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[4-B-03] Numerical estimation of the leakage source of large floating marine plastic debris washed ashore on the Tsushima coast using the adjoint method

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Numerical Estimation of Leakage Sources of Large Floating Marine Plastic Debris Washed Ashore on Tsushima Coast Using the Adjoint Method

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Abstract: Marine plastic has become a global problem and the situation is also very serious in the Sea of Japan. Tsushima Island, Japan is the area encountering severe problems with beach plastics, followed by many other beaches facing the Sea of Japan. The total cost of beach clean-up is nontrivial for municipalities facing the sea. Therefore, it is necessary to identify the possible leakage sources. For this purpose, we used the time-backward adjoint marginal sensitivity method, where the sea surface of the East China Sea is the target sea area and beach clean-up data of these islands were input data. The numerical results suggested that the major sources of the debris washed up on the shores of Tsushima Island may be the Yellow River and the Hai River in China.

Keywords: Floating Large Plastic Debris, East China Sea, Detection of Leakage Source, Adjoint Marginal Sensitivity Method.

1 Introduction

Today, there are around 5.25 trillion pieces of plastic weighing 268,940 tons floating in the world's oceans. This could lead to economic damage and ecological problems. East Asian area is responsible for the largest quantity of plastic waste discharge into oceans nearby, thus the East Asian seas have dense concentrations of marine plastic. Strong ocean currents from the East China Sea then carry large quantity of plastic waste into the Sea of Japan. Tsushima Island, which faces the strong Tsushima current, has been seriously polluted by marine plastic. A proper numerical method may help identify the debris sources facing the East China Sea. Isobe et al. [1] developed two-way particle tracking method (PTM): a time-backward PTM with beaches as particle sources and then a time-forward PTM with the destinations of the time-backward PTM as particle sources. Kako et al. [2] improved the two-way PTM of Isobe et al. [1] by introducing the method of undetermined multipliers. Other than those, the time-backward "inverse" method is also considered useful. However, a usual inverse method has disadvantages: it is difficult to capture the whole distribution of a pollutant and the negative diffusivity often makes the inverse calculation unstable. The adjoint sensitivity method is a time-backward probabilistic method, where the advection-diffusion of an adjoint probability is calculated in the time-backward direction with a positive diffusion coefficient. The method has been used to identify a source position of CO_2 leakage under three-dimensional unsteady flows in the ocean (e.g. Sakaizawa et al. [3], Kanao and Sato [4]). Gan et al. [5] and Hui et al. [6] successfully applied this adjoint method to detect sources of PET bottles and plastic bags, respectively, arriving on the south coast of Singapore and the beaches facing the Sea of Japan. In this study, the adjoint marginal sensitivity method is propose as a powerful tool to treat plastic waste pollution. The objective of this study is to numerically identify the leakage sources of marine plastic debris that reach the coasts of the Sea of Japan including Tsushima Island.

2 Method

2.1 Adjoint Marginal Sensitivity Method

The adjoint marginal sensitivity method is a method of estimating leakage source, using the observation data and the flow field data obtained in advance. The advection-diffusion equation of debris concentration C is expressed as

$$\frac{\partial C}{\partial t} + \frac{\partial(u_j C)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D_C \frac{\partial C}{\partial x_j}\right) + \sum_k [f_k \Pi(\boldsymbol{x} - \boldsymbol{x}_k)\Pi(t - t_k)], \tag{1}$$

$$C(\boldsymbol{x}, t = 0) = 0, \tag{2}$$

$$C(\boldsymbol{x}, t) = g_1(t) \quad \text{on } \Gamma_1, \tag{3}$$

$$D_C \frac{\partial C}{\partial x_j} n_j = g_2(t) \quad \text{on } \Gamma_2, \tag{4}$$

where C is the pollutant concentration at a position $\boldsymbol{x}$ and a time t, u_j $(j = 1, 2, 3)$ is the flow velocity in the x_j direction, D_C is the diffusion coefficient, $g_1(t)$ and $g_2(t)$ are the known functions on the boundaries Γ_1 and Γ_2, respectively, and n_j is the normal vector at each boundary. The second term on the RHS of Eq. (1) is the source term of pollutant leakage: the range of leakage position is $\Delta \boldsymbol{x}_k$ about $\boldsymbol{x} = \boldsymbol{x}_k$ and the range of leakage time is Δt_k after $t = t_k$, the volumetric leakage flux is f, and Π is a rectangular function defined as

$$\Pi(y - y_0) = \begin{cases} 1 & \text{when } \; y_0 \le y \le y_0 + \Delta y_0 \\ 0 & \text{otherwise} \end{cases}. \tag{5}$$

