Modeling the distribution of floating marine debris movement in tourism area in Pelabuhan Ratu Bay, West Java

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Abstract. Marine debris is an important marine environmental issue in Indonesia. The impact of marine debris pollution influences life in the coastal areas including tourist areas. The coastal area of Pelabuhan Ratu in the southern part of West Java province is well-known as a tourist area. Therefore, it is vital to understand the cycle of marine debris movement in this area. We conducted research using observation data to create a Delft3D model. The coupled hydrodynamic and trajectory models were simulated to detect marine debris movement. The generating force of this model was natural forces present in the environment; i.e., tidal and wind forces, and the flow of river discharge. Plastic is the dominant type of debris. The simulation was only run during the western monsoon when there is an extremely large amount of marine debris due to the increased rainfall. The majority of marine debris particles originate from the Cimandiri River (90%) and reaches as far as the nearest estuary, which shows the role of tidal circulation. The maximum distances from the marine debris source to the furthest trajectory are 17.49 and 15.54 kms for the discontinue and continue particle source simulations, respectively. The marine debris particles which originated from the tourist beach area move westward along the coastline, following the wind direction. After reaching the area of the estuary area, some particles enter the river, but most (98%) move to the coastal area as far as the nearest estuary.
Key Words: marine debris, Pelabuhan Ratu Bay, trajectory model, west monsoon.

Introduction. Waste production is a type of human activity that has a negative impact on the environment. In addition to damaging the environment, waste can also have a negative impact on humans, animals, and plants. Waste can be found anywhere from land, rivers, and oceans. Waste in marine areas, known as marine debris, is a big problem nowadays. According to Lippiatt et al (2013), marine debris can be described as persistent solid material that is produced or processed by humans, which, directly or indirectly, intentionally or accidentally, ends up in the ocean environment or in streamed-through rivers. Almost 80% of marine debris comes from land-based human activities sources (Jambeck et al 2015). Marine debris can be categorized by types of material: plastic, cloth, foam, styrofoam, glass, ceramic, metal, paper, rubber and wood (UNEP 2011; NOAA 2013). Plastic is the predominant type of marine debris. Plastic is a synthetic organic polymer whose characteristics fit well for use in daily activities (Derraik 2002). As far as the other types of waste, marine debris can also be divided into two types: organic (biodegradable), and inorganic (non-biodegradable) (NOAA 2013).

Besides the type of material, marine debris can also be categorized based on its source, and size. There are two sources of marine debris: from the ocean, or from the land. Meanwhile when classified by size, according to Lippiatt et al (2013) marine debris can be sorted from largest to smallest, which is termed as: mega-debris, macro-debris, meso-debris, and micro-debris.

The movement of marine debris in oceans can be observed on a global or local scale, depending on the study area being researched. To observe the movement of marine debris on a global scale, three factors need to be considered: Ekman drift, stoke drift, and geostrophic current (Kubota 1994). On the other hand, to observe the movement of marine debris on a local scale, certain natural phenomena need to be considered: ocean currents (especially tidal currents and residue currents), wind, amount of rainfall, and natural hazards such as storms and tsunamis (Yosafat 2012; Putuhena 2013; Husrin et al 2017; Jasmin et al 2019; Cordova & Nurhati 2019).

The distribution of marine debris can be affected by either natural factors or human activity. Most plastic waste in oceans, especially in highly-populated coastal areas, gains entry through shipping and fishing activities, and industrial waste that is piped and flows into rivers (Dixon & Dixon 1981). Floating marine debris can become concentrated as a result of natural processes that occur along the convergence line between discret water, in the center of a gyre, or in underwater beaches and rocks; most of these are important marine habitats (Carr 1987).

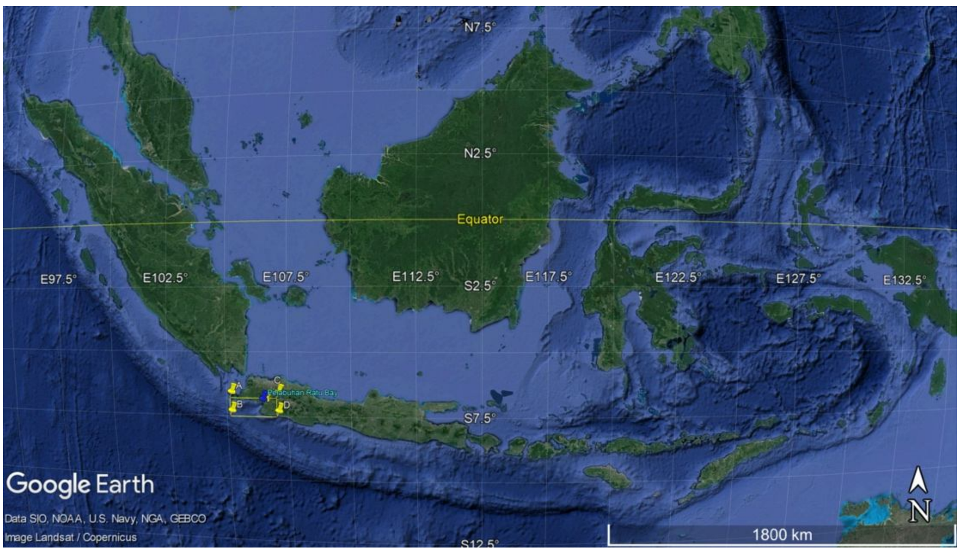
Pelabuhan Ratu is a tourist location in the southern part of West Java that directly faces the Indian Ocean. The beaches in this area generate a large amount of marine waste, such as plastic water bottles and random plastic that is scattered along the coastline. Waste on the Pelabuhan Ratu beaches is mainly contributed by tourists, nearby restaurants, and small river outlets around the coast. It was reported by the Department of Tourism, Culture, Youth, and Sports (The Department of Tourism Cultural Youth and Sports 2016) that 3,600,613 tourists visited Pelabuhan Ratu in 2016, which is more than its expected carrying capacity of 3,124,833 people.

