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Cover Page Footnote
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Study of Heavy Metal Distribution and Hydrodynamic Simulation in Green Mussel Culture Net, Cilincing Water - Jakarta Bay

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Abstract

This study aimed to investigate the heavy metals distribution in the surrounding area of green mussel culture net, Cilincing water, Jakarta Bay, and its distribution behavior. The water sampling was carried out during the ebb tide. The heavy metal concentration was then measured by using atomic absorption spectroscopy (AAS). In order to understand the water circulation behavior related to heavy metal distribution in the study area, the Princeton Ocean Model was applied, and the model design was developed based on a scenario of an open canal in the eastern and western sides, while the center canal was placed with net cages in the water column resembling the green mussel culture net. The observed heavy metal distribution showed an intensified concentration in the green mussel culture location. The observed water current also showed a reduced velocity in the location. The modeling approach could explain the water circulation behavior in response to the presence of net units in the water column. In this case, the density of net units for green mussel culture potentially produced shear stress in the water column, which affected the flow pattern and the distribution of heavy metals. Therefore, the existence of green mussel culture nets has a potential to become a trap for pollutant distribution in the water.

Introduction

Jakarta Bay has become the biggest waste disposal site for the people in Jakarta Metropolitan Area (JMA) and its surrounding areas, including domestic sewage, industrial waste, agricultural waste, and urban run-off, as well as pollutant load from upstream. The main problem related to pollution in Jakarta Bay results from human population, which has been increasing yearly. According to statistics from the period of 1971 to 2010, the population...
of JMA has increased by 109% to total 9.6 million people by 2010. In addition, JMA has seen significant land-use changes during the last four decades. It can be clearly seen from satellite imagery between 1971 and 2004 that the conversion of vegetative areas into urban use in JMA has reached 80% [1].

The geographical features of JMA are characterized with several rivers that flow into Jakarta Bay. Therefore, the high population and urban activities play an important role in contaminating the rivers as well as Jakarta Bay [2]. All the pollutants, especially categorized as hazardous and toxic substances (e.g., heavy metals), will negatively affect the biota [3], and this has resulted in unviable larvae of green mussel [4]. Generally, the green mussel is a bioindicator of heavy metal pollution in seawater [5].

Green mussel culture is one of the livelihood activities, especially in the coasts of Jakarta Bay and Banten Bay. The culture activity in Jakarta Bay is mainly focused at several locations such as Muara Kamal, MuaraAngke, and Cilincing. According to [6], since the 1980s to 2003, green mussel culture has grown around 4200 units of nets in Jakarta Bay. One of the characteristics of green mussel is its ability to survive under high ecological stress, and it is therefore easy to culture. This ecological stress could be in the form of water pollution, which derived from the domestic sewage and industrial waste. In general, green mussel can live well in nutrient-rich water, such as in estuaries, coastal waters with muddy bed sediment, well-water circulation, sufficient light extinction, and moderate salinity [7]. However, marine pollution is becoming a big problem in Jakarta Bay, particularly the effect of heavy metals absorbed by the cultured mussels to humans. A previous study [8] reported that the capacity of green mussels, especially the small size mussels, to absorb heavy metals is high. Therefore, green mussels are recommended as a heavy metals biofilter (especially for Hg) and also as a “vacuum cleaner” for waters contaminated with heavy metals.

The content of heavy metals in green mussels from Jakarta Bay has attracted interest from several researchers [9-15], who have mainly focused on the rate of heavy metals bioaccumulation in green mussels. The present study will focus on the effect of the net unit density to hydrodynamic behavior in the coastal water surrounded by green mussel culture activities. The pre-hypothesis in this case is related with the shear stress in the water column caused by net unit density that influences water circulation and subsequently affects the pollutant distributions. Therefore, this study aimed to investigate the heavy metals distribution in the surrounding area of the green mussel culture nets in Cilincing water, Jakarta Bay, and its distribution behavior owing to the water circulation dynamics.

**Materials and Methods**

The seawater sampling was carried out on June 7, 2003, during ebb tide hours, between 8.30 a.m. and 12.30 p.m, and by using van Dorn Water Sampler. The sampling stations were located in the surrounding area of the green mussel culture location of Cilincing waters, as shown in Figure 1. The geographic position of the sampling stations was determined by using a GPS tool. The seawater parameters measured in this study are presented in Table 1. In order to present the distribution of heavy metals concentration in the sea surface, the concentration value for each station was interpolated by using the Kriging method embedded in the Surfer software.