By introducing backward time τ $(= t_\mathrm{m} - t)$, we can derive the adjoint equation corresponding to the original advection-diffusion equation (1):

$$\frac{\partial \psi^*{}_n}{\partial \tau} - u_j \frac{\partial \psi^*{}_n}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D_C \frac{\partial \psi^*{}_n}{\partial x_j}\right) + \Pi(\boldsymbol{x} - \boldsymbol{x}_n)\Pi(\tau - \tau_n), \tag{6}$$

$$\psi^*{}_n(\boldsymbol{x}, \tau = 0) = 0, \tag{7}$$

$$\psi^*{}_n(\boldsymbol{x}, \tau) = 0 \quad \text{on } \Gamma_1, \qquad (8$$

$$\left(u_j \psi^*{}_n + D_C \frac{\partial \psi^*{}_n}{\partial x_j}\right) n_j = 0 \quad \text{on } \Gamma_2, \tag{9}$$

where $\psi^*{}_n$ is now called the adjoint probability and is released at an observation position $\boldsymbol{x}_n$ during a time range of Δt_n from $\tau = \tau_n$ in the backward time direction. When comparing Eq. (6) with Eq. (1), we can find that the velocity u_j has opposite signs: however, the diffusion coefficient D_C is positive in both equations. The latter means that Eq. (6) is as stable as Eq. (1) when analysed in numerical simulations.

Any position in the domain where ψ^* reaches can have an estimated flux f_k as follows. When we have multiple observation positions $\boldsymbol{x}_n$ $(n = 1, 2, \cdots, N)$, any position $\psi^*{}_n$ $(n = 1, 2, \cdots, N)$ reaches in the domain has N values of f_k. At the correct leakage position $\boldsymbol{x}_k$, we expect f_k are the same:

$$f_k = \frac{G_1}{\Psi_{k,1}} = \cdots = \frac{G_n}{\Psi_{k,n}} = \cdots = \frac{G_N}{\Psi_{k,N}}, \tag{10}$$

where

$$G_n = \int_{t_n + \Delta t_n}^{t_n} C(\boldsymbol{x}_n, t)dt, \tag{11}$$

$$\Psi_{k,n} = \int_{\tau_k + \Delta\tau_k}^{\tau_k} \psi^*{}_n(\boldsymbol{x}_k, \tau)d\tau, \tag{12}$$

where $\psi^*{}_n(\boldsymbol{x}_k, \tau_k)$ is ψ^* release at $\boldsymbol{x}_n$ and observed at $\boldsymbol{x}_k$ at τ_k, t_n and Δt_n are the observation start time and time period, respectively, for each observation point n and τ_k and $\Delta\tau_k$ are the leakage start time and time period, respectively, for each leakage point k. In this study, the debris leakage is assumed to be instantaneous and, therefore, $\Delta\tau_k = \Delta t$. On the other hand, the debris observation is continuous for Δt_n, which is the time interval of beach clean-up.

However, in a numerical simulation, Eq. (10) is always accompanied with some errors. Therefore, the estimated leakage flux $\overline{f_k}$ is expressed as

$$\sum_k \Psi_{k,n} \overline{f_k} = G_n, \tag{13}$$

which is n simultaneous equations with k unknowns. To solve Eq. (13), we adopted quadratic programming with the restraint condition: $\overline{f_k} > 0$.