Some of the waste produced is carried to the ocean where it is distributed not only on the surface of the water, but also in depths of 1,156 m in the South Java deep water, which was discovered during The South Java Deep Sea Biodiversity Expedition (SJADES) 2018 cruise made by the Indonesian Institute of Sciences (LIPI) in February 2018 as reported by Septian (2018). Marine debris gets carried by ocean currents and sometimes gets beached when high waves occur (Poskota News, February 3, 2018). This research aims to simulate the tracking, movement and fate of the floating marine debris originated the land-based and sea-based sources in Pelabuhan Ratu Bay.

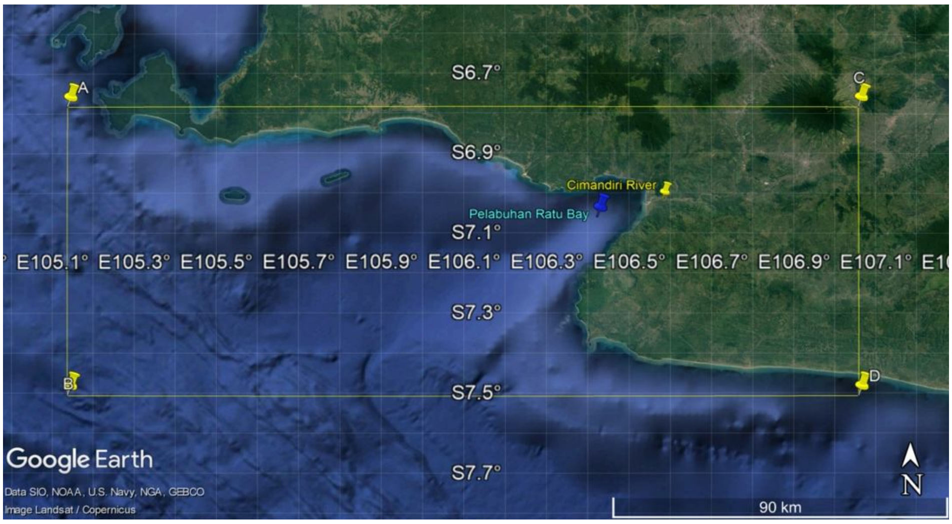
Material and Method

Description of the study sites. Pelabuhan Ratu Bay is the largest bay in the southern part of West Java. The model domain is located at 6.76-7.98°S and 105.01-107.24°E (Figure 1a). Pelabuhan Ratu Bay is where four rivers meet; namely, the Cimandiri, Cibareno, Cilentuk, and Cikanteh Rivers. In this simulation, we only put the model in the Cimandiri River.

Pelabuhan Ratu Bay is a semi-enclosed bay in the south of West Java, directly facing the Indian Ocean (Figure 1b). The deepest part of the bay is 350 m, which is in the most northeastern part of the bay and also in the most southwestern part which transitions to the Indian Ocean.



(a)



(b)

Figure 1. Indonesia area (a) and research area (b) (Source: Google Earth).

Numerical model. To understand the outcome and distribution of marine debris, we use the coupled hydrodynamic model with a particle-tracking model, using the DELFT3D Model (Delft3D 2014) to simulate floating marine debris. Modelling is an effective tool to understand the sources, fate, distribution, transport and accumulation of debris in oceans (NOAA 2016). Numerical models have been implemented for marine debris simulation on a global scale (Lebreton et al 2012), a regional scale (Yoon et al 2009), as well as on a local scale (Yosafat 2012; Putuhena 2013; Husrin et al 2017; Jasmin et al 2019; Cordova & Nurhati 2019).

This simulation was done using a hydrodynamics model and the Delft3D-Flow program. The Cartesian coordinate system is the coordinate system used, and the Delft3D hydrodynamic model uses continuity and momentum equations as the foundation of the model. ξ -axis and η -axis indicated as x-axis and y-axis.