In order to understand the water circulation behavior related to heavy metal distribution in the study area, Princeton Ocean Model version 2000 (POM2K) was applied. In general, POM2K is based on a 3-dimensional (3-D) primitive equation for a numerical ocean model [16]. The POM2K development is mainly designed for the 3-D model (barotropic and baroclinic) using mode splitting and sigma coordinates. The use of mode splitting is expected to reduce time computation during calculation. The main idea of mode splitting is related
with physical characteristics of the fast-moving external gravity waves and slow-moving internal gravity waves. Therefore, the propagation of external gravity waves should not be calculated by using complete 3-D equations, since it can be solved using 2-D equations. Conversely, internal gravity wave needs to be solved with 3-D equations with longer time computation. Therefore, the computation using mode splitting was composed of two time steps, i.e., short time phase (external mode) for 2-D equations integrated vertically or depth averaged and long-time phase (internal mode) for 3-D equations.

The POM2K has also accommodated output data in NetCDF (network Common Data Form), so that the analysis and visualization can be processed easily using common free software, for example Ferret (http://ferret.wrc.noaa.gov/Ferret/). The model design was developed based on a scenario of an open canal in the eastern and western sides, while the central part was placed with net cages in a beam shape hanging in the water column, to resemble the green mussel culture net. The canal grid was 40 x 25 for each x-axis (grid-i) and y-axis (grid-j). The widths of grid-i and grid-j were 10 m, but at the net location in the center, the widths of grid-i and grid-j were 5 m. The beams were placed alternately in the middle part, such that the x-axis was on grid-i = 16, 18, 20, 22, 24, and 28, while for the y-axis was on grid-j = 4, 6, 8, 10, 12, 14, 16, and 18. This numerical design might not perfectly represent the condition of net units in the mussel culture location, but the beam density condition was expected to simulate the impact of shear stress in the water column to water circulation. These beams were suspended on the water surface to a 6 m depth. The total depth of the canal was 10 m. The simple illustration of the canal and the beams location can be seen in Figure 2. In addition, the model was calculated for 1.5 days and forced by wind (wind speed = 0.005 m/s) where the time steps for external and internal modes were 0.1 s and 3 s, respectively. The model was applied using the baroclinic mode, where the initial conditions of temperature and salinity were 28 °C and 33 psu, which were constant vertically and horizontally. The initial value was only applied on the eastward current velocity component (u), with similar velocity for all depth levels that was 0.1 m/s.

**Results and Discussion**

The bathymetry condition of Cilincing waters is relatively shallow and flat, with a depth of 2–9 m. According to tide model of ORI.96, tidal prediction near the estuary in Cilincing showed a mixed tide dominant in diurnal tides, which is consistent with the results of Koropitan and Ikeda [1]. Therefore, the sea level of Jakarta Bay is generally once flood tide and once ebb tide during around 24 h. However, the diurnal tide significantly appears during spring tide. During water sampling activities, the tidal prediction of ORI.96 showed diurnal tide (Figure 3).

![Figure 2. The Sketch of Canal as a Model Region where the Beams were Suspended in the Center of the Canal to Resemble the Net Units of the Green Mussels Culture. The Wind Direction was Represented by the Arrow above the Canal](image)

![Figure 3. Tidal Prediction of ORI.96 in Jakarta Bay (the Shadow Box Indicated Water Sampling Activities)](image)

![Figure 4. The Observed Flow Pattern in Cilincing Water](image)
According to a previous study using a Seawatch buoy [17] and hydrodynamic model [1], the water circulation in Jakarta Bay was generally dominated by wind system (monsoon). During northwest monsoon (December–February), the current moves from west to east with a velocity of 0.8–1.4 m/s. On the contrary, during southeast monsoon (June–August), the current moves from east to west with a velocity of 0.8–1.2 m/s. The observed surface current in Cilincing water is presented in Figure 4, showing the flow to the west. However, water current in station 8 has opposite direction flow, which may be influenced by the existence of net units. In general, the current velocity was relatively low at the green mussel culture area (stations 3, 4, 7, and 9), ranging from 0.05–0.08 m/s. However, the current velocity in areas surrounding the culture area at stations 6 and 8 were higher, i.e., 0.14 and 0.23 m/s, respectively. In stations of Muara Cilincing and Muara Marunda, the velocities were also higher than that in the culture area. Therefore, it is clear that the green mussel culture area with high density of net units could reduce the current velocity in the Cilincing waters. In particular, the current velocity at station 5 at the Kali Baru location was low (0.05 cm/s) owing to the shears in the shallow water area and the closeness to the coast.