2.2 Flow Field

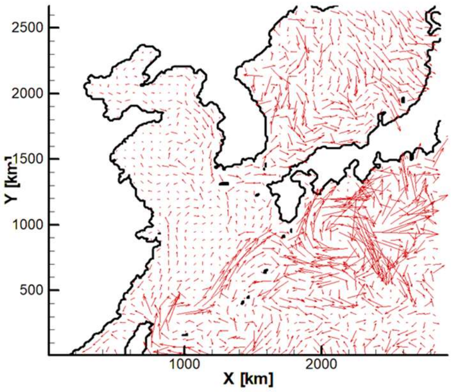


Figure 1: Velocity field interpolated from HYCOM [7]

The flow field considered in this study is the sea surface of of the East China Sea including Tsushima Strait, as shown in Fig. 1. Therefore, the calculation is 2D. We obtained the bathymetry data and 3-hourly surface velocity data from the server of the Hybrid Coordinate Ocean Model (HYCOM) developed by Center for Ocean-Atmospheric Prediction Studies (COAPS) [7]. HYCOM considers the effects of tide and wind on the current velocity: that is, the body force due to tidal potentials is added and the wind effect is taken into account as a shear stress at the sea surface boundary. To include the effect of wind on the movement of plastic bags, we used the 6-hourly blended sea wind data at standard reference height of 10 m above ocean surface (U10) of the area, taken from the server of National Centers for Environmental Information (NCEI), National Oceanic and Atmospheric Administration (NOAA) [8]. Following Schwabl et al. [9], we incorporated the wind velocity as

$$u_j = u_{Cj} + \mathrm{c}_W u_{Wj}, \tag{14}$$

where u_{Cj} is the ocean current velocity, u_{Wj} is the U10, and c_W is the wind factor, which was set to be 0.004 in this study, after validating the c_W value by comparing with the field tracking measurement of a buoy conducted by Chang et a l. [10].

Isobe et al. [1] estimated the suitable value of D_C for marine debris including marine plastics in the East China Sea to be within the 10 to 100 $\mathrm{m^2s^{-1}}$ range. This is a range instead of a specific number because the diffusivity for marine plastics must be different depending on the species, shapes, sizes, *etc*. In this study, we set a value of D_C of 12.63 $\mathrm{m^2s^{-1}}$ for PET bottles.

2.4 Leak Position Candidates and Beach Clean-up Data

The adjoint method requires observational data y_i, which are in this study the collection of beach clean-up data in Tsushima Island monitored by the Tsushima CAPAA [11]. The debris collected during beach clean-ups contains various types and it is thought that the diffusion coefficient of each type of debris varies. Therefore, in this study, we focused on the PET bottles, which is almost 50% of those collected on the beaches [12], as this has the advantages of being able to assume that the diffusion coefficient and wind influence are almost the same and that data for each country can be identified by labelling.

Debris was collected at six beaches in Tsushima: Nairahama, Kamitsuke, Shuri-tahama, Aomi, Tagama, and Goneo. A collection frame (50m × the distance between shoreline and vegetation) was set up on each beach, and stranded debris was collected regularly within the frame. After sorting the debris by type, the number, volume, weight, etc. were measured to determine the type and amount of debris. Collection is carried out four times a year.

In the adjoint method calculation, the collected debris is considered to have washed ashore between the end of the previous clean-up and the end of the clean-up on that day. In addition, the area was calculated by examining the shoreline distance from aerial photographs of each beach and converting the observation data. The clean-up was conducted from 2014 to 2021, except for 2015 and 2016, a total of six years of data was used. Therefore, the number of observational data y_i is 24, calculated over 6 years × 4 times per year.

Because the quadratic programming method is used to calculate the data in this study, the number of unknowns x_j must be equal to or less than the number of data y_i. In reality, there are many rivers that emit debris, but this time, we narrowed it down to a few major rivers. Lebreton et al. [13] used data on population and illegal debris dumping to calculate the number of plastic debris that flowed into the ocean in one year for the world's rivers. Of the top 20, three rivers, the Yangtze River, the Yellow River, and the Hai River, whose estuaries are included in the calculation area, were selected for the calculation. The Tamsui River was excluded because almost no debris reaches to Japanese beaches from Taiwan. In addition, a lot of debris from South Korea washes up on Tsushima's beaches [14], so we also included the four major rivers in South Korea: the Han River, the Yeongsan River, the Geum River, and the Nakdong River.