Model design and scenarios. In this research, simulations were done using a Delft3D-Flow model for 29 days, starting from February 1 to February 29, 2016. This period of time was chosen because it represents the western monsoon season when the amount of marine debris is high. In this simulation, the input data are the bathymetry of Pelabuhan Ratu with the generating force due to seasonal winds, river discharge, and hourly tides. The simulation was run in two separate ways: namely, the hydrodynamics model and the trajectory mode. The output of the hydrodynamic model is sea elevation and ocean current, and that of the trajectory is marine debris particle trajectory. The sea elevation from the model was verified using observation data to verify the accuracy of the model. If the verification of elevation and ocean current in a particular observed spot is accurate, then the model can represent the actual conditions of the Pelabuhan Ratu waters. Afterwards, the results of the hydrodynamic simulation as well as the particle movement trajectory will be visualized and integrated inside the Delft3D-QUICKPLOT module (Delft3D 2014).

The area of observation of this research directly borders the Indian Ocean and the provinces of Banten and West Java. The model domain for this research has two boundary conditions: open condition and closed condition. In this research, the simulation began on February 1st and ended on February 29, 2016. Marine debris particles started to come out on February 5, 2016 and continued coming out at every interval of that scenario. The time interval of the hydrodynamic simulation is three minutes. For more details, see Table 1.

This simulation was conducted using four different scenarios. Four scenarios were chosen to observe the influence of the source of the marine debris and also to see the impact of different time intervals on the distribution of marine debris particles at the source using the discontinue and continue particle release scheme. Scenario-1 and Scenario-2 are set to distribute marine debris particles that come from the Cimandiri River, while Scenario-3 and Scenario-4 are set to distribute marine debris particles that come from the Pelabuhan Ratu beaches. Our findings regarding debris from tourist activities can be seen in Figures 2 and 3; Table 2 shows the location of the particles.

Continuity equation:

$$\frac{\partial \zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)]U\sqrt{G_{\eta\eta}}}{\partial \xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial[(d+\zeta)]V\sqrt{G_{\xi\xi}}}{\partial \eta}=(d+\zeta)Q \quad (1)$$

with

$$U=\frac{1}{d+\zeta}\int_{d}^{\zeta}u\,dz=\int_{-1}^{0}u\,d\sigma \quad (2)$$

$$V=\frac{1}{d+\zeta}\int_{d}^{\zeta}v\,dz=\int_{-1}^{0}v\,d\sigma \quad (3)$$

Momentum equations:

ξ **-axis**

$$\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta}-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}-fv=-\frac{1}{\rho_o\sqrt{G_{\xi\xi}}}P_\xi+F_\xi+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}\left(v_V\frac{\partial u}{\partial \sigma}\right)+M_\xi \quad (4)$$

η **-axis**

$$\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta}-\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}+fu=-\frac{1}{\rho_o\sqrt{G_{\xi\xi}}}P_\eta+F_\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}\left(v_V\frac{\partial v}{\partial \sigma}\right)+M_\eta \quad (5)$$

where *u* and *v* are the velocity components on ξ and η axis (m/s), U and V are the averaged velocity component on ξ and η axis (m/s), *d* is depth (m), ζ is water elevation (m), *t* is time (s), $\sqrt{G_{\xi\xi}}$ & $\sqrt{G_{\eta\eta}}$ are transformation coeficients from curvilinear to rectangular coordinates, *f* is Coriolis factor (s^{-1}), *g* is gravitational acceleration (m/s^2), v_V is vertical eddy viscosity ($m^2\ s^{-1}$), ρ_0 is water density (kg/m^3), P_ξ and P_η are hydrostatic pressure gradient on ξ and η axis ($kg\ m^{-2}\ s^{-2}$), F_ξ and F_η are turbulence force ($m\ s^{-2}$), and M_ξ and M_η are other momentum forces ($m\ s^{-2}$).

The particle tracking model was done by using a particle trajectory model (Yosafat 2012). Say the position of a particle is in (x_t, y_t) on *t* time and Δt time-step, then the position of that certain particle on ($t+\Delta t$) according to the Euler method can be applied as follows:

$$x_{t+\Delta t}=x_t+u(x_t,y_t,t)\Delta t \quad (6)$$

$$y_{t+\Delta t}=y_t+v(x_t,y_t,t)\Delta t \quad (7)$$

Equations (6) and (7) are then adapted into sigma coordinate, which is used by Delft3D, and these equations can be applied as follows:

$$\xi_{t+\Delta t}=\xi_t+\frac{u(\xi_t,\eta_t,t)}{\sqrt{G_{\xi\xi}}}\Delta t \quad (8)$$

$$\eta_{t+\Delta t}=\eta_t+\frac{v(\xi_t,\eta_t,t)}{\sqrt{G_{\eta\eta}}}\Delta t \quad (9)$$

Table 1

Simulation parameter setting

Parameter	Data
Grid number (ξ x η)	732 x 730
Length of domain	248.25 km
Width of domain	135.81 km
Range for axis – $\xi(\Delta x)$	330 m
Range for axis – $\eta(\Delta y)$	190 m
Simulation time	29 days
Simulation start time	1-February-2016
Simulation end time	29-February-2016
Simulation time interval (Δt)	3 minutes

