Dispersion of conservative floating material from Pamurapa River in Amurang Bay, North Sulawesi - Indonesia

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Abstract. Pamurapa River as a continuation of Ranoyapo River is the largest river that empties into Amurang Bay. The discharge of this river may carry pollutant materials from inland. A Lagrangian field experiment was conducted to determine the dispersion coefficient of conservative floating materials like plastic debris from the Pamurapa River into Amurang Bay. Two groups of five floats were released consecutively from the river mouth during ebb tides. The position of these floats was recorded hourly using a handheld GPS. The observations were carried out for eight days representing spring tides and neap tides between early July and early August 2019. Measurements were also made for tidal height and surface winds. At spring tides with southerly winds, the patch of floats moved away more than 5 km along the southern part of the bay. The RMS distance between floats reached more than 2 km, and the maximum value of the dispersion coefficient was 24 $m^2 s^{-1}$.

Key Words: Lagrangian, plastic debris, dispersion coefficient, ebb tides, Ranoyapo River.

Introduction. Conservative buoyant materials, or persistent materials like plastics, have become an important issue in recent years (Vegter et al 2014; Borrelle et al 2017). In the sea, plastic debris comes from various sources. One of the main sources is the settlement in the coastal and river basin areas (Jambeck et al 2015; Lebreton et al 2017). Entering through a river, these floating materials disperse in the sea following the movement of water mass.

The flow of water mass in coastal waters is influenced by various oceanographic and meteorological factors. These factors include winds, tides, and river discharges (Geyer 1997; Lewis 1997). The winds push and drag the water surface to move along with the wind. In an estuary or river mouth, the winds can push or block the water from coming out of the area, or vice versa to enter the area (Geyer 1997). High tidal range allows a water parcel to move away farther. Similarly, strong tidal currents may increase tidal excursion distance. In an area with complex bottom topography and shorelines, tidal currents become considerably turbulent which leads to an increase in particle dispersion. Besides determines the dynamic of coastal waters, tidal oscillation is also important in the mixing process. Other important factors influencing the dynamics around river mouths are the buoyancy and momentum of river discharges (Cole & Hetland 2016; Yuan et al 2018).

Dispersion of floating objects has been investigated using floating drifters (Tseng 2002; Spencer et al 2014). In estuaries, Tseng (2002) found that the dispersion coefficient was 12-15 $m^2 s^{-1}$, whereas in open ocean waters, the dispersion coefficient can reach 1000 $m^2 s^{-1}$ (Lewis 1997). In addition to meteorological and oceanographic conditions, the magnitude of dispersion coefficient is influenced by the design of the drogues (Spencer et al 2014) and the operational depth of the drogues (van Aken 2002).

In Amurang Bay, information on the dispersion of floating conservative materials is not available yet. The aim of this study was to explore the dispersal characteristics of floating materials during ebb tides and to determine the coefficient of dispersion. The rapid development in Amurang city and in the settlements along the Pamurapa River will create greater pressure on the bay due to litter input. This research is, therefore, expected to contribute to the management of plastic debris in the area.

Material and Method

Description of the study site. This research was focused on the Pamurapa River's influential area in the southern part of Amurang Bay, North Sulawesi, Indonesia (Figure 1). The surface area of the bay is more than 100 km^2. Amurang Bay opens to the west making it vulnerable to the devastating westerly winds. The eastern coastal area is a densely populated city of Amurang. The bay receives freshwater inputs from several rivers. The most important river is the Pamurapa River (also known as the Ranoyapo River). Estimated based on the channel's size and the speed of river flow, river discharges during the observation period were 7.5-10.0 m^3 s^{-1}.