Wagner et al. [15] investigated data on the amount of debris flowing through the Elbe River and the river flow rate, and found that the increase in the amount of debris in the river is proportional to approximately the 2.6th power of the flow rate in the urban areas located downstream. Therefore, in this study, it was assumed that debris flowing from the river into the sea is concentrated when the river flow rate increases significantly due to typhoons or heavy rain.

In other words, the unknown quantity x_j to be calculated must consider both spatial information of the river positions and temporal information of periods of their high flow rate. The flow rate data was downloaded from the ECMWF data server, which is the flow rate at the mouth of the river. Figure 2 shows the time change in flow rate at the mouth of the Han River in 2021. It is recognised that several large peaks appeared. Among these flow rate peaks, the time when the flow rate showed a value of 10% or more of the maximum value during the calculation period was adopted as one of x_j. We selected the unknowns for the other rivers in the same way.

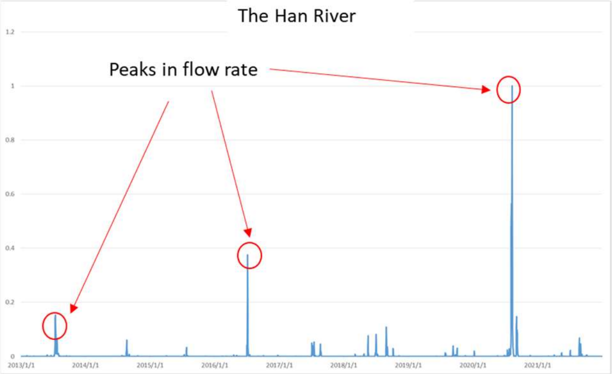


Figure 2: Flow rate at the mouth of the Han River in 2021

In quadratic programming, the accuracy of calculations decreases when there are many unknowns x_j, so it is necessary to find ways to reduce the number of unknowns. Therefore, when formulating simultaneous equations, the maximum number of temporal unknowns for each river was set to four. If debris discharged from a river due to a heavy rain does not reach the target beach, removing this leakage source from the simultaneous equations does not have a significant impact on the calculations.

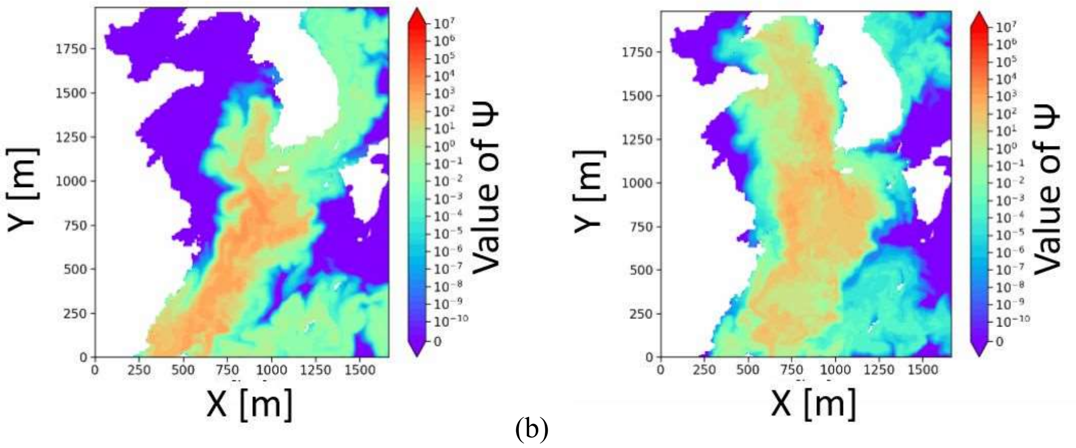
To further reduce the number of unknowns, since the clean-up data of PET bottle collected in Tsushima also includes the number of pieces by country, we used the number of PET bottles released from each country as data and calculate the simultaneous equations for each country. This allows us to set only the rivers of one country as unknowns in each calculation.

