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Numerical Simulation and Analysis of Marine Debris Distribution in Pulo Aceh Waters, Indonesia

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ABSTRACT

The movement of marine debris in the ocean relies on hydrodynamic conditions formed by the seabed topography and coastal morphology. Therefore, it is important to understand debris distribution patterns using numerical simulations. Pulo Aceh is situated in the north of Aceh Province, the westernmost province of Indonesia, featuring small islands and marine waters that are connected to the Indian Ocean, Malacca Strait, and the Andaman Sea. The geographical position of this island results in dynamic particle movement. The purpose of this study was to analyze the distribution of marine debris around Pulo Aceh waters through numerical simulation of particle tracking. The basic hydrodynamic model used before running the particle-tracking module was the FM flow model. This model relies on essential input data including bathymetry, tides, and wind information. Four particle release points were established in the Pulo Aceh waters: Krueng Aceh, near Nasi Island, Sabang, and north of Breueh Island. Field observations were also conducted at two locations on Nasi Island, Alue Riyeung and Nipah Beach, to obtain information on the distribution and concentration of the marine debris. The model showed that the water circulation generally moved northward through the waters between Weh Island and Pulo Aceh, resulting in the movement of debris particles towards the Andaman Sea beyond the boundary conditions. However, some particles are also stranded on the beach, potentially contaminating the coastal environment, including Nasi Island. Field validation confirmed that marine debris is dominated by plastics originating from several countries, mostly Indonesia. Notably, the model particle trajectories suggest the potential presence of particles reaching the beach, causing environmental pollution.

Keywords: marine debris, flow model FM, Nasi Island, particle tracking, boundary conditions.

INTRODUCTION

Coastal areas are essential for supporting tourism and transportation, providing sea-sourced food, and for playing a significant role in the economy. However, anthropogenic activities directly impact coastal zones by deteriorating their environmental conditions (Britton et al., 2021; Thushari and Senevirathna, 2020). Human behavior and massive activities in coastal areas produce a plethora of waste, and the amount of waste produced is increasing globally (Chenillat et al., 2021; Cordova et al., 2022b; Susilawati et al., 2022). Consequently, marine debris has emerged as a critical global issue, particularly in Indonesia (Adyasari et al., 2021; Purba et al., 2019).

Marine debris, also known as marine litter, is defined as an object that is intentionally, unintentionally, directly, or indirectly released or disposed in marine areas or rivers (Chenillat et al., 2021). Marine debris can be classified into several forms such as plastic, metal, nets, Styrofoam, broken glass, cloth, paper, and wood. However, the majority of marine debris are plastic particles (non-biodegradable) that require long decomposition times (O'Brine and Thompson, 2010).

Waste contamination and pollution significantly reduce the aesthetic value of marine tourism areas, leading to a decline in tourism and visitor numbers (Pervez and Lai, 2022). Moreover, plastic waste in coastal and aquatic zones poses a severe threat to coastal and marine ecosystems, endangering organisms inhabiting these areas (Sari et al., 2021). Macroplastics in marine environments could potentially endanger the survival ability of biota as these organisms may ingest plastic fragments or become entangled in them (Winarni et al., 2022). Microplastic fragments are often found in the digestive systems of marine organisms (Andreas et al., 2021; Riani and Cordova, 2022) and can accumulate in the sediments (Mu et al., 2019). Plastic waste in the ocean originates from human activities on land, shipping, and fishing (Bilgili et al., 2019). Poorly managed terrestrial waste is frequently transported to the ocean through river flow (Cordova and Nurhati, 2019; Liedermann et al., 2018). However, oceanographic factors, such as tides, wind strength and direction, and ocean currents, are the primary forces responsible for the distribution of marine debris across different regions (Schwarz et al., 2019).