Table 2

The scenarios of marine debris modeling

Parameter	*Scenario-1*	*Scenario-2*	*Scenario-3*	*Scenario-4*
Marine debris source	Cimandiri River		Pelabuhan Ratu beaches	
Particle distribution scheme	Discontinue	Continue	Discontinue	Continue
Particle number 11	100	100	100	100
Particle number interval	25	10	25	10
Particle distribution interval	3 minutes	12 hours	3 minutes	12 hours
Particle release start time		February 5, 2016	6 00:00	
Particle release end time	February 5, 2016 00:09	February 9, 2016 12:00	February 5, 2016 00:09	February 9 2016 12:00

(a)

(b)

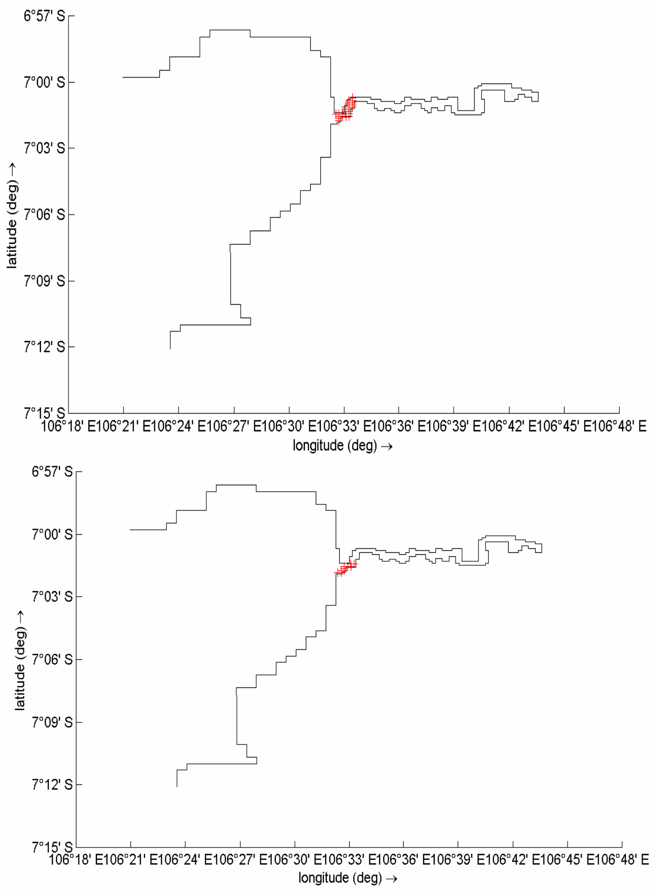
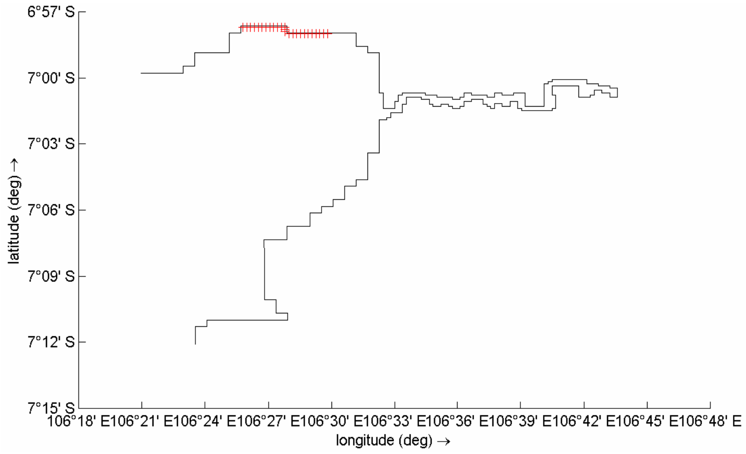


Figure 2. (a) Particle source originating from the Cimandiri River in Scenarios-1 (a) and -2 (b).



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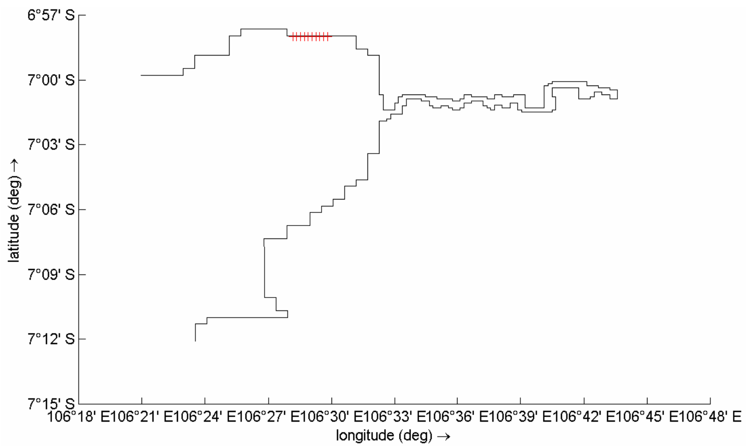


(b)

Figure 3. Particle source originated from beach activities on scenario-3(a) and scenario 4(b).