3 Results and Discussion

Table 1 Estimated numbers of debris released from major rivers in Korea and China

Nation	River	Date	Number of released debris
Korea	The Geum River	2014/8/18	2880
		2014/9/25	91100
		2020/9/5	76800
		2021/8/25	0
		2021/9/1	0
	The Nakdong River	2014/8/3	249000
		2014/9/25	91100
		2017/9/12	197000
		2019/9/23	17600
		2019/10/4	32100
		2020/9/4	248000
	The Han River	2017/8/21	60800
		2018/8/30	21800
		2020/9/6	0
		2021/9/2	68500
	The Yeongsan River	2017/10/2	1380
		2018/9/13	12000
		2019/9/22	1120
		2019/10/2	7130
		2020/9/4	4120
China	The Yangtze River	2016/4/27	108000
		2019/3/17	0
		2020/7/10	33500
	The Yellow River	2015/4/8	0.0743
		2016/7/22	147000
		2017/4/14	0
		2017/6/9	3280000
		2017/4/14	455000
		2017/6/9	1730000
		2018/4/17	38200
		2019/8/13	205000000
	The Hai River	2015/10/1	106000
		2015/11/8	18600000
		2016/10/8	25900000
		2017/10/10	137000000
		2019/11/11	40800
		2020/2/15	859000

Korean rivers are close to Japanese beaches, so debris discharged during heavy rains always flows into Japan, but Chinese rivers are far from Japan, so depending on the time of discharge, the debris may flow south and not reach Japan. Therefore, we performed an adjoint calculation to discharge ψ^* from all the beaches where the debris was collected, and set only the periods when ψ^* was large at the mouths of the candidate rivers, as unknowns in the simultaneous equations.



(a) (b)

Figure 3: Distribution of ψ^* emitted from six beaches of Tsushima Island 1 year (a) and 2 years (b) after the start of time-backward calculation

The solutions of the simultaneous equations using quadratic programming are shown in Table 1. Some values close to 0 were estimated and these were probably due to low river flow rates, i.e., small rainfalls.

Using these data, debris accumulating area around Tsushima Island can be predicted. While data for South Korea in 2022 was used, data for the Yangtze River in 2021 and those of the Yellow River and the Hai River in 2020 and 2021 were used, because it takes time for debris discharged from Chinese rivers to reach Japan. Using them, a forward time advection-diffusion simulation was performed for the calculation period from 2020 to 2022. As a result, it was found that there are areas around Tsushima Island where large amounts of debris accumulated on 1 October, 2022.

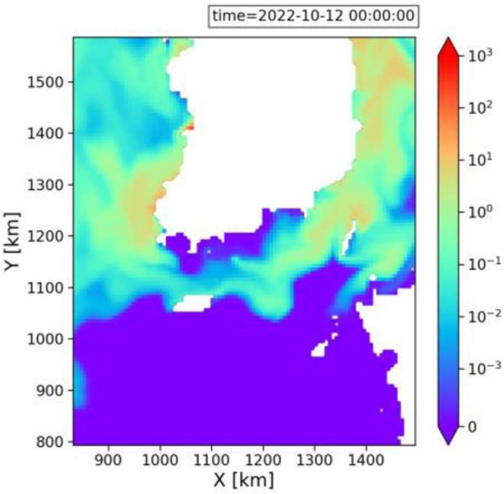


Figure 4: Predicted debris accumulating area around Tsushima Island on 1 Oct. 2020.

4 Conclusion

In this study, we applied the adjoint method and quadratic programming to calculate the amount of PETR bottles discharged from large rivers facing the East China Sea, using data of the debris washed up on the beaches of Tsushima Island.

It was predicted that if the predicted amount of debris was released from each river at the time of heavy rainfall, debris accumulating areas formed in the sea around Tsushima Island. Ocean currents and wind flow change significantly with the seasons, so the direction in which debris flows also varies greatly with the seasons. As a result, debris may flow from the East China Sea to Japan in concentrated amounts at certain times. In addition, because debris released from the rivers in Korea and China gathers in one place all at once, if it can be efficiently collected at the accumulating sea areas, the cost of removing debris offshore may be less than the total cost of beach clean-ups undertaken by many municipalities along the coast of the Sea of Japan.

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