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Identifying marine debris source position using adjoint marginal sensitivity method and stranded beach litter data in Singapore

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ABSTRACT

Movement of marine debris is transboundary and complex, travelling vast distances and accumulating on shorelines. These marine debris wash ashore as stranded beach litter. The objective of this work is to identify release sources of marine debris accumulated along the Singapore coastlines collected by applying a time-backward adjoint marginal sensitivity method and citizen science data of stranded beach litter by a voluntary beach clean-up group. A popular tourist hotspot on the opposite shore was estimated as a possible release source contributing to the marine debris accumulation. This analytical result was validated by population density, industry types, rainfall, and inference from product packaging labels. The use of the citizen science data also illustrated potential as a data source for baseline monitoring and long-term cross-border research that influence policymaking. Future research can be conducted in an expanded domain, considering monsoon effects and instantaneous release events.

1. Introduction

Volunteers participating in many non-profit organisations have decided to combat marine debris by picking up stranded beach litter in coastal clean-up sessions. Some of these highly committed clean-up groups also perform data recording to track their efforts and archive activity logs when they remove marine debris washed ashore. However, many individuals expressed a sense of futility as they return after a few weeks to a beach renewed with trash. One volunteer reflected in an online community that their efforts are "endless because the rubbish never decreases". Hence, an opportunity arose to engage these clean-up groups to not only fix the symptoms but address the root of the problem. Since collecting accumulation data of stranded beach litter over many months at different positions is time-consuming and manpower-intensive, it may be rewarding if existing records kept by beach clean-up groups is re-highlighted by serving as an alternative contribution through the adjoint method.

Within Southeast Asia, strong commitments have recently been made to combat ocean-bound litter, such as the Indonesian Action Plan (Ministry for Marine Affairs, Republic of Indonesia, 2017), Thailand's Roadmap on Plastic Waste Management 2018–2030 (Ministry of Natural Resources and Environment (MONRE), 2019), Malaysia's Roadmap Towards Zero Single-Use Plastics 2018–2030 (Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC), 2018) and the Association of Southeast Asian Nations Regional Action Plan for Combating Marine Debris (ASEAN Secretariat, 2021). While these initiatives are expected to provide long-term and essential solutions to the marine debris problem, it remains unclear whether they can provide urgent solutions.

A numerical approach such as the adjoint method can be used to estimate the pollution source via time-backward diffusion of adjoint probability. Wilson and Liu (1994) illustrated this concept by showing heuristically that the time-backward position and flux probabilities can be obtained from their time-forward counterparts. Neupauer and Wilson (1999) formally derived a general form of the adjoint method to represent the relationship described by Wilson and Liu (1994) and arrived at the same probabilities as the heuristic method for a one-dimensional system. This result was extended to a multidimensional groundwater system comprising of a rectangular two-dimensional confined aquifer with pumping well (Neupauer and Wilson, 2001). It was shown that the model can be extended to non-uniform and transient flows (Neupauer and Wilson, 2002) and it can also delineate the possible capture zone in 3D space (Neupauer and Wilson, 2004). Liu and Zhai (2007) evaluated inverse methods and found the method described by

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the series of researches of Neupauer and Wilson to be suitable for indoor air quality studies and applied the method in indoor air pollution scenarios. Furthermore, it was shown that the method does not require concentration information. Instead, an array of threshold-based sensors can be used for source identification.

For ocean contaminant transport, Mori et al. (2017) adopted the adjoint marginal sensitivity method of Dimov et al. (1996) to successfully predict the position and flux of CO_2 seepage generated from a time-forward tidal current model. Sakaizawa et al. (2019) employed the method to estimate a continuous CO_2 seepage source with volumetric flux in three-dimensional unsteady flow. Kanao and Sato (2022) showed that the method can be used for estimating multiple seepage sources and their fluxes. Due to the flexibility of the adjoint method, it can be applied to contaminants other than CO_2, such as marine plastics debris. Hui et al. (2021) tried to identify marine plastics hotspots within the Tsushima Strait, a narrow channel west of the Sea of Japan.

This paper aims to apply the adjoint marginal sensitivity method to marine debris floating in the seas around Singapore, which is a new case study of the method that has not previously been performed, and to identify the source locations of debris washed ashore on Singapore's beaches, using beach clean-up data. To validate the adjoint simulation result, circumstantial evidences are enumerated from social and metocean aspects. If this attempt using the adjoint method is successful and widely used, voluntary beach clean-up activities, as citizen science data, can contribute to long-term reduction of plastic debris in cities identified as sources.

2. Materials and methods

2.1. Adjoint marginal sensitivity method

Fig. 1 illustrates that marine debris is released from a yet unknown source ("release source"), while stranded beach litter accumulation is an observed variable observed on another shoreline ("sensor"). An adjoint marginal sensitivity (AMS) is then released from this position in the time-backward direction, with the minimization of an evaluation index, to estimate the source position and flux.

The model equation of the advection-diffusion of a pollutant is

$$\frac{\partial C}{\partial t}+\frac{\partial (V_j C)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(D_C\frac{\partial C}{\partial x_j}\right)+\Pi(\boldsymbol{x}-\boldsymbol{x}_0:\Delta\boldsymbol{x}_0)\Pi(t-0:\Delta t_0), \tag{1}$$

where C is the pollutant concentration [kg/m^2], D_c is the eddy diffusivity [m^2/s] of the pollutant, $\boldsymbol{x}_0$ is the source position vector [m], and $\Delta\boldsymbol{x}_0$ is the spatial range of the source position, Δt_0 is the time range [s] of the release of C, at the same time, the time range of the observation of ψ^*, which is defined in (2) below, and Π is the rectangular function.

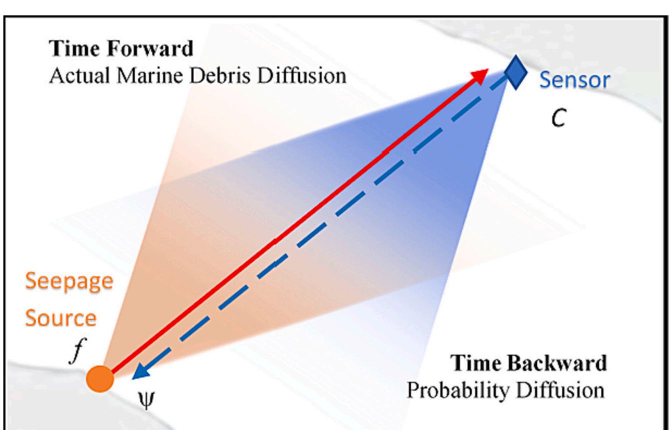

Fig. 1. Illustration of time-forward advection-diffusion of marine debris and time-backward advection-diffusion of adjoint marginal sensitivity (AMS), where f is the release flux, C is the observed concentration, and ψ is the released AMS.