The distribution of debris in the ocean relies on oceanographic parameters such as sea currents. Several previous studies have shown that particle tracking methods can be effectively used to describe particle movements on the ocean surface (Iskandar et al., 2021; Lebreton and Borrero, 2013; Lebreton et al., 2012; Wisha et al., 2022). Indonesia is geographically vast, surrounded by the ocean, and dynamically interacts with other marine areas, presenting a complex and challenging situation (Cordova et al., 2022a). Nevertheless, the application of particle tracking has only recently emerged (Iskandar et al., 2022; Purba et al., 2021), with subsequent small-scale studies conducted in several regions (Marganita et al., 2022; Wisha et al., 2022). As the westernmost region of Indonesia, studies related to the trace of marine debris are limited in Aceh Province (Ondara et al., 2021), although they play an important role in explaining the dynamic distribution of marine debris particles in western Indonesia and their interactions with regional water masses (Haditiar et al., 2024; Rizal et al., 2012). Therefore, more extensive studies are crucial to understand and predict the distribution scheme of marine debris in the surrounding Aceh Province.

Pulo Aceh is an administrative area of Aceh province consisting of some small islands, located in the northwest part of Sumatra, becoming one of the outermost areas of Indonesia. Nasi Island and Breueh Island are the two islands inhabiting this area. These islands are surrounded by several significant seas, such as the Andaman Sea in the northeast, Malacca Strait in the southeast, and Indian Ocean in the west, making it strategic for the inter-ocean transport of marine debris in the surrounding waters (Connan et al., 2021; Haditiar et al., 2020). Moreover, Pulo Aceh waters are very close to busy international shipping lanes, inducing the potency of littering (MarineTraffic, 2022). However, these waters are closely connected to major rivers in mainland Aceh, such as the Krueng Aceh River, which is the largest river runoff from the city of Banda Aceh, and may be the primary pathway for anthropogenic debris to enter the northern waters of Aceh (Agustina et al., 2021; Ondara and Dhiauddin, 2021; Purnawan and Ondara, 2021). Local-scale studies were conducted in the Aceh Province to investigate the distribution and types of debris found in both water bodies and beaches. These studies have revealed that a significant portion of marine debris consists of plastic, with some originating abroad (Kusumawati et al., 2019; ModusAceh, 2018; Ondara and Dhiauddin, 2020; Tribunnews, 2017). Although marine debris in the coastal waters of North Aceh has become one of the main concerns, no scientific research has been conducted using numerical analysis to study sources and distribution patterns. This research fills this gap by using advanced numerical simulations to understand how currents transport and deposit debris along these coastlines, particularly on the Pulo Aceh Islands. This approach will enable government and transboundary agencies to mitigate the impacts of marine debris more effectively and reduce the risk of environmental pollution in the region.

MATERIALS AND METHODS

Research location

This study focused on the waters of Aceh Province, particularly those around Pulo Aceh.

(Fig. 1). The simulated particle release points were Krueng Aceh (source 1), Pulo Aceh (source 2), Sabang (source 3), and Andaman Sea (source 4). These locations were selected based on strong presumptions and observations of field conditions that are sources of marine debris disposal and significant ocean currents. Four sources were simulated and each source was used to indicate the direction of the particle distribution generated by each discharge point. The first source was Krueng Aceh, the main source of debris from mainland Banda Aceh (a densely populated area in the north of Sumatra Island). The second source was located in the surrounding Nasi and Breueh Islands, where this location was reported to have abundant stranded marine debris resulting from the anthropogenic activities of the local community. The third point was in northern Aceh, a place of local fishing activity, where this area is also a channel connecting the Malacca Strait and Andaman Sea. We considered that the presence of marine litter from other countries was possible at this location. The fourth point was at the northern tip of Pulo Aceh, which was related to suspected garbage disposal (littering) from the international shipping lanes.

Field data collection

Marine debris sampling was conducted in April 2022 to validate the data for the debris that landed in the observation area. Two beaches located on Nasi Island were designated as debris collection sites: Nipah and Alue Riyeung Beach, located on the east and west sides of the island, respectively (Fig. 1). These sites were chosen because of their limited anthropogenic activity and distance from residential areas, making it possible to infer that debris particles accumulated on beaches were primarily the result of hydrodynamic processes and marine debris deposition.