Heavy metals are toxic contaminants that generally become a problem in Jakarta Bay, since the water receives direct influence from several rivers that flow through various urban and industrial areas. Although the existence heavy metal pollution in Jakarta Bay has been generally known, the analysis results of heavy metals in the water samples have showed varying concentrations. For example, a previous study [18] showed a range between 0.029 and 0.136 mg Cu/L, more than 0.001–0.067 mg Cd/L, and 0.29–0.874 mg Pb/L. Although the observation of heavy metals in Jakarta Bay has been quite intensive, the results thus far do not show a definite trend of decrease or increase. All results of heavy metal monitoring in Jakarta Bay during the period of 1983–2014, including data from Urban and Environmental Assessment Office of JMA, are presented in Table 2.

The variation in the data, as shown in Table 2, are due to a few reasons. First, a lot of data at the same station from year to year, and it was unclear whether this loss of data was a result of data ‘to not be analyzed’ or ‘to not be detected’. Second, the detection limit standard was not clear. Third, the variation in the values obtained from each laboratory was quite high. Fourth, it was too difficult to find the average of the heavy metal concentrations in each station. Apart from those difficulties, by looking the highest limit of the observed concentration from the range above, it can be said that Jakarta Bay was vulnerable to the contamination of heavy metals, such as Cd, Cu, and Pb.

The description above can be related with the condition in Cilincing water. The observation result from [19] in August 2009 obtained the range of Cu concentrations of 0.05–0.08 mg Cu/L in Cilincing water, whereas in the Cilincing estuary, it reached 0.06 mg Cu/L. Cd and Pb were not detected in that observation [19]. This study obtained the range of Cd concentration of 0.014–0.064 mg Cd/L (Figure 5), Cu concentration of 0.015–0.47 mg Cu/L (Figure 6), and Pb concentration of 0.033–0.067 mg Pb/L (Figure 7). Those three figures explain that the distribution of Cd, Cu, and Pb in the sea surface was intensified in the green mussel culture locations. In addition, Cd (Figure 5) and Pb (Figure 7) showed higher concentrations in the culture location, compared to the concentrations in estuaries, which are a source of heavy metal load into the Cilincing water.

The intensification of heavy metal concentrations in the surrounding area of the green mussel culture did not originate from the green mussel culture location itself, but the source was still the riverine input. The source of heavy metals in the riverine input was also found in previous studies [20], [21]. Cd was probably derived

### Table 2. The Status of Heavy Metals Concentrations in Jakarta Bay during Period of 1983–2014

<table>
<thead>
<tr>
<th>Year</th>
<th>Cd (mg/L)</th>
<th>Cu (mg/L)</th>
<th>Pb (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>0.02-0.07</td>
<td>0.02-0.09</td>
<td>0.03-0.06</td>
</tr>
<tr>
<td>1984</td>
<td>0.01-0.15</td>
<td>0.01-0.12</td>
<td>0.01-0.03</td>
</tr>
<tr>
<td>1985</td>
<td>&lt;DL</td>
<td>&lt;DL</td>
<td>&lt;DL</td>
</tr>
<tr>
<td>1987</td>
<td>&lt;DL-0.08</td>
<td>&lt;DL-0.08</td>
<td>&lt;DL-0.09</td>
</tr>
<tr>
<td>1988</td>
<td>&lt;DL-0.05</td>
<td>0.06-0.10</td>
<td>&lt;DL-0.09</td>
</tr>
<tr>
<td>1989</td>
<td>&lt;DL-0.05</td>
<td>&lt;DL-0.09</td>
<td>&lt;DL-0.10</td>
</tr>
<tr>
<td>1990</td>
<td>&lt;DL-0.50</td>
<td>&lt;DL-2.30</td>
<td>&lt;DL-1.15</td>
</tr>
<tr>
<td>1991</td>
<td>&lt;DL-0.50</td>
<td>&lt;DL-0.05</td>
<td>&lt;DL-0.10</td>
</tr>
<tr>
<td>1994</td>
<td>&lt;DL-0.03</td>
<td>&lt;DL-0.08</td>
<td>&lt;DL-0.11</td>
</tr>
<tr>
<td>1995</td>
<td>&lt;DL-0.60</td>
<td>&lt;DL-0.20</td>
<td>&lt;DL-1.01</td>
</tr>
<tr>
<td>1996</td>
<td>&lt;DL-0.07</td>
<td>&lt;DL-1.58</td>
<td>&lt;DL-0.77</td>
</tr>
<tr>
<td>1997</td>
<td>0.04-0.07</td>
<td>&lt;DL-0.84</td>
<td>0.06-1.66</td>
</tr>
<tr>
<td>2000</td>
<td>&lt;DL-0.07</td>
<td>&lt;DL-1.24</td>
<td>&lt;DL-1.52</td>
</tr>
<tr>
<td>2001</td>
<td>0.06-0.08</td>
<td>&lt;DL-2.17</td>
<td>&lt;DL-2.14</td>
</tr>
<tr>
<td>2004</td>
<td>&lt;DL-0.88</td>
<td>&lt;DL-1.93</td>
<td>&lt;DL-1.34</td>
</tr>
<tr>
<td>2006</td>
<td>&lt;DL-0.07</td>
<td>0.05-1.12</td>
<td>0.67-2.49</td>
</tr>
<tr>
<td>2008</td>
<td>0.04-0.08</td>
<td>0.08-1.56</td>
<td>&lt;DL-1.70</td>
</tr>
<tr>
<td>2011</td>
<td>&lt;DL-0.09</td>
<td>&lt;DL-2.48</td>
<td>&lt;DL-1.80</td>
</tr>
<tr>
<td>2013</td>
<td>&lt;DL-0.06</td>
<td>&lt;DL-1.60</td>
<td>&lt;DL-1.74</td>
</tr>
<tr>
<td>2014</td>
<td>&lt;DL-0.09</td>
<td>&lt;DL-2.69</td>
<td>&lt;DL-2.10</td>
</tr>
</tbody>
</table>