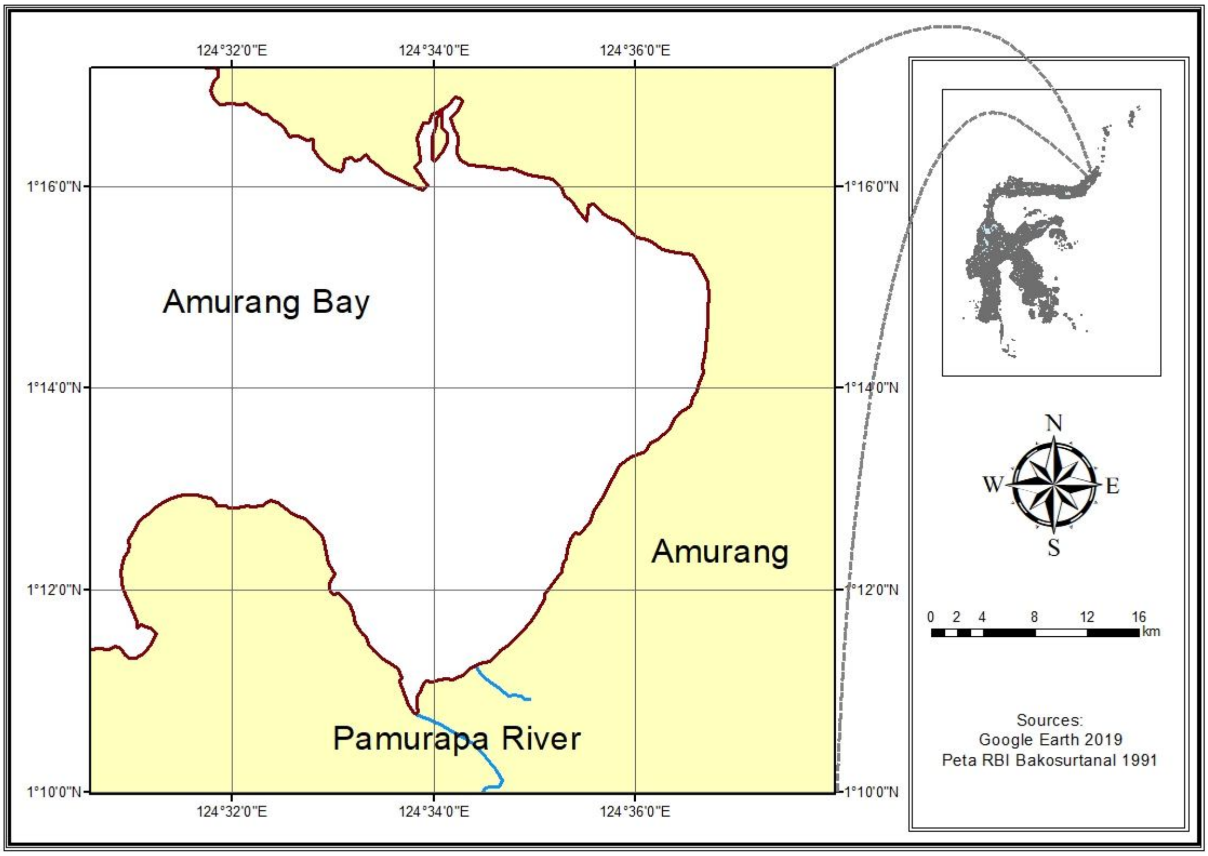

Figure 1. Location map of Amurang Bay, North Sulawesi, Indonesia.
Map source: extracted from Google Earth online 2019.

Field experiment. This research employed the Lagrangian method, namely by following the drift of floats. The model of floats unit (Figure 2) is similar to that used in Manado Bay by Kamat et al (2014) and Suruan et al (2015). The float unit consisted of a drogue, a buoy, and a flag. The drogue consists of two crossed PVC sheets of 234×360×3 mm in size. This drogue was positioned at a depth of 1 m from the surface. The buoy is oval of 10 cm in diameter and 15 cm long and made of PVC foam plastic. The flag was attached to a PVC flagpole. This flag was used for placing float identity as well as an indicator to ease searching.

The floats were released in two consecutive groups of 5 floats from a point in the middle of the Pamurapa River mouth. The first group was released at about the water just to start ebbing, and the second group was released in about two hours later. The group of floats with their occupied area will be called a patch. The position of floats in a patch was monitored every about one hour using a Garmin 64s GPS from a motorboat.

The observations were carried out for 6-8 hours. However, if most of the floats in the patch were stranded or when sea conditions became risky then the observation would be terminated. This experiment was carried out for eight days during spring tides and neap tides in early July to early August 2019.

Figure 2. The float units.

Besides, the wind speed was measured at about 2.5 m above sea surface using a handheld anemometer Benetech GM8902. Wind direction was determined based on the four main cardinal directions. Water level changes related to tides were observed manually from a tidal pole.