***Model input**.* The bathymetry data used was obtained from GEBCO 30-seconds. The data obtained are shown as dots with each having a latitude and longitude number and also the depth of that said dot (Figure 4). The wind data used were obtained from apps.ecmwf.int. The data obtained was daily wind data (at 12 am) in the observed area, where each interval of the data had its own data. The data was then averaged spatially until it was only one data of wind speed and one data of wind direction for each day of the simulation. Data of tidal components were used to generate tides in this simulation. The tidal component data was obtained from TMD with the amplitude number and phases of eight tidal components (S2, M2, K1, O1, N2, P1, K2, Q1) being used. The tidal component data are taken from four different sites: the top-left corner, bottom-left corner, top-right corner, and bottom-right corner of the domain of the simulation. Lastly, data from the river discharge was used as one of the factors that influence the ocean current pattern and marine debris movement. The data of the river discharge were daily data in February 2013 of the Cimandiri River which was obtained from the Ministry of Public Works.

***Verification**.* Verification is done to check the accuracy of a simulation. The data that was used to verify the model with the actual conditions was tide data. The observation tide data used is from the Indonesian Geospatial Agency (Badan Informasi Geospasial; hereinafter known as BIG) in February 2016 with 60-minute intervals (Table 3).

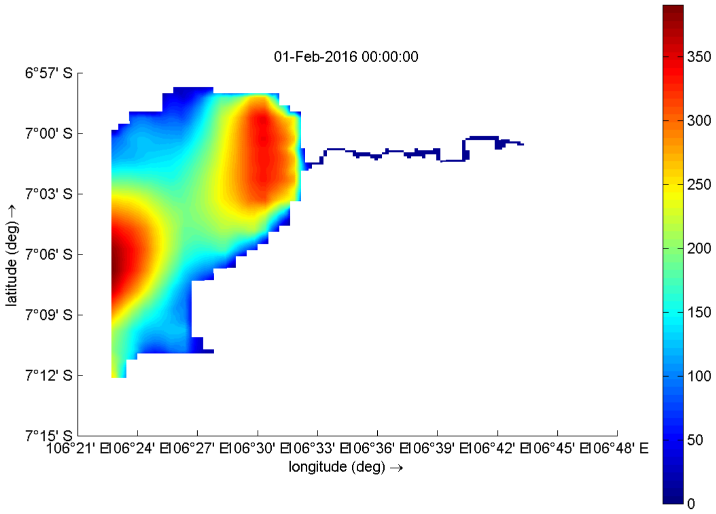


Figure 4. Bathymetry of Pelabuhan Ratu Bay from GEBCO 30-seconds.

Table3

Tidal verification setting

Parameter	*Data*
Verification location	7.019° S; 106.48° E
Observed time	1 – 29 February 2016
Data length	29 days
Data interval storage	60 minutes

Figure 5 shows the comparison between the tidal elevation from the model and observation data from BIG; Figure 6 shows the difference. It was found that the result of the simulation is accurate with a maximum difference of 0.073 m, or 7.3 cm.

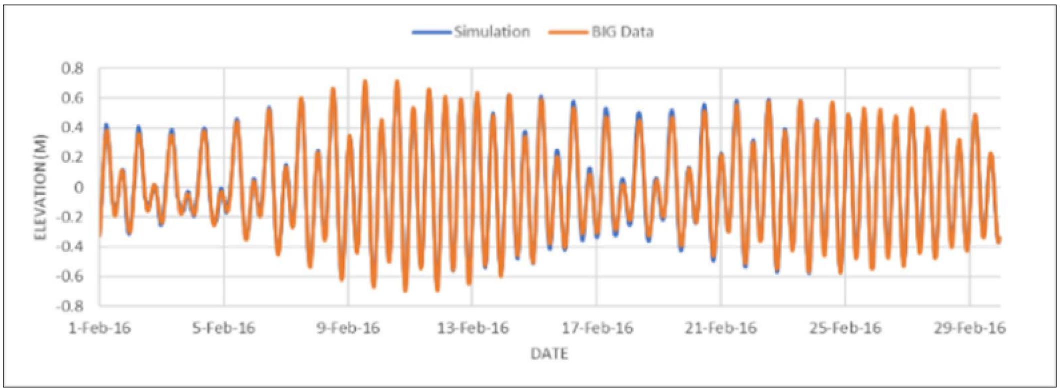


Figure 5. Tidal verification from simulation result and BIG data.

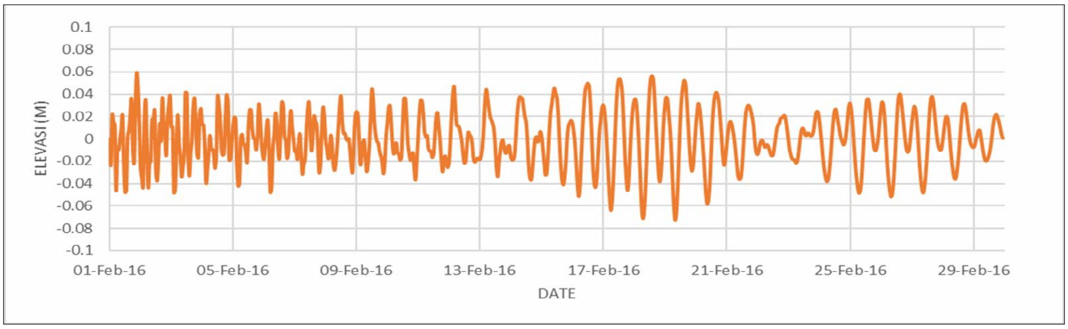


Figure 6. Tidal verification difference between model and observation data.