Marine debris samples were collected along defined transects measuring 100 m long and positioned parallel to the shoreline. The width of each transect extended from the shoreline to the inland back barrier, resulting in variable widths, depending on the landscape.

After collection, the samples were transported to the Marine Chemistry Laboratory at the Universitas Syiah Kuala for further analysis. Prior to the analysis, the samples were cleaned and dried. The identification of collected samples followed the guidelines established by the United Nations

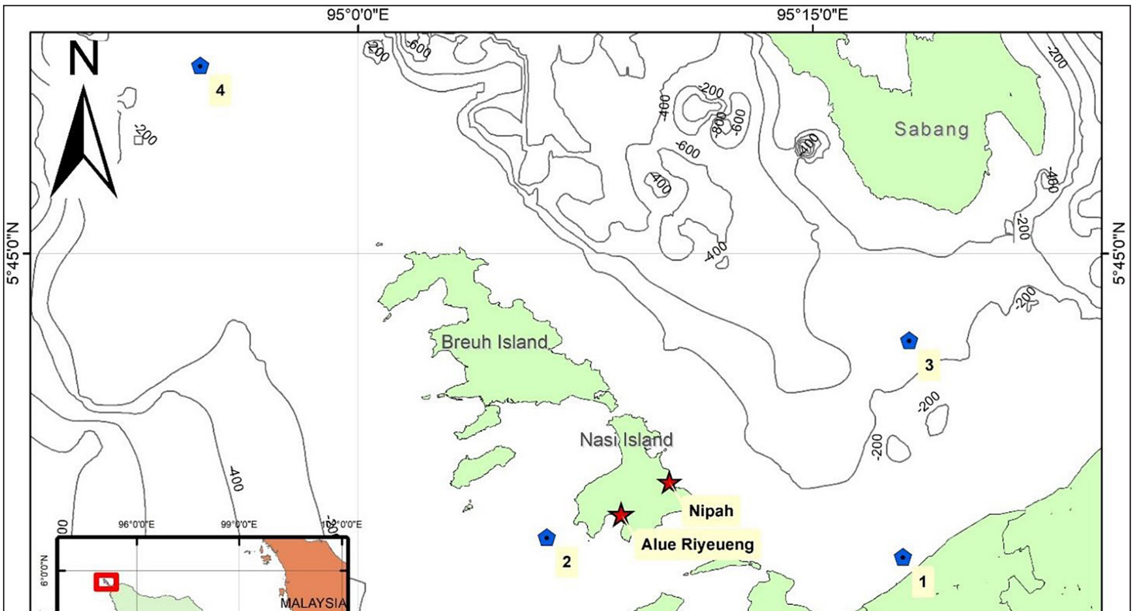

Figure 1. In the study area in Pulo Aceh Waters of Aceh Province, blue pentagons denote particle release sites and red stars denote field sampling points

Environment Programme (UNEP) for marine debris surveys (Cheshire et al., 2009). These guidelines categorize marine debris into nine material composition categories: plastic, foamed plastic, cloth, glass and ceramic, metal, paper and cardboard, rubber, wood, and miscellaneous. Each material was further subdivided into relevant subcategories based on its association with daily human activities. Following the identification, the concentration of the debris was calculated using Equation 1 (Lippiatt et al., 2013).

$$Concentration = \frac{number\ of\ items}{wide(m)xlength(m)} \quad (1)$$

Hydro-oceanographic data input in the simulation

We employed the MIKE 21/3 Coupled Model FM computational system to simulate the flow and particle tracking models. Specifically, the system was utilized for mesh generation, hydrodynamic modeling, and particle tracking of marine debris for the year 2021. The simulation was divided into four monsoon systems: NE Monsoon from December to February, first Transitional Season from March to May, the SW Monsoon from June to August, and second Transitional Season from September to November.