The adjoint equation corresponding to the original advection-diffusion equation of a pollutant is

$$\frac{\partial \varphi^*}{\partial \tau}-\frac{\partial V_j\varphi^*}{\partial x_j}=\frac{\partial}{\partial x_j}\left[D_c\frac{\partial \varphi^*}{\partial x_j}\right]+\Pi(\boldsymbol{x}-\boldsymbol{x}_m:\Delta\boldsymbol{x}_m)\Pi(\tau-0:\Delta t_m), \tag{2}$$

where $\varphi^*$is the AMS [s], $\tau = t_m - t$ is the backward time [s], t is the forward time [s], t_m is the observation time [s], Δt_m is the time range of the observation and, at the same time, the time range of the release of φ^*, $\boldsymbol{x}_m$ is the observation position vector [m], and $\Delta\boldsymbol{x}_m$ is the spatial range of the observation position.

The debris velocity is considered the combination of ocean current velocity and wind velocity, following Tong et al. (2021), who validated this simple relationship by comparing the observation and their numerical simulation:

$$V_j = V_{jc} + C_w V_{jw}, \tag{3}$$

where V_{jc} is the ocean current velocity [m/s] taken from HYbrid Coordinate Ocean Model (HYCOM), V_{jw} is the wind velocity [m/s] from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5, and C_w is the wind coefficient.

Flux of the pollutant at any position k can be estimated as

$$f_k=\frac{\int_{t_m-\Delta t_m}^{t_m} C(\boldsymbol{x}_m,t)dt}{\int_{|t_m|-\Delta t_0}^{|t_m|}\psi^*(\boldsymbol{x}_0,\tau)d\tau}. \tag{4}$$

In fact, there is no need to solve (1) if we know all the numerators of (4) by the observation.

If the fluxes at a position estimated using multiple sensors are the same, this position is the source point. However, numerical simulations cannot escape errors, and Kanao and Sato (2022) introduced an evaluation index SDN, which is the non-dimensional standard deviation of the residuals for multiple source points:

$$\mathrm{SDN}(K)=\frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(C_n\Delta t_m-\sum_{k=1}^{K}\Psi_{n,k}\bar{f}_k\right)^2}}{\frac{1}{N}\sum_{n=1}^{N}C_n\Delta t_m}, \tag{5}$$

where K is the number of source points, N is the number of observation points, C_n is the observed pollutant concentration, Δt_m is release duration [s], $\bar{f}_k$ is the average of release fluxes f_k [kg/m^2/s], and $\Psi_{n,k}$ is the adjoint probability [s] at the source position and time, defined as:

$$\Psi_{n,k}=\int_{|t_{m,n}|-\Delta t_{0,k}}^{|t_{m,n}|}\psi_n^*(\boldsymbol{x}_{0,k},\tau)\,\mathrm{d}\tau. \tag{6}$$

It is assumed that release flux is constant in the continuous release mode and that multiple sourse positions begin the releases simultaneously. The spatially smallest value of the SDN signifies the least difference between observed and estimated pollutant concentration and the position of the smallest SDN indicates the source position.

2.2. Study site profile: Singapore

As shown in Fig. 2, the study site defined as the waters surrounding Singapore (longitude: 103° to 105°, latitude: 0° to 1.75°) serves as a suitable choice for a preliminary case study of the adjoint method. With a small land area of 725.7 km^2 and dense population of 5.69 million, many residential, recreational, and commercial activities occur near coasts (Department of Statistics, 2020). For example, Jurong Island is a petrochemical hub situated on the southwest edge of Singapore, and Lazarus Island and Sentosa Island are tourist hotspots in the south, while East Coast Park is a recreational shoreline extending across the entire southeast of the country. Hence, marine debris accumulation can have

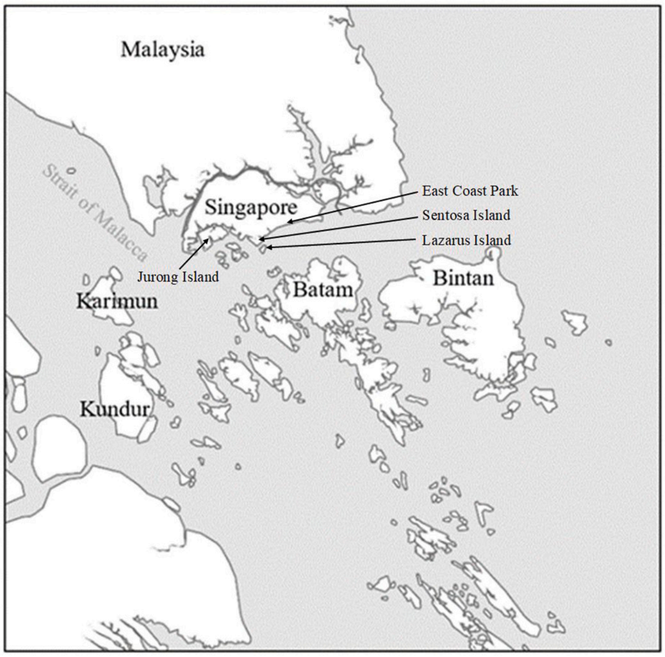

Fig. 2. Locations of Singapore, part of Malaysia, Indonesian islands, and the Strait of Malacca: 103.00°E to 105.00°E, 0.00° to 1.75°N.

an impact on multiple aspects of the activities in Singapore.

Additionally, the United Nations Environment Programme (2020) reported a lack of major research focused on marine plastics in Singapore, highlighting the lack of survey and monitoring, as well as hotspots and source differentiation studies. Marine plastics source identification and standardisation of their protocol were cited as knowledge gaps. Thus, these various economic and social aspects, environmental implication, along with the presence of many coastal clean-up groups in the region, were reasons to select this region as the study site.

Fig. 3 shows the grid system of the numerical simulation and the positions of the field observation data in the northern half of the computational domain. The adjoint simulation is two-dimensional (2D) only on the sea surface. The narrow waters between the islands were converted to land areas because of the lack of the grid resolution and the expected low flow rates. Since the entire domain was discretised into the structured grids with a size of 2 km by 2 km, beach clean-up activities at distinct but nearby positions were collapsed into the same position during simulation and generalised as the same cell. However, each observation is retained as data in different time ranges and the total number of the observation data does not decrease. Although it is better to use finer grids for the computational accuracy, the grid resolution of the HYCOM, from which velocity data were interpolated to the 2 km grids, is 1/12°, about 9 km and, therefore, smaller ones are not always better. Unstructured grids can help to better represent topography, but resolution is important anyway.

2.3. Data processing

The methodology comprises of data collection, data pre-processing, adjoint method simulation and post-processing. Since data sources varied, transformation into a standard X-Y, i.e. East-West and South-North, structured grid system with equal grid spacing and time interval was performed. The files were converted to appropriate input formats, followed by the simulation, and post-processing to generate graphs and maps for subsequent analysis. The processes are summarised in Fig. 4.