Result and Discussion. The results of the simulation model show that the movement of 100 marine debris particles that had been distributed varied. Figure 7 describes all movements of the marine debris particles in Scenarios 1-4. To obtain the features of marine debris particle tracking movement for the results of all four scenarios, we used range and displacement parameters. Range is how far the particle moves from the starting point to its final position. Meanwhile, displacement is the distance between the starting point and the final position of a particle. A statistical calculation was aplied to obtain the average of the range and displacement, as well as the maximum and minimum numbers.

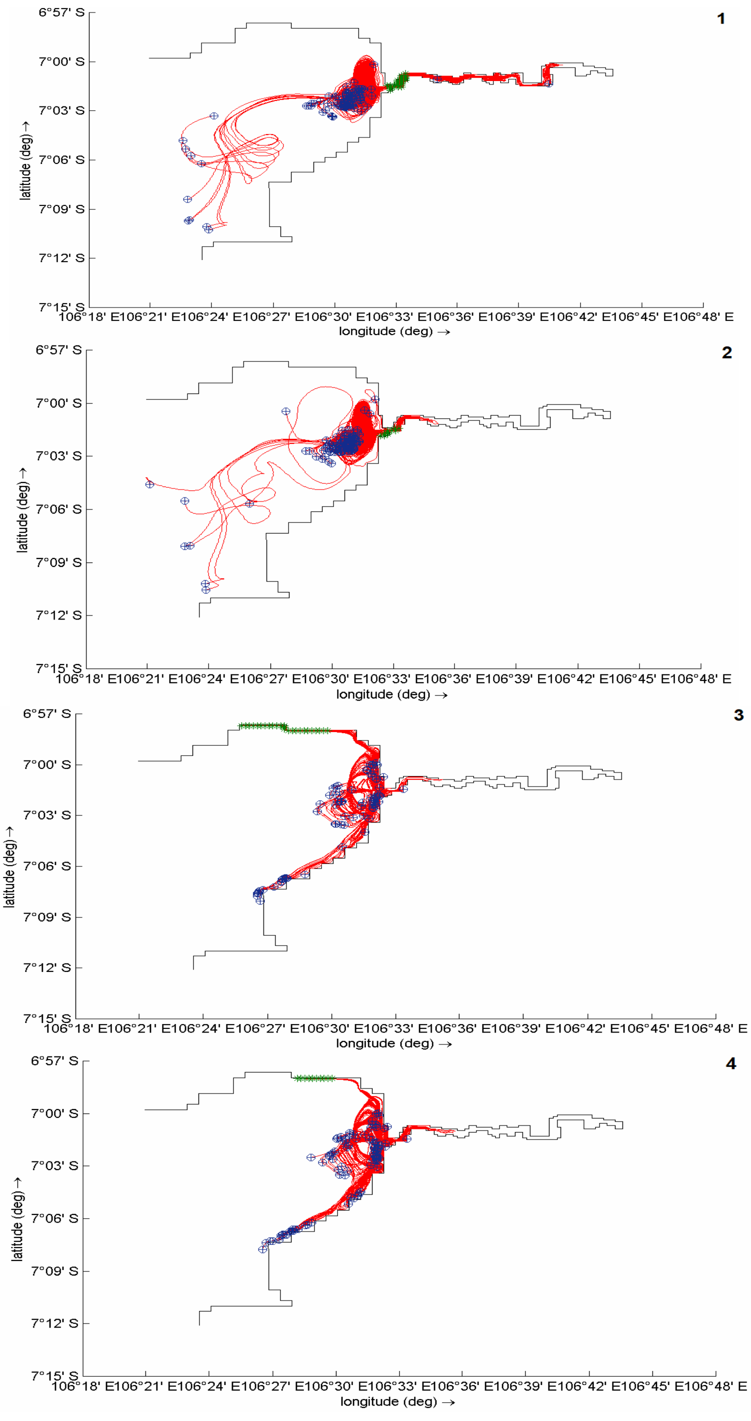


Figure 7. Marine debris movement trajectory with green asterisks as the starting position of the particle; the red lines are the track of the movement, the blue dots are the final position of the marine debris particles, and the numbers indicate the scenarios number.

