coastal resource is equal, or exceeds seasonally buoyancy inputs as heat happening in all sea exposures [9]. The effect of overflowing suspended material moving in the water column (plume) in coastal waters is a way to understanding the behavior of physical (plume) and front because plume and front are strongly influenced by river flow, tidal and meteorological conditions [10]. The main characteristic of the ROFI system is the significant buoyancy of the freshwater source, which has important implications for the structure and dynamics of the water column. If spatial scales are constrained by coastal features and weak stirring, freshwater inputs tend to encourage parallel beach
densities where the effects of the Earth's rotation (Coriolis force) act to limit spread and form a baroclinic (density driven) that can affect the hydrodynamics of hundreds kilometres of coastal waters [9].

Other factors effect ROFI zone are convergence current, bathymetry, solar heating, and other oceanographic vectors [11]. The happening system in ROFI zone is very important and it is needed to be accounted practically. Freshwater input from estuaries that are mixed with suspended materials will give any impact to sea exposure environments [12]. Run-off input input maintain highly nutritive concentration in ROFI zones which induces blooming phytoplankton and in some cases it can endanger or faze [13]. Combination between tides and river buoyancy produces sea organism groups, and highly dispersive water current affects to sea creatures dynamic [14,15]. [16] reveals that biota live coastal areas are highly affected by chemic-physical condition. This is figured by coastal community activity of Pelabuhan Ratu Bay in each month collect impun, or called by local as “ngala impun”. Impun are small fish/juveniles that are captured in some river estuaries such Citepus, Sukawayana, Cibuntu and Cimandiri. The caught impun by local abandontly happens on July, and their abundance found in two estuaries, Cimandiri and Citepus, with 12.6 kg/people/day and 4.2 kg/people/day, respectively.

There are many researches conducted in Cimandiri’s estuary, such as [17] studied up-welling in Southern Java shows that sea water temperature of Palabuhan Ratu bay on September to October (end east monsoon) and November to Desember (early west monsoon) are 26 °C are 28 °C, respectively. Salinity the bay was affected by seasonality which the main factor is freshwater input from rivers. Freshwater input from rivers especially in west monsoon result lowering the water salinity of the bay, however the central bay have relative small different surface salinity between two season, west and east monsoon. Salinity measurement conducted on two different season, August to October period and May to July are 32.96 ‰ and 32.33 ‰, respectively. Other researchers such [18] chemical characteristics and water fertility of Pelabuhan Ratu Bay on west and East monsoon, [1] two-dimensional simulation water current pattern of the bay, [19] oceanographic condition as the basis for fish resource preservation in the bay.

So far, research about seasonally physical characteristics of ROFI zone in Cimandiri estuary Pelabuhan Ratu Bay is still not conducted yet. This research were aimed to calculate salinity anomaly, freshwater fraction, volume transport of freshwater and water mass stability in two different season. This research was expected resulting beneficial information about physical process of the water in the bay which can be used for further management, both government bodies and research.

2. Methods

This research was conducted in Cimandiri estuary of Pelabuhan Ratu Bay at two different field observational surveys namely January and August, 2016. Observation locations consisted of three section which are directed divergently or a whole station directed away against to the estuary mouth. First section consisted of five stations (st. 1 to st. 5) which is spread diagonally between the estuary mouth and the second section. Second section was consisted of 5 stations (st. 6 to st. 10) that was perpendicular to the estuary mouth. The last section was stretches diagonally between second section and the estuary mouth. All data sampling sites were assumed to be representatives for research locations at all. Research map is displayed in figure 1.

Equipment were used in the data sampling consisted of GPS MAP for determining observation location, boat track directions and other supported information, CTD (Conductivity, Temperature and Depth) has a role for collecting salinity, temperature and density data, Surface current data in January and August 2016 is derived from the measurement data directly in the field as well as the observation model data derived from INDESO (Infrastructure Development for Space Oceanography) and survey boat from local fisherman was operated to carry out research phases.
Calculating anomaly salinity is based [20,21] as the following formula:

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

(1)

Where \( S'(x,z) \) is salinity anomaly value (PSU), \( S(x,z) \) is salinity value that is measured at research location and \( S_{\text{ref}}(z) \) is reference salinity is averaged at depth \( z \) (PSU).

Freshwater fraction is in volume unit which is defined according to [20,21] formula as follow.