In this study, two types of data were used: model input and validation. The data obtained from various sources were used to build the model (Table 1). Validation data were used to examine the accuracy of the model. The figures and calculations presented in this study, particularly those related to hydrodynamics and particle tracking, were generated using the MIKE 21/3 Coupled Model FM system.

The wind data employed in our model were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) and originated from the development of numerical weather predictions (Owens and Hewson, 2018). The data were taken at hourly intervals, specifically at coordinates 95.38 °N and 5.66 °E. This dataset comprises two crucial components: the u-component and v-component, which are representative of both wind direction and speed. Wind forcing was configured to exhibit temporal variability, while remaining spatially constant within the domain. To align with the temporal scenarios of the western and eastern monsoons, the input wind data for our model were adapted to the prevailing wind conditions in each scenario.

Hydrodynamic module

This study employed seasonal hydrodynamic simulations of Pulo Aceh waters. Utilizing particle tracking, this technique leverages coastal currents for efficient predictions (Suara et al., 2020). The basic flow model hydrodynamics forms the foundation of the particle-tracking module. Thus, the flow model should be simulated beforehand to determine the spatial oceanographic features. The flow model is based on the 3D Reynolds and Navier-Stokes incompressible fluid equations, which apply continuity to the two horizontal momentum equations for the *x*- and *y*-components (Zhao et al., 1994), as described in Equations 2–4. The necessary input data are listed in Table 2.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S \quad (2)$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} = fv - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_o}\frac{\partial P_a}{\partial x} - - \frac{g}{\rho_o}\int_z^\eta \frac{\partial \rho}{\partial x}dz - \frac{1}{\rho_o h}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) + F_u + \frac{\partial}{\partial z}\left(V_t\frac{\partial u}{\partial z}\right) + U_s S \quad (3)$$

Table 1. Model input data

Data	Source	Specification	Description
Base map	Indonesia Geospatial Information Agency (BIG), Google Earth	scale 1:25000, (94.774E 5.474N – 95.44E 6.00N	Model input
Bathymetry	SIBATNAS (National Bathymetry System, provided by the Geospatial Information Agency of Indonesia) with a resolution of 180 meters	Data depth range (0 to 1400 m), contour range (per 10 m, 50 m, 100 m.)	Model input
wind	ECMWF (European Centre for Medium-Range Weather Forecasts.), with a grid of 0.125 × 0.125	Data time range January 01, 2021 to December 31, 2021, hourly data acquisition period (average data set).	Model input
Mesh generation	MIKE Zero	Unstructured triangle mesh	Model input
Tides	Sea Level. Station Monitoring Facility (Sabang station)	January 23 to January 29, 2021, hourly data acquisition period, 5.88N, 95.316E, type of sensor: pressure	Model validation

Table 2. Hydrodynamic data input to the model

Data	Source
Time	Number of time steps = 1,500 Time step interval = 3.600 sec Simulation start date = 01/01/2021 01:00 AM Simulation end date = 04/03/2021 13:00 AM
Mesh boundary	Bathymetry = SIBATNAS map digitation
Hydrodynamic module algorithm	Solution technique – low order, fast
Wind forcing	Format = varying in time, constant in domain
Bed resistance	Constant value: 15 [m^(1/3)/s]
Boundary conditions	Type – specified level Format – varying in time, constant along the boundary
Outputs items	Parameters: Surface elevation Current speed Current direction

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} + \frac{\partial wv}{\partial z} = -fu - g\frac{\partial n}{\partial y} - \frac{1}{\rho_o}\frac{\partial P_a}{\partial y} - $$
$$- \frac{g}{\rho_o}\int_z^{\eta} \frac{\partial \rho}{\partial y} dz - \frac{1}{\rho_o h}\left(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y}\right) + F_v + \frac{\partial}{\partial z}\left(V_t \frac{\partial v}{\partial z}\right) + V_s S \quad (4)$$