The particles originating from the river movement according to the tidal circulation which enters the river upstream during high tide and moves to the sea during ebb tide, as seen in Figures 7a and 7b. The reverse circulation of the tidal current can be clearly seen in both simulations. The discontinue simulation (Scenario-1) results shows higher range and displacement as well as the average values compared with the continue simulation (Scenario 2). At the end of the simulation, most particles were located in the estuary area for both simulations. The maximum range is 205 km for Scenario-1 and only around 1/3rd of that distance for Scenario-2; i.e., 61 km. The maximum distances from the source to the furthest trajectory are 17.49 and 15.54 kms for the discontinue and continue particle source simulations.

The marine debris particles originating from the beaches move along the shore on the western side of the bay for both simulations (Scenarios 3 and 4) following the dominant wind direction during the western monsoon. After arriving in the estuary area, some particles enter the river but some particles area are stranded in the coastal area. This movement shows the role of tidal circulation and river streams.

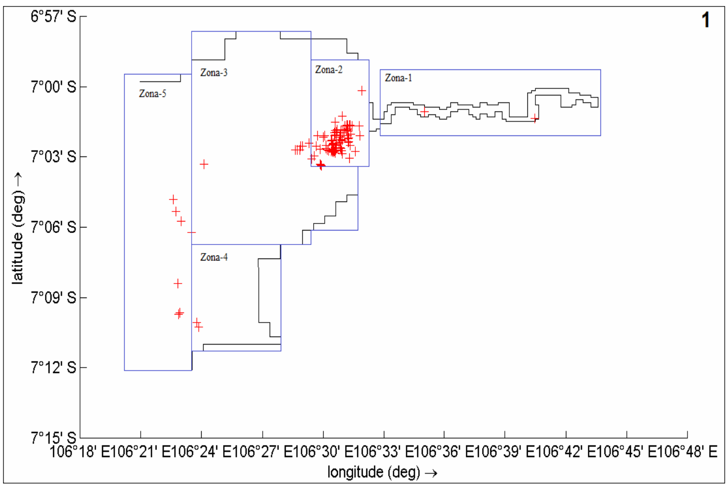
Table 4 shows the result of the statistical calculation of range and displacement.

Table 4

Marine debris range and displacement using statistical calculation

Scenario	*Range (km)*			*Displacement (km)*		
	Maximum	*Minimum*	*Average*	*Maximum*	*Minimum*	*Average*
1	205.11	36.45	61.73	17.49	1.85	4.12
2	61.07	18.39	47.06	15.54	1.37	3.47
3	33.32	18.09	29.85	13.95	9.38	10.99
4	31.49	23.17	28.37	11.07	4.39	8.99

From the position of the marine debris particle at the end of the simulation, we could determine the percentage of particles that either end up in the Cimandiri River, near the estuary of the Cimandiri River, in the Pelabuhan Ratu beach areas, in Pelabuhan Ratu Bay, or outside of Pelabuhan Ratu Bay. These five locations form the benchmark for the zones that will be used to determine the percentage of marine debris particles accumulated in their final position. Zone 1 is the area of Cimandiri River, while Zone 2 is the location of estuary i.e the meeting area between mouth of Cimandiri river and Pelabuhan Ratu Bay. Zone 3 represents the Pelabuhan Ratu tourism area. Zone 4 is inner area of Pelabuhan Ratu Bay and Zone 5 is outer area of the bay. In Figure 8, the number of floating marine debris particles that end up in each zone are calculated and presented as percentages; the results are shown in Table 5.