Bathymetric data was obtained from HYCOM and Navy Coupled Ocean Data (NCODA) Global 1/12° Analysis experiment GLBa0.08. Working with marine debris clusters floating on the sea surface, the eastward and northward 2D current velocity components, *u* and *v* respectively, were extracted from Global Ocean Forecasting System (GOFS) 3.1 41-layer HYCOM + NCODA Global 1/12° Analysis. (Naval

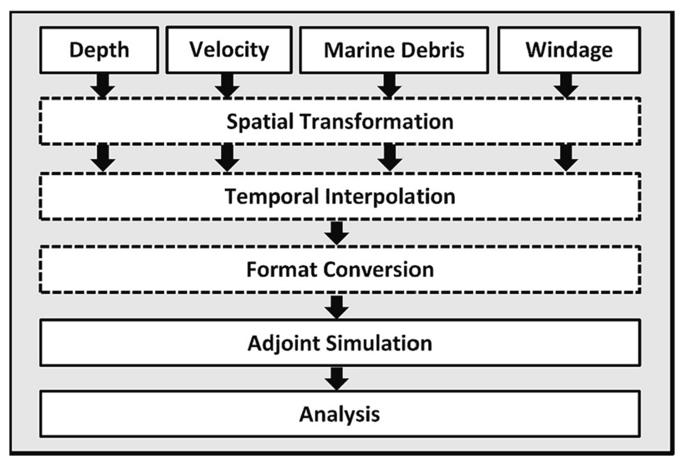

Fig. 4. Pre-processing steps required to create standard input files for the adjoint method, followed by analysis.

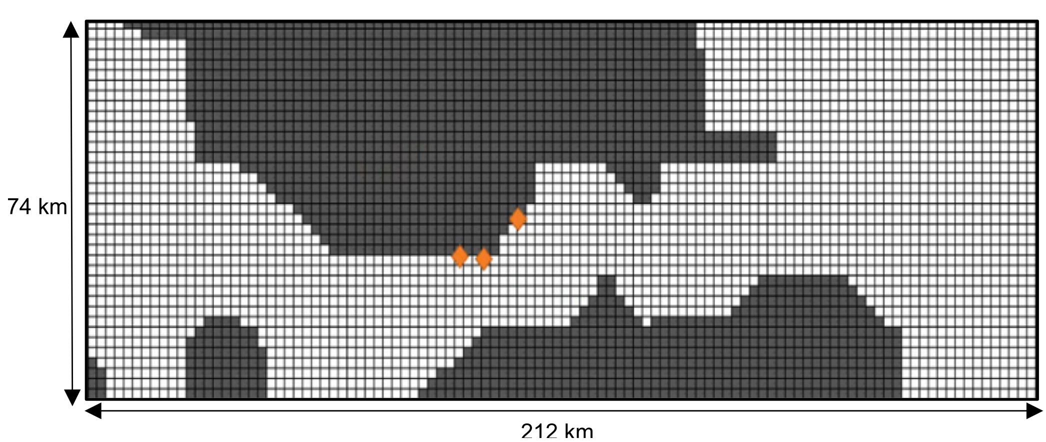

Fig. 3. Northern half of the computational grid system, where grey and white cells indicate land and sea, respectively. Observation positions within a single computational cell are spatially merged and indicated by orange diamonds: approximately, (130.7679°E, 1.25°N), (130.8214°E, 1.25°N), and (130.8929°E, 1.3214°N), which, however, contain 14 data points with different time ranges.

Research Laboratory, 2021; Metzger et al., 2017; Cummings and Smedstad, 2013; Cummings, 2005) and combined using the Climate Data Operators (CDO) code package along the time axis into a single NetCDF file.

Coordinate transformation was performed to convert the HYCOM native Mercator-curvilinear horizontal grid to a structured X-Y grid system preserving velocity data corresponding to each point. The data sources are interpolated to proceed at 0.1 hourly time step between 01 Jun 2020 and 01 Dec 2020.

Near-surface sea wind velocity was incorporated to account for the impacts of wind velocities on the sea surface debris movement. Dataset was obtained from ECMWF ERA5 reanalysis product at standard reference height of 10 m above ocean surface (Copernicus Climate Change Service (C3S), 2017; Hersbach et al., 2020). The ERA5 reanalysis has the highest temporal and spatial resolution: 6-hourly daily data and 0.25° spatial resolution (Gualtieri, 2021), and the key distinction of covering the desired study site. Particularly, the "10m u-v components of wind" was selected instead of the equivalent neutral winds. Equivalent neutral winds are calculated assuming a neutral atmospheric stratification, hence when wind stability is low, the calculated wind speeds can be exceedingly large. Stability conditions over open sea is commonly non-neutral (Baas et al., 2015) and wind speeds around Singapore are usually large so equivalent wind estimated will be higher than normal winds (Liu and Tang, 1996), making the former variable more applicable.

Li et al. (2021) suggested that the Indian Ocean, due to its geographical location and monsoon climate, has a significant impact on microplastics in the Pacific Ocean through the Straits of Malacca. Jong et al. (2022) systematically quantified the effect of monsoons on microplastic distributions in beaches and mangroves of Singapore and concluded that microplastic abundance strongly correlated with windage. Therefore, although their target is microplastics, it is presumed that the effects of monsoon winds are even more important for our target, floating debris. Fig. 5 shows an example of the velocity field, containing current and wind converted from HYCOM and ERA5, respectively, to the grid of this study at the start of the simulation, 01-June 2020. This day is almost the beginning of the Southwest Monsoon season, during which the wind velocity tends to be predominantly southwest to northeast. However, as explained later in 4.3, the velocity direction changes from time to time.

Weight-concentration raw data of marine debris were obtained from a voluntary beach clean-up group, Singapore Beach Warriors (SGBW), as shown in Table 1. The total weights were standardised by area coverage into kg/m^2 basis and used as $C(\boldsymbol{x}_m, t)$ in (4).

Each time range between two stranded beach litter collection events at the same position is defined as a separate data. Therefore, there are 16 observation points used in the adjoint method: namely $N = 16$ in (5). It is also assumed that marine debris is continuously accumulated on the beaches within these time ranges, meaning that the AMS was released in the time-backward simulation in the same continuous manner as that of the debris accumulation. Actually, marine debris is accumulated on the beach intermittently or continuously. To investigate the validity of the continuous accumulation assumption, the results of sensitivity analysis for the amplitude and period of the debris accumulation will be discussed later in Sections 3.3.3 and 3.3.4, respectively. Intermittent accumulation may be regarded as an extreme case of periodic accumulation.

Table 1
Marine debris beach clean-up data with courtesy of Singapore Beach Warriors (SGBW).

Location	Start of collection (YYYY-MM-DD HH:MM)	End of collection (YYYY-MM-DD HH:MM)	Total weight (kg)	Area coverage (m^2)
East Coast Park (Zone C)	2020-07-24 04:00	2020-07-25 03:00	32	2080
East Coast Park (Zone E)	2020-07-23 04:00	2020-07-25 11:00	30	3420
Tanah Merah	2020-07-20 10:00	2020-07-26 04:00	131	2900
Tanah Merah	2020-07-26 04:00	2020-08-01 03:30	194.5	2900
Tanah Merah	2020-08-01 03:30	2020-08-08 03:30	309.35	2900
Tanah Merah	2020-08-08 03:30	2020-08-09 03:30	270.42	2900
Tanah Merah	2020-08-09 03:30	2020-08-10 03:30	209.65	2900
Tanah Merah	2020-08-10 03:30	2020-08-15 03:30	200	2900
Tanah Merah	2020-08-15 03:30	2020-08-22 03:30	253.03	2900
Tanah Merah	2020-08-22 03:30	2020-08-29 11:00	212.1	2900
Tanah Merah	2020-08-29 11:00	2020-09-05 03:30	140.53	2900
Tanah Merah	2020-09-05 03:30	2020-09-06 03:30	127.3	2900
Tanah Merah	2020-09-06 03:30	2020-09-19 03:30	504.66	2900
Tanah Merah	2020-09-19 03:30	2020-09-19 03:00	125.95	2900
Tanah Merah	2020-09-19 03:00	2020-10-31 10:00	78.35	2900
Tanah Merah	2020-10-31 10:00	2020-11-29 10:00	332.42	2900

The start time of the adjoint simulation, $\tau = 0$ in (2) and (4), was set to be later than the latest collection time in Table 1, 2020-11-29 10:00. Each observation point has different t_m and Δt_m.