where: x, y, z – Cartesian coordinates; t – time, h – total water depth; given by $h = \eta + d$, η – surface elevation; d – water depth; u, v, w – velocity components in x, y, and z directions; f – coriolis force parameter, given by $f = 2\Omega sin\phi$, where Ω is the Earth's angular velocity and ϕ is the latitude; ρ – fluid density; ρ_o – reference density; g – gravity; P_a – atmospheric pressure acting on the water surface, S_{xx}, S_{xy}, S_{yx}, S_{yy} – radiation stress tensor components; V_t – vertical turbulence (eddy viscosity); (U_s, V_s) – velocity at which water conditions discharge to ambient water body; S – magnitude of discharge from the point source; F_u, F_v – horizontal stress terms, representing the forces due to shear stresses in the fluid in the x and y directions, respectively. F_u and F_v are given by

$$F_u = \frac{\partial}{\partial x}\left(2A\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) \quad (5)$$

and,

$$F_v = \frac{\partial}{\partial x}\left(A\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) + \frac{\partial}{\partial y}\left(2A\frac{\partial v}{\partial y}\right) \quad (6)$$

The horizontal eddy viscosity coefficient, A, governs the mixing of momentum in the horizontal plane.

The surface and bottom boundary conditions for the velocity components u, v, and w are as follows (Equation 7 and 8):

Boundary Condition at $z = \eta$

$$\frac{\partial \eta}{\partial t} + u\frac{\partial \eta}{\partial x} + v\frac{\partial \eta}{\partial y} - w = 0,$$
$$\left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}\right) = \frac{-1}{\rho_0 v_t}\left(\tau_{sx}, \tau_{sy}\right) \quad (7)$$

Boundary condition at $z = -d$

$$u\frac{\partial d}{\partial x} + v\frac{\partial d}{\partial y} + w = 0,$$
$$\left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}\right) = \frac{-1}{\rho_0 v_t}\left(\tau_{bx}, \tau_{by}\right) \quad (8)$$

where: τ_{sx}, τ_{sx} – x and y components of the surface winds; τ_{bx}, τ_{by} – x and y components of the bottom stresses.

Particle tracking models employ a discrete Lagrangian approach to facilitate interactions among moving particles. Moreover, this methodology characterizes the dynamics of particle motion through the utilization of stochastic differential equations, wherein the Langevin equation serves as the descriptive framework for particle movement and dispersion (Bayram et al., 2018). The particle motion dynamics were formulated as follows:

$$dX = a(t, X)dt + b(t, X)\xi dt \quad (9)$$

where: a – the drift term, b – the diffusion term, ξ – random number reflecting the stochastic nature of particle movement.

To simulate the particle trajectories, we applied a discretized Euler method starting from an initial value of $Y_0 = X_0$. The resulting equation is given by Equation 10 and 11.

$$Y_{n+1} = Y_n + a(t_n, X_n)Y_n\Delta_n + $$
$$+ b(t_n, X_n)Y_n\Delta W_n \quad (10)$$

$$\Delta W_n = W_{n+1} - W_n,$$
$$\Delta W_n \in N(\mu = 0, \sigma^2 = \Delta_n) \quad (11)$$

where: $n = 1, 2, 3,...$ refers to the steps in the Euler scheme, with a as the drift term and b as the diffusion coefficient; ΔW_n – the Gaussian increments of the Wiener process W_n; W – Continuous Gaussian stochastic process with independent increments.

Mesh generation

To create the mesh for our model, we relied on bathymetry data, coastline data, and water boundary information to define essential boundary conditions. The bathymetry data, initially obtained from SIBATNAS (https://sibatnas.big.go.id/), underwent a comprehensive processing step to extract the depth information. This data was then transformed into Geographic (Latitude/Longitude) coordinates and saved in the (.xyz) data file format.

Using the MIKE 21/3 Coupled Model FM system, an unstructured triangulation process was applied to enable a flexible mesh approach. This approach employed a three-angle mesh to delineate the simulation area. To enhance the simulation accuracy, ten iterations of mesh smoothing were conducted. In addition, the depth information for the entire simulation area was obtained using a natural neighbor interpolation technique. The resulting depth interpolation is illustrated in Figure 2.