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

(2)

where \( F(x,z) \) is freshwater fraction value, \( S_{\text{ref}}(z) \) is the salinity reference at depth \( z \) (PSU) and \( S(x,z) \) is the salinity value measured at each station \( x \) and the depth \( z \) (PSU). The reference salinity used in this study is 33.76 PSU which is the salinity value of a research station located far from the mouth of the river mouth, in other words have not gained influence from the fresh water supply flowing from the mouth of the Cimandiri River. The average value of freshwater fractions along the section can be defined:

\[ F_r = \frac{1}{h} \int_0^h \frac{S_{\text{ref}}(z) - S}{S_{\text{ref}}(z)} \, dz \]  

(3)

\( F_r \) is the average value of freshwater fractions along the transect, \( h \) is the depth of the waters of each depth of the station (m).

The volume transport of freshwater is estimated [20,21].

\[ V_{fw} = \int_A F_r u dA \]  

(4)

Where \( V_{fw} \) is volume transport of freshwater (m³s⁻¹), \( F_r \) is the average of freshwater fraction, \( A \) is the area of low salinity water band (m²) and \( u \) is the average alongshore velocity across section \( A \) (ms⁻¹).
The stability of the water mass can be determined by the stability equation (E) [22]:

$$E = -\frac{1}{g} \frac{\partial \rho}{\rho} \frac{\partial z}{z}$$  \hspace{1cm} (5)

where $\rho$ is the water density (kg m$^{-3}$) and $z$ is the depth (m). Fluid is stable if $E > 0$, neutral if $E = 0$ and unstable if $E < 0$. If the difference in density value to the depth is greater, then the water layer will be more stable. Movements rise and fall of the fluid to reach a stable position known with buoyancy frequency or Brunt Vaisala frequency. Counting Brunt Vaisala Frequency is generated by salinity data, temperature per dept data which is extracted from CTD of research station. $N^2$ value is calculated to determine stratified value [23].

$$N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}$$  \hspace{1cm} (6)

where $N^2$ is Brunt Vaisala frequency, $g$ is earth's gravitational acceleration (9.8 ms$^{-2}$), $\rho_0$ is background density is the average density of the measurement results, $\partial \rho$ changes (gradient) density to depth $\partial z$ (1 m).

3. Results and discussion

3.1. Salinity anomaly

Dispersed salinity anomaly values on west season at all station section are in ranged of -7.44 to -1.406 (section 1), -1.397 to -23.701 (section 2), and -19.983 to -1.546 (section 3). The lowest value is the nearest stations to the estuary mouth and the salinity values go up paralellly to the water depth increases and getting further away of the estuary mouth. In this research, changes in section on depth are section 1 (-5.47) with 1.5 meter depth from the surface, and section 2 (-21.8) with 2 meter depth from the surface and it still decreases until sea bottom surface. The distribution of salinity anomaly is influenced by salinity change. Salinity at the mouth of the Cimandiri River is influenced by tides and seasons. Towards the mouth of the estuary, the lower salinity anomaly. Flavor during the dry season when the river flow decreases, sea air entering further towards the mouth of the estuary cause the salinity. Compound in the rainy season, fresh water flows from the ocean into larger amounts so that the anomalous salinity in the estuary decreases. Field observation carried out [24] in Mesoamerican Barrier Reef System states that salinity has low value in the surface layer with more prominent in 5-10 meter depth which is an effect of freshwater input from mainland. The difference in salinity seawater with river water that meets in the rofi zone causes both to be mixed. Because the sea salt content is greater, the seawater tends to move in the bottom of freshwater waters in the surface layer.

Furthermore, dispersed anomaly salinity on east season in all research station section are -1.124 to -0.886 (section 1), -1.114 to -0.881 (section 2), -9.571 to -0.908 (section 3). Those values exhibits less freshwater input to the seawater column, so that anomaly salinity almost disperse evenly in the water column. The salinity values is so less compare with the salinity anomaly on January measurement. [25] Seawater salinity under goes change causing by evaporation and precipitation, run off from rivers, coldness or ice melting. Areas close to the river estuary will have lower salinity about 20‰ and it is varied depends on depth.
Figure 2. Vertical cross section salinity anomaly section 1, 2 and 3 on West Season.

The anomaly salinity on east season distribution in section 3 has an extremely high salinity anomaly value in the water columns compared to section 1 and 2 so it provides information that the freshwater supply coming from more rivers is carried along the coast towards southeastern south and south of the bay.