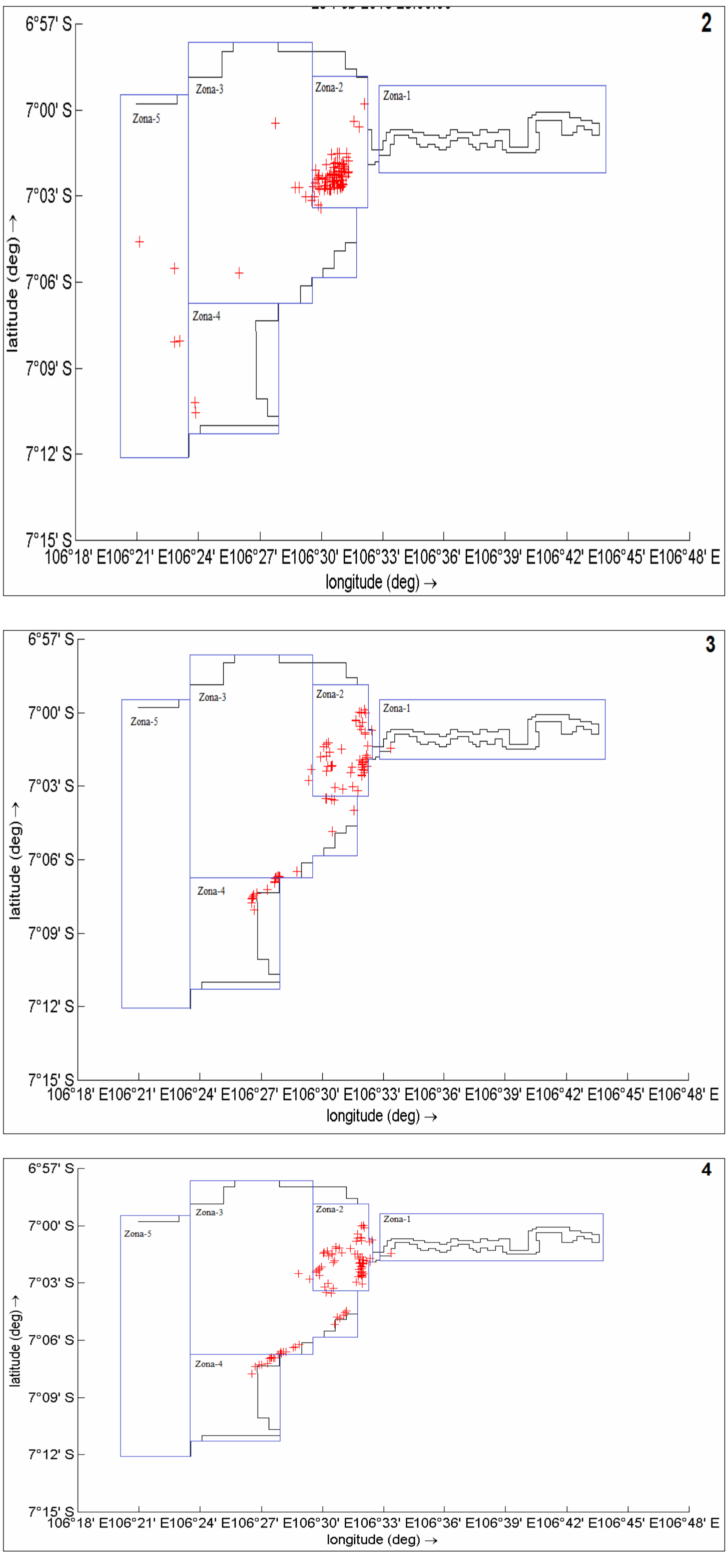


Figure 8. Marine debris particle final position after 29days simulation. The blue boxes represent the zone, and the red (+) signs represent the marine debris particle.

Table 5 clearly shows that in Scenarios-1 and 2, an average of 90% of the particles accumulate end up in Zone-2 at the end of the simulation, which is near the estuary of the Cimandiri River. Furthermore, in Scenarios-3 and 4, an average of 98% of the particles end up in the same zone, which is Zone-2, near the estuary of the Cimandiri River.

Table 5

Marine debris final accumulation position

Scenario	*Zone*	*Location*	*Particle number*	*Percentage (%)*
1	Zone-1	Cimandiri River	2	2
	Zone-2	Cimandiri River Estuary	88	88
	Zone-3	Pelabuhan Ratu Bay	0	0
	Zone-4	South of Pelabuhan Ratu Bay	7	7
	Zone-5	Southwest of Pelabuhan Ratu Bay	3	3
		Total	100	100
2	Zone-1	Cimandiri River	0	0
	Zone-2	Cimandiri River Estuary	92	92
	Zone-3	Pelabuhan Ratu Bay	0	0
	Zone-4	South of Pelabuhan Ratu Bay	5	5
	Zone-5	Southwest of Pelabuhan Ratu Bay	3	3
		Total	100	100
3	Zone-1	Cimandiri River	0	0
	Zone-2	Cimandiri River Estuary	96	96
	Zone-3	Pelabuhan Ratu Bay	0	0
	Zone-4	South of Pelabuhan Ratu Bay	4	4
	Zone-5	Southwest of Pelabuhan Ratu Bay	0	0
		Total	100	100
4	Zone-1	Cimandiri River	0	0
	Zone-2	Cimandiri River Estuary	100	100
	Zone-3	Pelabuhan Ratu Bay	0	0
	Zone-4	South of Pelabuhan Ratu Bay	0	0
	Zone-5	Southwest of Pelabuhan Ratu Bay	0	0
		Total	100	100

Conclusions. Our understanding of tracking, movement, and fate of the floating marine debris from both sources i.e. land based and sea based enhanced. Marine debris particles that originate from the Cimandiri River are strongly influenced by tidal current movement with in and out of the bay to the river direction. Majority of the particles terminated in the estuary of the Cimandiri River in the coastal area.

The marine debris particles that originate from the Pelabuhan Ratu beaches move along the coastline to the western part of the bay, influenced by to dominant wind direction during the west monsoon. After reaching the estuary area, the majority of the particles also accumulate around the estuary in the coastal area.

Further, the understanding of floating marine debris movement would give benefit for the policy and decision making on waste management in this area. We need to improve our knowledge with high data sampling collection and variety of numerical modeling scenarios simulation.

Acknowledgements. Part of this paper was supported by BP-PTNBH 2019-2020 Research Grant funded by Ministry of Research and Technology/National Research and Innovation Agency award to Ivonne M. Radjawane.

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Received: 17 March 2020. Accepted: 29 August 2020. Published online: 30 October 2020.
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How to cite this article:
Juliandri M. R., Radjawane I. M., Tarya A., 2020 Modeling the distribution of floating marine debris movement in tourism area in Pelabuhan Ratu Bay, West Java. AACL Bioflux 13(5):3105-3116.