Settings and conditions are prepared prior to conducting the simulation in accordance with the various conditions that must be satisfied. Table 2 summarises the settings, followed by brief descriptions of the fulfilled conditions.

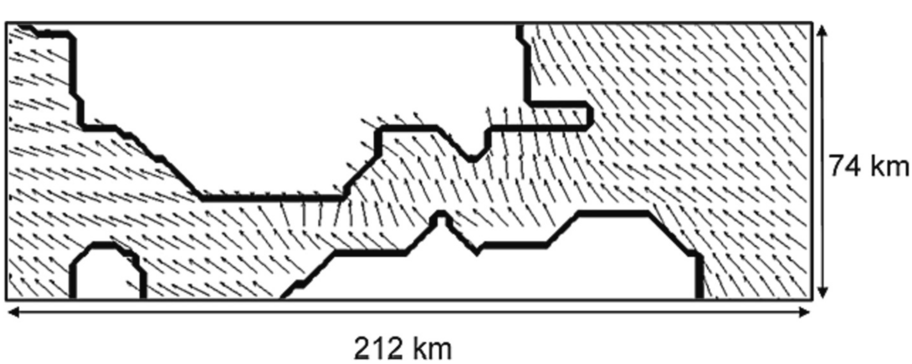

Fig. 5. Example of velocity vector map including wind and current, which were interpolated from ECMWF-ERA5 and HYCOM, respectively, to the grids of this study, based on (3) with $C_w = 0.04$. The vectors are shown every three cells in south-north direction.

Table 2
Conditions and parameters for horizontal 2D adjoint simulation.

Parameters	Values
Longitude/latitude	Lon: 103°–105°/lat: 0°–1.75°
Grid spacing	2 km × 2 km
Time span	01 Jun 2020 to 01 Dec 2020
Time increment	0.1 hour
Release candidates	All coasts + open boundaries
Eddy diffusivity $\boldsymbol{D_c}$	65.0 m^2/s
Wind coefficient $\boldsymbol{C_w}$	0.04

From the velocity data obtained from HYCOM, it was found that the maximum absolute velocity throughout the entire time-range and computational domain is 0.9249 m/s in the eastward direction. Hence, with predefined settings of time increment of 0.1 hourly (360 s) and grid spacing of 2.0 km, the Courant–Friedrichs–Lewy (CFL) Condition (Courant et al., 1967) is satisfied as the Courant number is 0.1665 (<1.0). The eddy diffusivity D_c and the wind coefficient C_w were set to be 63.5 m^2/s following Isobe et al. (2009) and 0.04 following Tong et al. (2021), respectively.

The largest observation timespan is 2020-09-06 03:30:00 to 2020-09-19 03:00:00, as shown in Table 1. This is equivalent to 7,450,200 s minus 6,328,800 s in the backward time and, therefore, the time span shown in Table 2 is acceptably long.

The source candidates in Table 2 mean that any point, either multiple or single, can be selected as the source positions from all the points on the coastlines and the open boundaries.

2.4. Assumptions and limitations

Because the adjoint method can cope with either instantaneous or continuous release, the suitability depends on whether a temporally single pollutant-release event is expected, such as typhoon or flood. Lo et al. (2020) evaluated the effects of Typhoon Mangkhut in 2018 on marine debris pollution including macro debris and microplastics in Hong Kong and found that, for macro debris, 11.4-fold increase was obtained before and after the cyclone. Nevertheless, in this study, continuous release of marine debris was assumed. It is likely that marine debris does not accumulate at a constant rate across all the time. Therefore, a sensitivity analysis using fluctuating deposition rates was conducted in Section 3.3 to examine the effect of this assumption on the simulation results.

Next, the pollutant of interest is marine debris clusters instead of a specific target such as plastics, which poses a challenge in defining the pollutant characteristics. The diffusion coefficient D_C in (2) cannot be accurately defined because different clusters of debris must have different values of diffusivity. The same also holds for the wind coefficient C_w in (3). Thus, a sensitivity analyses were conducted in Section 3.3 for these values.

Finally, it was assumed that there is no backwash of stranded beach litter into the sea. It is likely that waves depositing litter onto the shore also remove some litter over time, but accounting for such a factor is infeasible. Thus, the recorded concentration of stranded beach litter is used to represent the total marine debris washed ashore.

3. Results and discussion

3.1. Detection of source positions using all observation data

For the adjoint method, it is possible to assume multiple source points. Hence, we performed simulations assuming that marine debris was released from three concurrent positions ($K = 3$), two concurrent positions ($K = 2$) and one position ($K = 1$). The preliminary results as shown in Table 3 indicated that the case of three source positions is an invalid scenario because the flux of one of the sources is negative, as shown in Table 3. One of the estimated source positions in the case with two sources is the same as that in the case with one source, suggesting that both the cases are possible and, in such a case, the case with the larger number of sources should be adopted so as not to lose any possible sources.

Table 3
Release fluxes and positions estimated by the adjoint method in the cases where the number of source positions is changed from 3 to 1.

Case where the number of source positions is changed	Estimated source positions in cell number	Estimated fluxes [kg/m^2/s]	Backward time τ when the temporal change of SDN reaches a plateau [day]
$K = 3$	78, 29	2.2451×10^{-5}	146.67
	59, 69	1.5408×10^{-10}	
	51, 76	-2.9748×10^{-9}	
$K = 2$	54, 64	1.1505×10^{-10}	142.50
	58, 69	1.1335×10^{-10}	
$K = 1$	58, 69	1.2437×10^{-10}	140.83

The two unique release source positions are denoted on the structured X-Y grid system in Fig. 6, where the grid indexes I and J mark the positions (54, 64) and (58, 69).

3.2. Elimination of observation outliers

Since there are numerous other places contributing small amount of wastes into the sea, the beach litter recorded may include debris released from sources other than the two points shown in Fig. 6. This means that observations contributed by other unidentified sources may mislead the results. To avoid this inconvenience, we tried to eliminate observation points that did not detect debris released from the two sources. For this purpose, we used the adjoint simulation result of SDN($K = 1$) shown in 3.1 and examined the detectability of observation points for each of the two sources, regardless of the position giving the minimum SDN.