Figure 3. Vertical cross section salinity anomaly section 1, 2 and 3 on East Season.

3.2. Freshwater fraction
Sampling on west season 2016, the averaged freshwater fractions enter sea water column in three station section are 0.05% leading away as far as 1.7 km from the estuary mouth (section 1), 0.07% taking for 2 km away from the estuary mouth (section 2), and 0.12% bring out for 2.5 km from the estuary (section 3). The distribution of freshwater fractions is more carried along the coast, toward the southeast and south of the bay. This is influenced by fresh water discharge, so the value of freshwater fraction varies for each line available at each research station. [26] freshwater discharge has an important effect on the estuary waters, thus providing salinity value. [27] freshwater fraction values are influenced by water mass mixing process due to the oscillation of tidal estuaries and solubility of salinity in estuary waters. Pelabuhan Ratu Bay waters have tidal phase 6 hours period just before its up and down with the type of tide mixed tide prevailing semidiurnal with the value of the Formzahl number is equal to 0.44. The tides that occur in Pelabuhan Ratu Bay are more influenced by the tidal propagation that occurs in the open sea (Indian Ocean) so that with the tidal period that occurs for 6 hours and stirring by the wave as it approaches the waters of the estuary with bathymetry conditions at the location of data collection that
varies from depth of 3.5 - 16.3 m can influence the distribution of high fresh water fraction value in water column. the occurrence of up and down the sea surface regularly is one of the important factors affecting the current around the coast as well as various oceanographic processes around the coastal waters, as well as a major influence on coastal geomorphology.

![Figure 4. Surface freshwater fraction on West Season.](image)

Sampling on east season 2016, the averaged fresh water fraction enter sea water column in three station section are 0.028 % leading away as far as 0.5 km form the estuary mouth (section 1), 0.029 % taking for 0.5 km away from the estuary mouth (section 2), and 0.038 % bring out for 2 km from the estuary (section 3). [28] that the amount of freshwater mass derived from the precipitation as well as freshwater input from the river may affect the value of the freshwater fraction in the waters.

![Figure 5. Surface freshwater fraction on East Season.](image)

3.3. Volume Transport of Freshwater
The volume transport of freshwater at the mouth of the Cimandiri River in the west season is 1,429,244 m³s⁻¹ while volume transport of freshwater at the mouth of the Cimandiri River in the east season is 1,066 m³s⁻¹. This is caused by freshwater discharge in the west season is greater than east season. The result of this research in line with Sanusi [18] conducting research in the whole of Pelabuhan Ratu Bay
on two seasons (east and west) where the salinity of the water (river discharge 95.19 m\(^3\)s\(^{-1}\)) was recorded 5 \(\%\) and 26 \(\%\) (river discharge 35.84 m\(^3\)s\(^{-1}\)), respectively.

**Tabel 1.** Current velocity, freshwater fraction, area of low sanity water and volume transport of freshwater.

| Month   | Freshwater fraction (%) | Current velocity (m/s) | Area of low salinity water (m\(^2\)) | Volume transport of freshwater (m\(^3\)s\(^{-1}\)) |
|---------|-------------------------|------------------------|--------------------------------------|-----------------------------------------------|
| January | 18.07                   | 0.21                   | 375.142                              | 1.429.244                                     |
| August  | 7.30                    | 0.09                   | 1.494                                | 1.066                                         |

Moreover, other factors affecting the differences of water mass transport are river’s mouth channel from, bathymetry slopes, freshwater currents entering the bay, and some oceanography factors. Others studies related to water mass transport influencing by inlet and outlet of currents in certain bay [3]. [29] express about structure of mouth river channel and estuary slope it is important to understand the transition of estuary circulation.

3.4. **Water mass stability**

Calculating of Brunt-Vaisala (N\(^2\)) values results that all research station section (Figure 10) on west season 2016 condition are in ranged of -0.697 \(\times\) \(10^{-3}\) – 0.128 Cycl/S (section 1), -0.00131 – 0.473 Cycl/S (section 2), and -0.043 – 0.336 Cycl/S (section 3), respectively.