<DL: below the detection limit (Cd: 0.0002mg/L; Cu: 0.002 mg/L; Pb: 0.005 mg/L)
from the input of Cilincing estuary (Figure 5), while Pb was expected to come from Marunda estuary (Figure 7). In particular, Cu was probably derived from two places, i.e., from the Marunda estuary and from the eastern part of Cilincing water (Bekasi) carried by the water current (Figure 6).

In general, [14] reported that bioaccumulation of heavy metals in the body of green mussels culture has occurred in Jakarta Bay, where the heavy metals originated from the polluted water. It was also reported [14] that green mussels, at the age of 6 months, could absorb mercury at concentrations of 209.82 ± 35.58 ppm. The bio-accumu-
lation of heavy metals in green mussel was possible since the heavy metals could be easily and quickly absorbed by the living body [22,23]. Another previous research [4] also reported that the green mussels can absorb mercury and accumulate it in their bodies effectively.

The present research presents another more physical mechanism than bioaccumulation. As summarized before, the dense green mussels culture equipment (bamboos and ropes) could reduce the velocity of water current, and can be a trap for the heavy metals carried by the water current. This leads to an intensified concentration of heavy metals supplied by riverine input. The density of net units could generate shears in the water column. Theoretically, the shears resulted in the water column are given by:

\[ \rho k \frac{\partial u}{\partial z} \]  

where \( \rho \) = density of water, \( k \) = viscosity, \( u \) = horizontal velocity component, and \( z \) = vertical axis (water depth).

To examine the influence of this density of net/raft unit to the circulation of water, a simulation was carried out, as described in Section 2, and the results can be seen in Figure 8. Figure 8a shows that the current velocity in the surface layer reduced in the middle of canal, where the beams suspended to a depth of 6 m. This model result is consistent with the observations (Figure 4). However, current velocity in the layer near the bottom or under the beams (Figure 8b) shows an increase as an implication of the law of continuity. This produces an acceleration of velocity in the water column below to reach the equilibrium. A similar mechanism is shown in Figure 8c, for the vertical profile of the current along the central line of the canal. The reduction in the surface to the depth of 6 m is caused by the presence of the beams, or in this case, the resemblance to the dense green mussels culture equipment. In addition, there was a strong eddy current on the location below the beams as a result of shear stresses around the beams and bottom drag that produce vertical eddy or turbulence.

In reality, the model simulations are not exactly the same as the condition of the units of net/raft used in the green mussel culture. The size of the bamboos used in the culture of the green mussels has a diameter of \( \pm 10 \) cm. However, the focus of this study is that the density of the units of net/raft could produce large shear stress and reduce water current, which affects the distribution of heavy metals in the waters.
Conclusion

The observed heavy metal concentration in the sea surface and the simulated water current could reproduce the impact of the green mussels culture equipment in Cilincing waters. It is clearly shown that the dense units of the net/raft could potentially become a trap for the heavy metal supplied by the riverine inputs. Future studies may focus on a large scale of the model region that covers Jakarta Bay, including modeling of heavy metal bioaccumulation by green mussels. The bioaccumulation model needs a specific coefficient, as shown by field or laboratory experiments.

Acknowledgements

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