Data analysis. Floats position data in GPS memory were transferred to a spreadsheet computer program. These positions were then plotted in the study location map for each observation to see the movement of floats with time. Based on these plots, a map of floats movement tracks was constructed. Expressed in terms of the root mean square (RMS) of the distance of floats from the center of the patch, the dispersion was calculated following the formula used by Yanagi et al (1982) and Heron et al (1998):

$$\sigma_{xi}^2 = \frac{1}{n-1}\sum\left(x_{ij} - \bar{x}_i\right)^2 \quad (1)$$

$$\sigma_{yi}^2 = \frac{1}{n-1}\sum\left(y_{ij} - \bar{y}_i\right)^2 \quad (2)$$

$$\sigma_i^2 = \frac{1}{n-1}\sum\left[\left(x_{ij} - \bar{x}_i\right)^2 + \left(y_{ij} - \bar{y}_i\right)^2\right] \quad (3)$$

where $\bar{x}_i = \frac{1}{n}\sum x_{ij}$, $\bar{y}_i = \frac{1}{n}\sum y_{ij}$, x_{ij} and y_{ij} are the respective latitude and longitude positions of the *j*-th float and *i*-th patch that aligned along the patch displacement direction, and *n* is the number of floats in the patch. Mapping and dispersion analyses were carried out using the Matlab computer program.

Dispersion coefficient *K* was calculated based on the change of separation distance along and across the patch with time using the formula of Tseng (2002) and Spencer et al (2014):

$$K = \frac{1}{4}\frac{\partial(\sigma_x \sigma_y)}{\partial t} \qquad (4)$$

The average value of the dispersion coefficient was estimated from the slope of the regression line between time and $\sigma_x\sigma_y$ (Tseng 2002).

Results and Discussion

Tides. The observation of tidal height was carried out during the ebb period along with the floats tracking experiment. At neap tides, the observations began at around 11:00, while during spring tides, the observations began at around 07.00. High tidal height occurs at the full moon and the new moon which was around 1.8-2.3 m, while low tidal height occurs at the quarters ranging between 1.0 and 1.3 m.

Winds. During the experiment, the southerly winds were dominant and the wind speed reached 9.5 m s^{-1}. During ebb tides, the southerly winds accelerated the floats to flow out of the estuary and the bay. When the tides reversed, a thin layer of the surface could keep moving with the wind, but the water layer just below flowed back into the bay. In this situation, the floats became very tilted in the direction of the wind.

Float movements. The group of floats released at the river mouth moved off following the ebb currents. At spring tides, the excursion distance of ebb tides was long that reached 5.7 km, while at neap tides, the excursion distance reached only 4.6 km (Figure 3). The second set of floats released about two hours after ebbing tides generally did not reach as far as the first group. However, on 18 and 19 July 2019 the second moved farther out (picture not shown here) than the first group. Actually, on 18 July the first group moved in a slower flow strip along and very close to the coast. While, on 19 July 2019 the observation to the first group was stopped because most floats were stranded on the south coast, while the others moved out of the bay.

The winds have an apparent influence on the movement of the floats. When the southerly winds blew quite strong, the patches generally flowed out along the left side (south of the bay). Also, the dominant southerly winds increased the excursion distance of ebb flows. This increase is similar to that observed by Kalangi et al (2018) in Manado Bay which allowed them to suggest that the southerly winds accelerated the arrival of marine debris to the waters around Bunaken Island. Conversely, when the westerly winds blew (although inconsistently) in Amurang Bay, the movement of the patches from the river were directed out to the bay proper.

Dispersion. The floats in the groups tend to move away from each other. This results in the coverage area of the group, the patch, increasing with time. In other words, the floats are experiencing dispersion. The distance between floats of the group which released at the beginning of ebb tides was more likely to be greater than that of the group released two hours later (Figure 4). The average distance between floats was generally less than 1 km, but on 3 August coincided with spring tides, the separation reached more than 2 km. This was because some of the floats were trapped in a small embayment, while the other floats entered the jet stream out of the bay.