The all values indicate that freshwater inputs to the seawater column of Pelabuhan Ratu Bay will give a result to be static stability of sea surface layer. It is proven by the water mass to be unstable condition with N\(^2\) is being negative when those water mass spread away the estuary to enter the center of the Bay. The higher value of a water layer, the morely static stability of the layer (something conditions in which the mass of water with low density is above the water masses with high density) and reversly when the value is going to be negative, the water column condition is going to be unstable or static un-stability condition [30]. However, in water column of station 12, 13 and 14 (section 3) undergo un stability.

Moreover, counting of Brunt-Vaisala values on August 2016 condition at all research section (Figure 17) are in ranged of -0.00996 – 0.010812 Cycl/S (section 1), -2.05 \(\times\) \(10^{-3}\) – 1.94 \(\times\) \(10^{-3}\) Cycl/S (section 2), -0.00336 – 0.4324 Cycl/S (section 3). The gained average value shows that the research location on August (east monsoon/dried season) is still on stable condition. However, the water mass stability is more less than January which is characterized by almost any negative value in each station. The less water column stability indicates that there is any influence of northwest monsoon wind blowing in southern equator which mixes water mass potentially disturbing water column stability. [31,32] state that, in Indonesia territory, on December to March the northeast monsoon wind blows in the northern and the northwest monsoon wind blows in the southern of equator, while June to August the southwest monsoon wind blows.
Figure 6. Brunt-Vaisala frequency research station section 1, 2 and on west season.
Figure 7. Brunt-Vaisala frequency research station section 1, 2 and on east season.

4. Conclusion
The main characteristic of ROFI (Region of freshwater influence) at the Cimandiri estuary is significant of buoyancy input from freshwater which has important effect for structure and water column dynamic. ROFI on the Cimandiri estuary are more influenced by freshwater supply that entering the sea, and this interaction could change the water mass characteristic. On the west and east season, fraction of freshwater with volume transport carried away from the river along the coast towards southeast and south direction of the bay. Brunt Vaisala frequency on west season at all line of research station was ranged between −0.043 – 0.473 Cycl/S with the highest stable water column formed at freshwater flow from the estuary to the water column while the instability of the column of the waters increasingly occurred at station 10 which getting away from the mouth of the estuary was marked with a negative
value and characterized by value 0 as a sign of area of the intersection (front). The calculation of Brunt Vaisala frequency in east season was ranged from -0.00996 – 0.4324 Cycl/S so that the water column entered the condition of unstable waters marked by almost negative value in each station at the research location. The occurrence of water mass instability in water column indicates the influence of the southwest monsoon blowing in the south of the equator, so it cause mixing of water masses in the water column. This is hypothesis confirmation that freshwater supply from Cimandiri River and its location facing the open sea causes the structure and dynamics of the water column.

Acknowledgments

Thanks to supervisor Biological Oceanography Laboratory Marine Science and Technology Mr. M. Tri Hartanto for field assistance and valuable discussion along with the research. This research would not be implemented without supporting by the Laboratory of Oceanography for research tolls and Data Processing.