Fig. 7 shows the relationship between the concentration observed by each sensor C_n and the estimated concentration $\frac{1}{\Delta t_m}\sum_{k=1}^{K}\Psi_{n,k}\bar{f}_k$ defined in (5), assuming each position of the two sources: namely, (54, 64) in (a) and (58, 69) in (b). If there is a large disparity between them, it suggests that such an observation C_n contains marine debris coming from sources other than the assumed single point. In this study, outliers that exceed one standard deviation were removed for each of the two selected source positions. Since they are simulations for $K = 1$, observation points that detected debris released from both the two sources may be eliminated. However, those that detected debris from one of the two sources definitely remain, serving our purpose. For (54, 64) in (a) and (58, 69) in (b), 11 and 6 observation points remained, respectively.

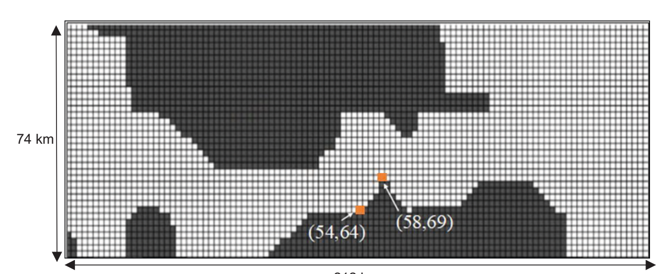

Fig. 6. Estimated positions of the marine debris release sources, which are indicated by orange diamonds: Position (54, 64) and Position (58, 69), approximately, (103.9642°E, 1.1429°N) and (104.0357°E, 1.2321°N), respectively.

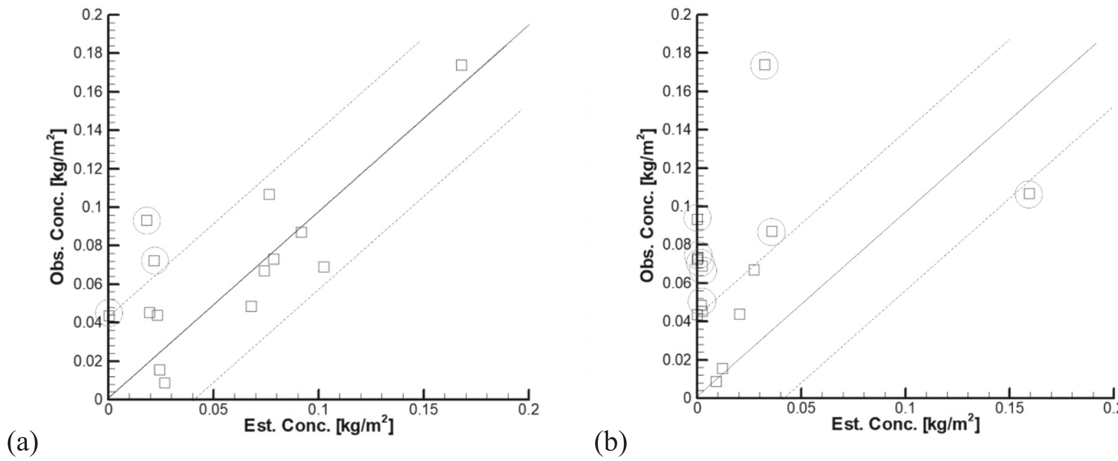

Fig. 7. Relationships between observed and estimated concentrations for Position (54, 64) in (a) and for Position (58, 69) in (b). The dashed lines and the squares indicate the standard deviations and outliers, respectively.

After removing the outlier observation points, an adjoint simulation of SDN($K = 1$) was performed again, using the remaining observation points for each of the two sources.

Fig. 8 indicates the temporal changes of the spatial minimum of the evaluation index SDN, using the remaining 11 and 6 observation points in (a) and (b), respectively. Although 11 and 6 points were originally selected for the position (54, 64) in (a) and (58, 69) in (b), we searched for new source positions in these SDN($K = 1$) simulations. As the simulation progressed, an estimated source position changed over time. However, after about 145th day in (a) and 150th day in (b), plateaus of the SDN values appeared, and SDN became the minimum at a single position during each plateau. Therefore, these positions are considered the renewed sources. The I-J coordinates of the renewed source positions are shown in Table 4. Although slight changes are found for Position 2 between the results before and after the removal of outlier observation points, it can be concluded that the two origins of the marine debris are at the northern coast of Batam, which is an Indonesian island situated near the south of Singapore. Since scientific validation for this result is not very easy, we will discuss this from social and metocean points of view later in Section 4.

It can be seen that the SDN value in Fig. 8(a) is larger than the SDN value in (b) over the entire simulation time. This is probably because the number of observation points in (a) is larger than that in (b), resulting in large errors when calculating SDN defined by (5). It is also thought that, for the same reason, the plateaus appeared earlier in (a) than (b).

Table 4
Comparison of source positions before and After the removal of outlier observation points.

Estimated positions	Before the removal of outlier observation points	After the removal of outlier observation points
Position 1	58, 69	58, 69
Position 2	54, 64	56, 67

3.3. *Sensitivity analysis*

As discussed in Sections 2.3. and 2.4, certain assumptions that can impact the validity of the results must be addressed. It is paramount to understand the effects of these input parameters on target variables to eliminate the possibility that the simulation settings change the results significantly. Three input parameters for the simulations were investigated: namely, the standard eddy diffusion coefficient D_C, the wind coefficient C_w, and the AMS release ways. The results of the sensitivity analyses are summarised in Table 5 and Fig. 9, which show that the effects are largest for changes of the wind coefficient. Elaboration for each of the three analyses follows.

3.3.1. *Wind coefficient*

The effects when wind coefficient C_w in (3) was doubled and halved were studied. The analysis showed that changing wind coefficient

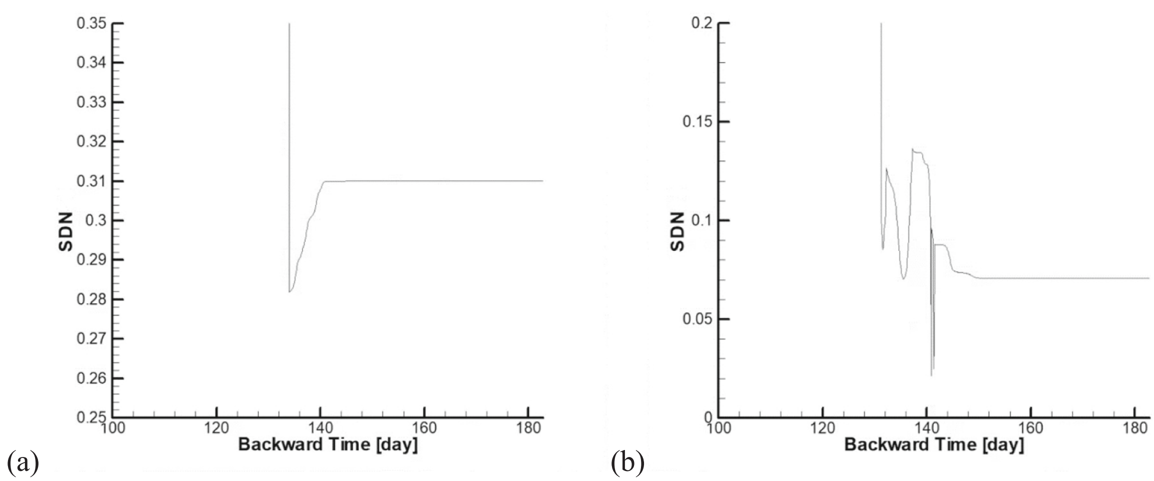

Fig. 8. Temporal change of the spatially minimum SDN using remaining 11 and 6 observation points in (a) and (b), respectively.