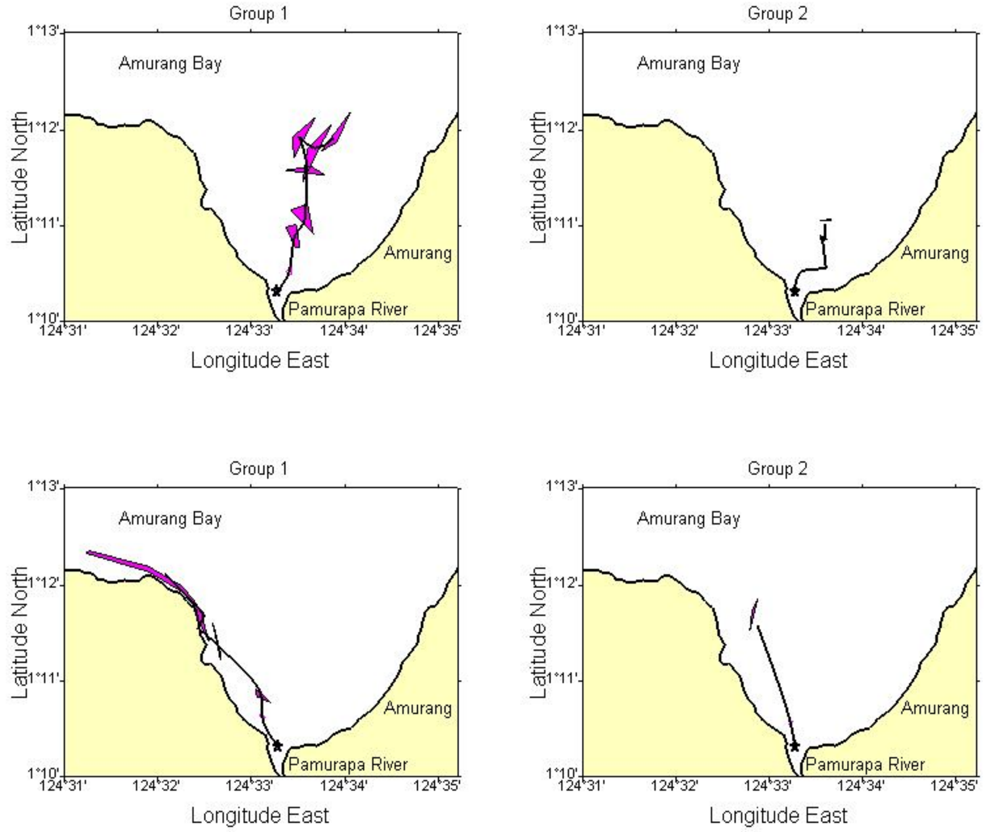

Figure 3. Examples of float patch tracks on 2 August 2019 (top panels) and 3 August 2019 (bottom panels).

In the first three hours of the observation period, the dispersion tended to increase slowly, and then increased sharply in the rest of the observation period (Figure 4). These characteristics are similar to the simulation results based on surface currents data measured using HF radar reported by Heron et al (1998) and the diffusion experiment using surface drifters by Tseng (2002). To estimate the value of the dispersion coefficient, the observation periods were divided into two segments base on their trends, namely the first segment comprised the first three hours of the observation period, and the second segment comprised the rest of the observation period. For the first segment, the maximum dispersion value of 0.770 $m^2 s^{-1}$ and the maximum average dispersion of 0.321 $m^2 s^{-1}$ occurred in the first group of spring tides. Whereas for the second segment, the maximum dispersion value was nearly 24 $m^2 s^{-1}$ with a maximum average dispersion value of 7,158 $m^2 s^{-1}$. The variability of the dispersion coefficient also increased with time, and generally, the variability shown by the value of standard deviation was greater than the average value, which indicates that the dispersion coefficient was greatly varied among the observation classifications. The complete dispersion coefficient values for each group and segment are shown in Table 1.

The dispersion coefficients were generally greater in the group which released at the beginning of ebb tides and spring tides. This might be caused by currents that varied with time and place, and also by the longer tidal excursion at spring tides. The time scale affects the magnitude of the dispersion coefficient. The maximum observation time for this experiment was only about 8 hours. Tseng (2002) carried out a longer experiment, which was around 17 to 26 hours, and obtained the dispersion coefficient in estuaries reaching 14.5 $m^2 s^{-1}$, and in the area affected by an island wake, the coefficient reached 45 $m^2 s^{-1}$. Spencer et al (2014) also obtained the dispersion coefficient of no more than 5 $m^2 s^{-1}$ in the first 8 hours of observation. They also found that different drogue models produced different dispersion coefficients.