References

[1] Nugroho R B A and Surbakti H 2009 Two dimensional simulation flow patterns in Pelabuhan Ratu Bay during September 2004 Nation Marine Science Journal 4(1) 48-55
[2] Zimmerman J T F 1986 The tidal whirlpool: a review of horizontal dispersion by tidal and residual currents Netherlands Journal of Sea Research 20 133-154
[3] Van Dam G C, Ozmidov R V, Korotenko K A and Suijlen J M 1999 Spectral structure of horizontal water movement in shallow seas with special reference to the North Sea, as related to the dispersion of dissolved matter Journal of Marine Systems 21 207-228
[4] Fong D A and Geyer W R 2002 The alongshore transport of freshwater in a surface-trapped river plume Journal of Physical Oceanography 32 957-72
[5] Yankovsky A E and Chapman D C 1997 A simple theory for the fate of buoyant coastal discharges Journal of Physical Oceanography 27 1386-401
[6] Hetland R D 2005 Relating river plume structure to vertical mixing Journal of Physical Oceanography 35 1667-688
[7] Boer de J G, Pietrzak D J and Winterwerp C J 2009 SST observations of upwelling induced by tidal straining in the Rhine ROFI. Continental Shelf Research 29 263-277
[8] Atmadipoera S A, Kusmanto E, Purwandana A and Nurjaya I W 2015 Observation of coastal front and circulation in the Northeastern Java Sea, Indonesia JITKT 7(1) 91-108
[9] Simpson J H 1997 Physical processes in the ROFI regime Journal of Marine Systems 12 1-15
[10] Ge J, Ding P and Chen C 2014 Low-salinity plume detachment under non-uniform summer wind off the Changjiang Estuary Estuarine Coastal and Shelf Science 30 1-10
[11] Mann K H and Lazier J R N 1996 Dynamics of Marine Ecosystems Biological–Physical Interactions in the Oceans 2nd Ed (Cambridge: Blackwell Science)
[12] Nedwell D B, Dong L F, Sage A and Underwood G J C 2002 Variations of the nutrients loads from the Mainland UK estuaries: correlation with catchment areas, urbanization and coastal eutrophication Estuarine Coastal and Shelf Science 54 951-970
[13] Desprez M, Rybarczyk H, Wilson J G, Ducrotot J P, Sueur F, Olivesi R and Elkaim B 1992 Biological impact of eutrophication in the bay of Somme and the induction and impact of anoxia Netherlands Journal of Sea Research 30 149-159
[14] Sentchev A and Korotenko K 2004 Stratification and tidal current effects on larvaltransport in the Eastern English Channel: observations and 3D modeling Environmental Fluid Mechanics 4 305-331
[15] Sentchev A and Korotenko K 2005 Dispersion processes and transport patterns in the ROFI of Eastern English Channel derived from a Particle Tracking Method Continent Shelf Res 25(4) 2293-308
[16] Nastiti A S, et al. 2010 Resource assessment of fish larvae in the Gulf Palabuhanratu, Sukabumi, West Java. Technical Report. Research colaboration BRKP- KKP with the Research and Technology [Unpublished]
[17] Pariwono J I, Eidman M, Rahardjo S, Purba M, Prartono T, Widodo R, Juariah U and Hutapea J H 1988 Study Up Wellin in The Waters of The South Island of Java (Bogor: Faculty of Fisheries and Marine Science, IPB)

[18] Sanusi H S 2004 Chemical characteristic and fertility of Pelabuhan Ratu Bay Waters at East and West Monsoon Journal of Aquatic Sciences and Fisheries Indonesia 2 93-100

[19] Nastiti A S 2011 Oceanographic conditions as the Basis for Preservation of Fish Resources in the Gulf of Pelabuhan Ratu, Sukabumi West Java Proceedings of the National Forum of Fish Resources Pacing III

[20] Gilbert P S, Lee T N and Podesta G P 1996 Transport of anomalous of low salinity waters from the mississippi River flood of 1993 to the Straits of Florida Con. Shelf Res.16(8) 1065-085

[21] Nurjaya I W 2002 Behavior of Low Salinity Water Near The Mouth of Tokyo Bay (Tokyo: Marine Science and Technology, Tokyo University of Fisheries)

[22] Stewart R H 2002 Introduction to Physical Oceanography (Texas: Texas A and M University)

[23] Griffiths R W 1986 Gravity currents in rotating system An. Ref. of Fluid Mech. 18 59-89

[24] Carillo L, Johns E M, Smith R H, Lamkin J T and Largier J L 2016 Pathways and hydrography in the Mesoamerican Barrier Reef System Part 2: Water masses and thermohaline structure Continental Shelf Research 120 41-58

[25] Bhatt J J 1978 Oceanography Exploring The Planet Ocean (New York: D.Van Nostrand Company)

[26] Song I J and Woo S B 2015 Study on variability of residual current and salinity structure according to river discharge at the Yeoungsan River Estuary, South Korea Procedia Engineering 116 1002-008

[27] Regnier P and O’Kane J P 2004 On the mixing processes in estuaries: the fractional freshwater method revisited Estuaries 27(4) 571-582

[28] Gustafsson B and Stigebrandt A 1996 Dynamics of the freshwater-influenced surface layers in the Skagerrak Journal of Sea Research 35 39-53

[29] Lee J and Valle-Levinson A 2016 Influence of bathymetry on hydrography and circulation at the region between an estuary mouth and the adjacent continental shelf Continental Shelf Research 41 77-91

[30] Pond S and Pickard G L 1983 Introductory Dynamical Oceanography 2nd Edition (Oxford: Pergamon Press)

[31] Wyrtki K 1961 Physical Oceanography of South East Asian Water. Naga Report. Vol 2. Scripps Institution of Oceanography. The University of California. La Jolla. California. Naga Rep. 2 1-195

[32] Tomczek M and Godfrey J S 1994 Regional Oceanography: An Introduction (Oxford:PP)