Table 5
Sensitivity analysis results in Case (1): wind coefficient, Case (2): diffusivity, Case (3): sinusoidal amplitude of AMS source term, and Case (4): sinusoidal period of AMS source term, tabulated by percentage deviation from original cases.

Target variable	Wind coefficient C_w			Diffusion coefficient D_C (m^2/s)			AMS source term						
	Lower (0.02)	Original (0.04)	Higher (0.08)	Lower (32.7)	Original (65.3)	Higher (130.6)	Original (Constant)	10 % amplitude	30 % amplitude	50 % amplitude	Pi/2 period	Pi/20 period	Pi/200 period
Min. SDN	−36.89 %	0 %	18.71 %	−4.94 %	0 %	2.45 %	0 %	0.08 %	0.02 %	0.03 %	0.03 %	0.08 %	0.02 %
Time	30.05 %	0 %	0.18 %	0.18 %	0 %	0.18 %	0 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
Flux	−38.03 %	0 %	76.54 %	4.60 %	0 %	0.37 %	0 %	−0.02 %	−0.01 %	−0.01 %	−0.01 %	−0.02 %	−0.01 %
Location	69,65	58,69	57,67	59,69	59,69	58,69	59,69	58,69	58,69	58,69	58,69	58,69	58,69

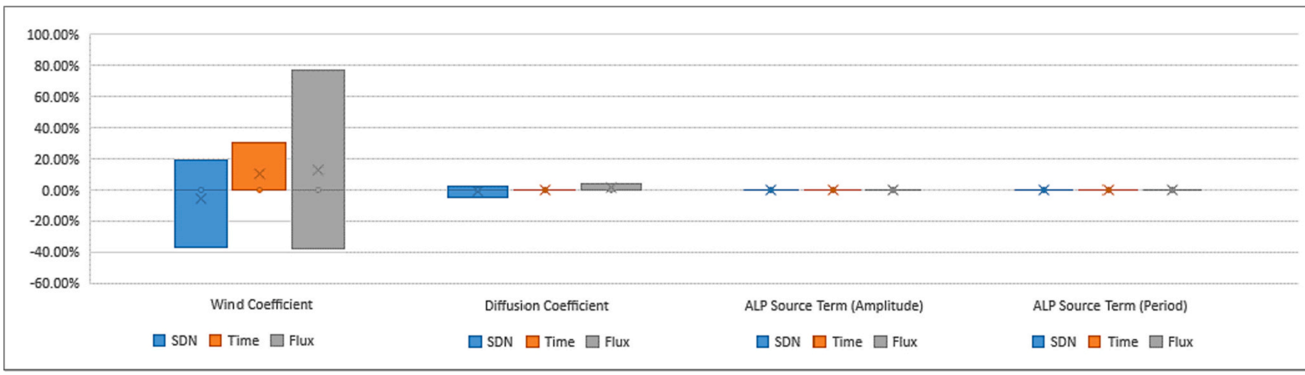

Fig. 9. Results of sensitivity analysis in debris release flux in Case (1): wind coefficient, Case (2): diffusivity, Case (3): sinusoidal amplitude of AMS source term, and Case (4): sinusoidal period of AMS source term, tabulated by percentage deviation from original cases.

significantly altered the estimated source position, as shown in Fig. 9. Tong et al. (2021) mentioned that suitable C_w values are between 0.03 and 0.05 and the value tested in this sensitivity analysis, 0.02 and 0.08, are out of their recommendation. The large discrepancy can be attributed to this: however, in any case, C_w is a very influential parameter and needs further investigation.

3.3.2. Diffusion coefficient

It is found that, although the range of the diffusivity D_C set in this sensitivity analysis is almost the maximum and minimum values proposed by Isobe et al. (2009), the changes in D_C did not have a significant impact on the estimated release source positions with only small changes in flux and time, as shown in Fig. 9. This may be because advection dominated for the debris transport rather than diffusion.

3.3.3. AMS source term amplitude

The temporal shape of the AMS source term *Sc* in (1) means how debris is temporally accumulated on the beach. The source term in (1) has the shape of a rectangular function, indicating a temporally constant release of the AMS. Now we consider the form of a sinusoid:

$$Sc = \gamma \Delta t + sin\left(\frac{\pi}{2} n_t\right), \tag{7}$$

where γ is the AMS flux, which was set to be 1.0, n_t is the time step, and Δt is the time increment [s].

Then, analyses were conducted to vary the release across time using the sinusoid function shown in Fig. 10. Ultimately, it is recognised that any variations in AMS source term did not influence the results, as the estimated source position remains unchanged, and the effects on marine debris flux and time was minimal, as shown in Fig. 9.

In this study, the AMS was released constantly in the time-backward simulation as a base case, suggesting that this assumption is acceptable.

3.3.4. AMS source term period

Finally, the effects of the period of the release flux of AMS were examined. A sensitivity analysis was conducted by increasing the period $\pi/2$ by one magnitude, followed by two magnitudes, as shown in Fig. 11.

After conducting the analysis, despite two orders of magnitude increase in the sinusoidal period, it was indicated that there was no effect on the simulation results, as the estimated source position remains unchanged, and the effects on marine debris flux and time is minimal, as shown in Fig. 9. This result is also suggestive in the sense that we do not

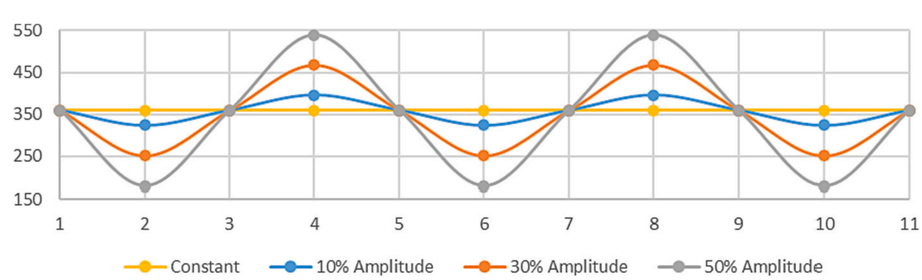

Fig. 10. Sensitivity analysis parameters for sinusoidal AMS source term at 10 %, 30 % and 50 % amplitude, compared to constant base case. The unit of the vertical axis is second and the original constant value of 360 s corresponds to one time step based on (7), while the horizontal axis indicates time steps.