RESULTS AND DISCUSSION

Seasonal wind characteristics in the Pulo Aceh

The wind direction and speed were visually conveyed using a wind rose diagram, denoted as the WR Plot. This diagram features a central radial line extending outwards, which serves as an indicator of prevailing wind direction (Fig. 3). In January 2021, the dominant wind direction fell within the range of 180–195°, frequently categorized as strong winds (6–9 m/s), with instances of very strong winds (>9 m/s) occurring quite frequently. As the first transitional monsoon arrived in April, the prevailing wind direction shifted to the Northeast (15–45°), with a notable proportion characterized by moderate wind speeds (3–6 m/s). Strong winds reappeared in July 2021, coinciding with the northeast as the dominant

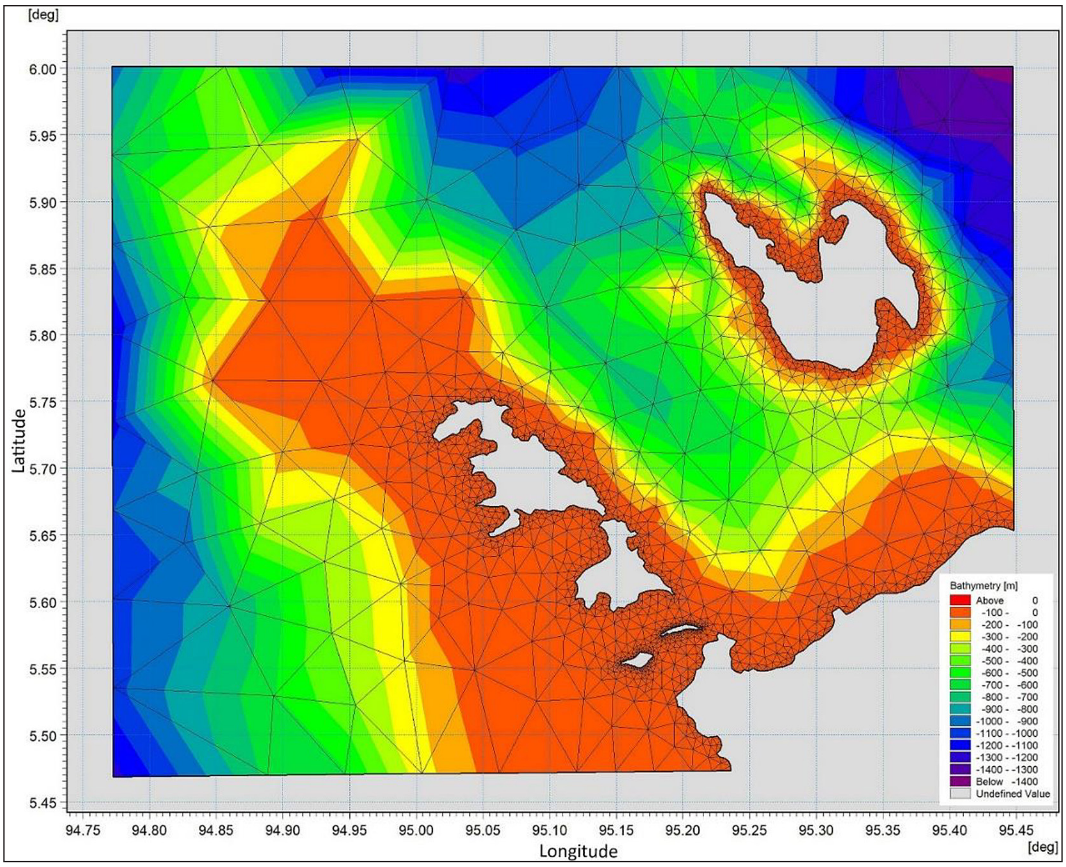

Figure 2. The mesh construction of the study area illustrates a triangulated grid overlay used for spatial analysis. The color gradient represents bathymetric depths, with red indicating shallow depths, and blue to purple indicating deeper areas.