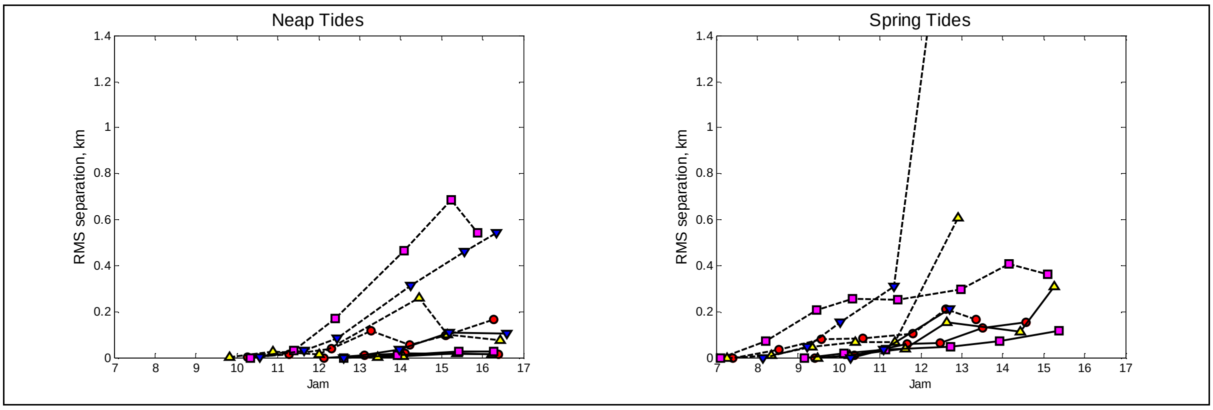

Figure 4. RMS distance from the patch center.

Table 1

Dispersion coefficient ($m^2 s^{-1}$)

Tides	*Group*	*Segment 1*		*Segment 2*	
		Range	*Mean, std*	*Range*	*Mean, std*
Neap	1	0.002-0.270	0.098, 0.106	0.056-4.179	1.629, 1.706
	2	0.003-0.183	0.050, 0.076	-0.009-0.012	0.003, 0.008
Spring	1	0.048-0.770	0.321, 0.284	0.229-23.943	7.158, 9.818
	2	0.020-0.270	0.091, 0.104	0.014-0.480	0.278, 0.195

At the beginning of observation periods, the floats were still in the estuary area and the flow in the area tended to be in one direction. This resulted in small dispersion coefficients. However, when the floats were already in the main part of the bay, they tangled with the more complex flow patterns. In some observations, a narrow strip with a fast flow developed along the southern coast. A couple of floats that caught in that flow were carried far out of the bay. On the other hand, a curve in a shoreline might trap some other floats. Since these two conditions occurred on 3 August, the dispersion coefficient was considerably large. This result agrees with Okubo's (1973) model that showed the importance of small indentations along the coastline that functioned as traps of some part of dispersion materials.

As shown in Table 1, there was also a negative dispersion coefficient. Such negative dispersion occurs when a group of floating materials is trapped in a surface current convergence system. The decreased distance between floats may occur on both main axes or only on one axis as shown in Figure 3. Under complex bathymetry and geometry conditions, dispersion oscillated with the tidal phase (Heron et al 1998). This indicates that there were alternating positive and negative in dispersion coefficient values of conservative materials. Such alternating values were, however, unnoticeable in this study since the observations were limited to the ebb tides only.

This experiment indicates that the Lagrangian tracks and dispersion coefficient in the area varied considerably. As also shown by Meyerjürgens et al (2019), drifter trajectory variabilities are influenced by a complex interaction of tides, winds and coastline structure. In addition, a frontal zone developed in the region of freshwater influence can affect the float tracks and dispersion. We observed a couple of floats trapped along the front. A similar phenomenon has been observed by Stanev & Ricker (2019).

Conclusions. The direction and range of movement of conservative floating materials from the Pamurapa River estuary into Amurang Bay are influenced by tidal and wind conditions, and coastline structure. The spring tides combined with southerly winds resulted in the floats moved away of > 5 km along the southern edge of the bay. In a period of fewer than eight hours, the RMS distance between floats was > 2 km, and the dispersion coefficient reached 24 $m^2 s^{-1}$.

Although the negative dispersion may occur, the size and location of the patches during low tides generally continue to evolve with time. This indicates that the debris management efforts, especially in removing debris from the sea, are less effective if they are carried out in such conditions. Alternatively, the removal of marine debris should be done in the river mouth area at high tides.

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