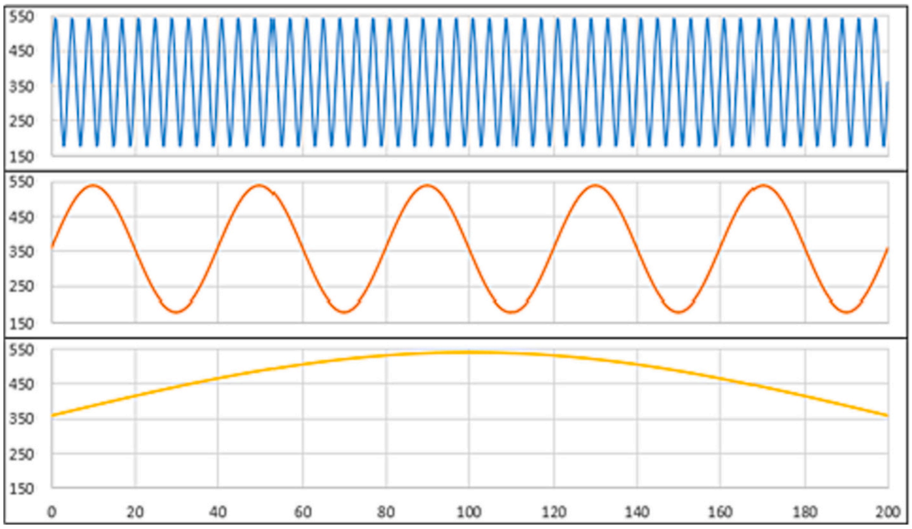

Fig. 11. Sensitivity analysis parameters for sinusoidal AMS source term at 50 % amplitude, with period π/2, π/20, and π/200 proceeding with time. The unit of the vertical axis is second and the horizontal axis indicates time steps.

need to pay attention to the time variation of the debris washed ashore.

4. Validation and discussion from social and metocean points of view

This paper sets out to accomplish the identification of marine debris release source using the adjoint method and evaluates the opportunities to engage voluntary beach clean-up groups as a data source for the method. The following sections will focus on validation of the calculated results by showing circumstantial evidences from the social and metocean points of view.

Batam, the identified marine debris release source, is an industrial boomtown situated approximately 20 km from Singapore, as shown in Fig. 1. It is the largest city in the Indonesian province of Riau Islands having the highest total population and urban density, as shown in Table 6. The size and proximity of the position suggests an increased likelihood of waste transport from this region to Singapore. However, Schuyler et al. (2021) found that population density was an inadequate primary indicator for marine debris generation due to a non-linear and highly variable relationship. Therefore, a nuanced approach with a range of factors was recommended and additional factors such as industry type and waste generation, waste management infrastructure, rainfall, monsoon seasonality and product packaging labels are discussed extensively in the following sections.

4.1. Industry type and waste generation

The economic growth of Batam is reliant on tourism, electronics manufacturing, as well as heavy industries such as steel and oil rig fabrication, equipment production and shipbuilding (Batam Center, 2002). Yuvita and Hadi (2019) found that the shipyard, electronics, and household wastes remain a problem in Batam City and suggests that the efforts to collect solid wastes have been insufficient. Lee (2018) added that the situation is exacerbated by an increasing population and economic growth. Importantly, it was noted that the city had weak regulatory enforcement and inadequate waste-handling facilities. In terms of tourism, 2018 statistics showed that Batam has the highest monthly arrival by an order of magnitude compared to the second largest city (BPS-Statistics Indonesia, 2019). It was confirmed that the high tourism rate correlates to an increased amount of solid waste generation (Martins and Cró, 2021).

Table 6
Populations and visitor arrivals of Batam, compared to other relevant areas in the computational domain (BPS-Statistics Indonesia, 2019).

Position	Population	Urban density	Monthly visitor arrivals
Batam	1,196,396	800/km^2	~172,000
Bintan	481,120	450/km^2	~14,625
Karimun	253,457	170/km^2	~8950
Lingga	98,633	44/km^2	(N.A.)

These waste-generating tourism and industrial sectors may not necessarily lead to greater release of marine debris if handled appropriately. Well-developed high population cities usually enjoy economies-of-scale in waste management infrastructure that allows them to better manage wastes using financial capital generated by these same sectors. However, a rapid assessment by the World Bank (Shuker and Cadman, 2018) showed that Batam did not have adequate waste management infrastructure that can allow municipal agents to prevent wastes release directly to the coast. As a result, 902.4 tons/day of waste are generated with 101.1 tons/day (11.20 %) unhandled. Nine hotspots were identified that can be considered "serious" debris release sources, based on frequency and volume (Shuker and Cadman, 2018).

Along the northern coast of Batam, which is the identified source position, there are two major rivers highlighted in Fig. 12. Both rivers are situated next to urban areas, where the build-up around the western river is much denser and urbanised, compared to the build-up around the eastern river.

Overall, it is speculated that the lack of waste management infrastructure discussed in various literature supports the idea that waste generated by economic sectors (e.g., tourism, electronics, shipbuilding) eventually enters the two highlighted rivers, and fails to be removed due to the inadequate downstream waste retrieval facilities, resulting in marine debris release into the sea.

4.2. Annual rainfall

The rainfall level around Batam is high all year round, increasing the likelihood of land-based wastes transport into the ocean. The consistently high rainfall supports the simulation assumption of a continuous release of marine debris, instead of an instantaneous event such as typhoon or floods.

Due to the COVID-19 pandemic, tourism and industrial sectors suffered reduced activity within the simulation period. Therefore, given Batam's aforementioned inadequate waste management infrastructure and existing unhandled wastes, the consistent rainfall could generate a

Fig. 12. Terrain map showing the prominent rivers in the northern coast of Batam, which is the identified release source. The orange rectangles indicate prominent rivers.

land-based release of previously accumulated wastes and daily usage in the form of surface run-off into rivers even during the pandemic.

4.3. Tidal and monsoon effects

The region has two general monsoon seasons, Northeast Monsoon from December to early March and Southwest Monsoon from June to September, with inter-monsoon periods in the transition months (Haire, 2021). This simulation used data in June to November 2020, which corresponds to the Southwest Monsoon going into the Inter-monsoon period. During this period, the sea and wind velocity direction tend towards the northeast from southwest, which also supports the calculated results.

However, it is important to highlight that the interactions between ocean current, wind, and monsoon seasonality are complex. These combined effects lead to variability in the flow direction from time to time and from one sea to another. In other words, the flow of marine debris may not always be in the expected general direction of the overall monsoon period. Therefore, there is incentive to conduct the same simulation process for Northeast monsoon period, as well as the inter-monsoon periods, both separately and within one extensive simulation. This will allow an understanding of the effects of monsoon seasonality and tidal interactions on the eventual fate of marine debris. The main implication is that the release source identified may not always be Batam if marine debris movement was in a different monsoon period.

4.4. Product label origin

Beach clean-up volunteers remarked that many pieces of product packaging are written in the same language, suggesting similar origins. Even though the clean-up group did not painstakingly record the data of every single product label, the majority of these brand origins can still reveal additional information about their production, usage, and disposal. For example, a search of “NoDrop” yielded an Indonesia-based brand origin, manufacturer, and sales channels. Similarly, even with position-based search settings turned off, 9 out of 9 of the first page Google search results for “Generasi Baru aerosol spray” led to Indonesian sales platforms only.

These indications point to the possibility that these products are primarily sold, and thus used and disposed, in their respective countries. In some cases, the origin required no guesswork, such as the bottle shown in the lower right of Fig. 13 printed specifically with the manufacturer's name and address in Batam. Although one can reasonably argue that the product might not be disposed in the same place as its production because of international exports. However, many national brands do not expect a lot of sales beyond their immediate region, especially when marketed in a native language. Therefore, the overwhelmingly large number of marine debris packaging in the Indonesian language suggests that the litter disposal originated from Indonesian sources, further corroborating the analysis results that Batam is a release source.