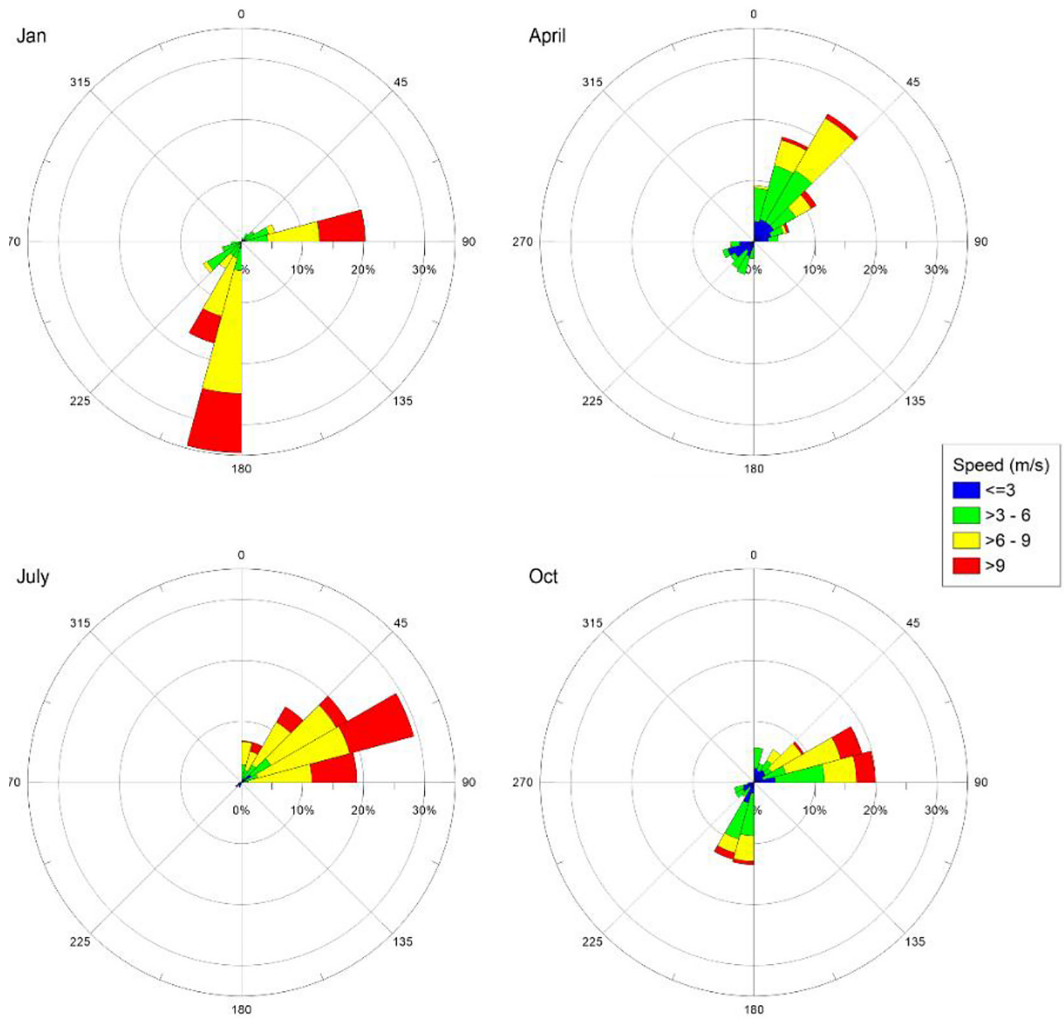

Figure 3. Windrose of the Pulo Aceh waters for each monsoonal season in 2021

wind direction, and featuring high speeds (> 9 m/s). In October, which encompasses the second transitional monsoon, no discernible dominant wind direction is observed. During this period, the wind movement was primarily oriented from 60° to 90°, with speeds ranging from 3 to 9 m/s.