4.5. Availability and quality of marine debris data

Beyond successfully estimating the release source, this study also raised an adjacent, but equally important issue, regarding the challenges of obtaining suitable marine debris concentration data for the adjoint method. As this paper has shown, the adjoint method uses a dataset of pollutant concentration that are recurring either in position or time. The source of these studies can be academia, for-profit organisations, and non-profit organisations. In the ideal case, the simulation would be fed with the accumulating marine debris concentration of many specific positions, and each of these positions would be observed and frequently sampled at many points in time. However, the reality is that the process of acquiring this data is fraught with difficulties in the aspects of accessibility (privately held data which are not shared), pertinence (data is incompatible with the method), and quality (data is complete but inconsistent or incorrect).

In literature, many studies are hyper-localised and conducted for short periods of time. Presumably, this is because the studies are designed to answer specific regional questions, or the methods for studying marine debris and beach-stranded litter are prohibitively time-consuming and expensive. For instance, researchers may be required to charter expensive ship expeditions and deploy personnel on ships to visually count marine debris floating on the sea surface. They may also wish to study the accumulation of stranded beach litter on a remote island, which requires returning regularly to monitor and record the data. Innovative methods like applying artificial intelligence on cameras to recognise and count litter are being investigated but have not reached maturity (Kako et al., 2018). As a result, attempts to amalgamate data sources become almost impossible. Browne et al. (2015) extensively discussed this problem of variations and incompatibilities across individual beach debris studies and found that very few can be adequately compared due to differences in debris types, sampling methods and sampling areas.

Additionally, access to these data can be restricted by various concerns. For example, academia may not be ready to share such data until after publications complete, some government sectors have a policy of not sharing data with the public, and several for-profit organisations cited “privacy concerns” as a reason for denying the request, while many other organisations simply did not respond to the enquiry.

These challenges are important to address, with data being fundamental to the adjoint method simulation. As discussed in 4.3, one recommended future work requires the study of monsoon season variability which requires recurring data at the same positions across an entire year. Obtaining such a range from a single source, or by amalgamating incompatible sources, is a tall order. Therefore, solutions should be explored.

4.6. Citizen science in beach clean-up groups

In this study, a release source was estimated in line with evidence using data from a beach clean-up group with a debris monitoring programme. The use of beach clean-up group data resolves many of the

Fig. 13. Selective samples of marine debris representing often identified product label languages taken from SG Beach Warriors.

issues highlighted with marine debris data sources. First, beach clean-up activities are recurrent in nature, providing a span of data at the same position across time. Second, data collection from such groups are often purely for archival reasons. Since the groups do not use the data for other functions, it removes conflicting interests that may drive data withholding. Third, it adds an element of public education and empowerment as the pool of volunteers change, oftentimes consisting of citizens with little exposure to the technical aspect of the marine debris problem.

The idea is not new. In Singapore, the Reach-Inspire-Synergise-Empower, R.I.S.E. network consists of 44 organisations contributing clean-up logs to a central database (Singapore Public Hygiene Council, 2018). Many institutions also work with International Coastal Cleanup Singapore (ICCS) as part of a global network coordinated by the US-based The Ocean Conservancy, which crystallises an annual report on the state of the issue (Sivasothi, 2021). Individual groups also have their own data collection practices to varying extent. However, in the context of the adjoint method applicability, R.I.S.E network was not able to provide records of the time and duration of clean-up activities, ICCS did not have sufficiently frequent data points, and individual beach clean-up groups often use inconsistent practices within their own internal data collection from session to session, such as selectively weighing some debris, or recategorising the same waste under different categories in different clean-up sessions.

It is proposed to engage and empower beach clean-up groups as a cornerstone of the data collection processes. As these beach clean-up efforts are voluntary, such proposals should not be organisational or directive in nature. One future work area could be a review of the existing beach clean-up groups operating in Singapore, assessing the quality and consistency of data collection, highlighting key issues, and rationalising a set of best practices, such as collecting beach litter within a defined quadrat, standardising manpower distribution, weighing of dry mass or wet mass, and other such factors.

Another recommendation is to implement a practice of metadata inclusion. Drawing inspiration from bioinformatics, metadata – which is data about data – can also be recorded (European Bioinformatics Institute, 2021). As highlighted before, one of the reasons for data incompatibility is due to inter-studies differences in methods and materials. Thus, descriptions, such as the number of tools used, participants profiles, condition of environment, can be introduced to help researchers determine if conditions are similar enough for two or more datasets to be combined.

Finally, moving beyond addressing the data challenges, the next step would be an implementation of long-term adjoint simulations based on sufficient beach clean-up data. Several use cases are available for consideration. Data can be built up over several years to be used for a baseline monitoring study to drive policy decision, perform trend analysis, and evaluate the effectiveness of action plans. The same data can also be used for specific tracking after instantaneous release event, for example, to locate the release source following a significant increase in stranded beach litter accumulation, such as natural events, releases, or illegal dumping of wastes.

5. Conclusion

This paper marks the first application of the adjoint marginal sensitivity method to detect possible release sources of marine debris to regional waters around Singapore. The Northern Coast of Batam, Province of Riau Islands, Indonesia, was estimated to be the marine debris release source. This calculated result was validated substantially with the high population density, strong presence of tourism and heavy industries, inadequate waste management infrastructure, heavy yearly rainfall, and inference from product packaging labels.

This study presents several new opportunities. Beyond immediate release sources, the computational domain can be greatly expanded to further investigate transboundary flow across Malaysia, and central and eastern Indonesia. Additionally, the complexity of the monsoon seasons with tidal levels causes significant changes in flow direction and velocity. Hence, further studies can be carried out to profile the marine debris transport differences between Southwest monsoon and Northeast monsoon in the region. It must also be noted that the method is also applicable for marine debris compositions and other pollutants, enabling targeted future investigations such as plastic bottles and product packaging.

Furthermore, perhaps more importantly, it was shown that beach-stranded marine debris data collected from volunteer beach clean-up groups can complement research institutes for effective usage in case studies. This has substantial implications for the development of citizen science data policy, which will contribute significantly to a field with limited availability of large datasets and a numerical method which requires consistent data across many positions and time.

It was recommended to engage, review, and empower these beach clean-up volunteers to begin and/or improve data collection consistency and quality. Many volunteer beach clean-up groups in Singapore practice some form of data collection, but data quality and consistency are low, and the data is underutilised. Observations include selectively weighing of collected litter, not recording duration or distance covered, and categorising the same objects differently from session to session.

These recommendations may help to circumvent the aforementioned challenges associated with accessibility, pertinence, and quality, allowing opportunities to evaluate and drive policies, to raise public awareness and to allow further research within and beyond the region.

CRediT authorship contribution statement

Hong Siang Gan: Methodology, Formal analysis, Visualization, Investigation, Writing – original draft. **Shunsuke Kanao:** Software. **Toru Sato:** Conceptualization, Supervision, Writing – review & editing. **Klaus Hellgardt:** Project administration. **Yusuke Uchiyama:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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