Model validation

To evaluate the model's accuracy, we compared the simulated surface elevation data with field measurements collected in January, April, July, and October 2021 (Fig. 4). The performance of the model varies across seasons. The calculated RMSE were 0.1337 for January, 0.181 for April, 0.2661 for July, and 0.282 for October. In October, the higher RMSE was attributed to the monsoon transition. Increased wind stress from the Indian Ocean, driven by the shifting wind direction, leads to stronger currents and waves, contributing to amplified tidal elevation. In July, the RMSE was slightly higher than that in January and April, but remained relatively similar to the October value.

Despite these discrepancies, the model effectively captured the overall phase and pattern of the surface elevation for all four seasons. However, the model tended to underestimate surface elevation, particularly during spring tides. This underestimation could be due to the complex interplay of ocean currents and tidal forces in narrow Aceh waters, especially as it transitions from broader, deeper oceanic areas to the more confined coastal region of Aceh.

Current

The average surface current speed appears to be dominant towards the northwest and southwest, as influenced by wind and tides (Fig. 5). During January and April, the current from the east dominated to the north, particularly under low-to high-tide conditions. The velocity of the current on the east coast of Weh Island was higher

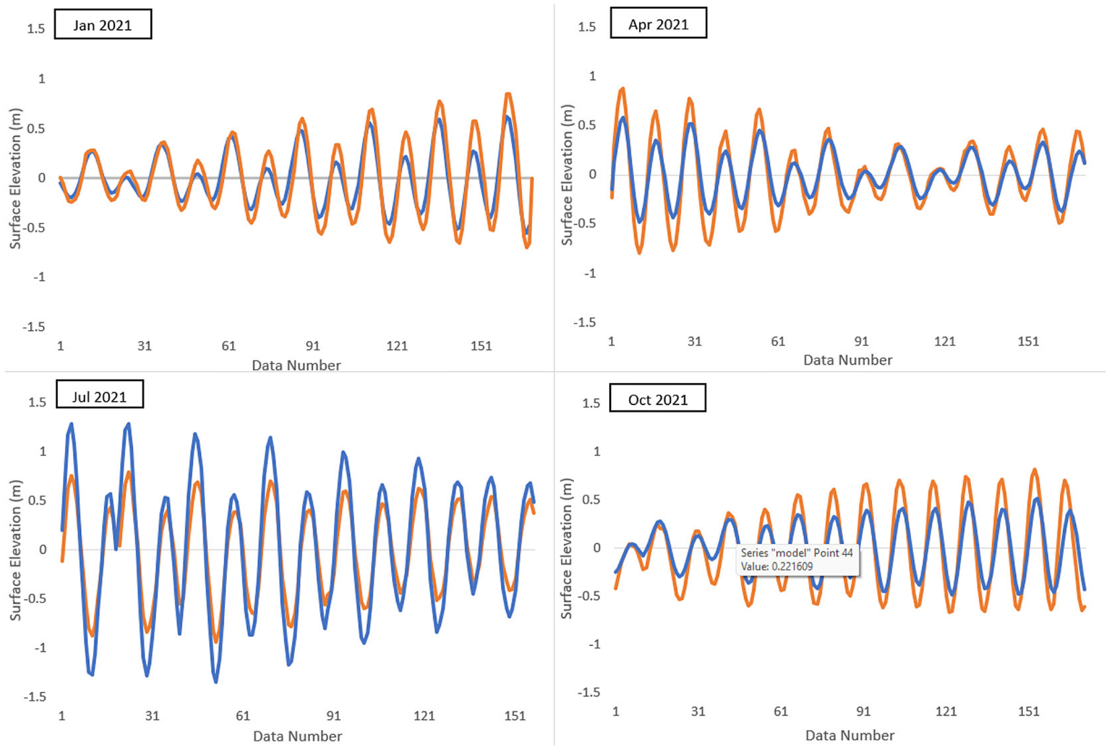

Figure 4. Model validation of surface elevation in Pulo Aceh waters: Comparison of simulated (blue line) and observed (orange line) data for four monsoonal seasons in 2021

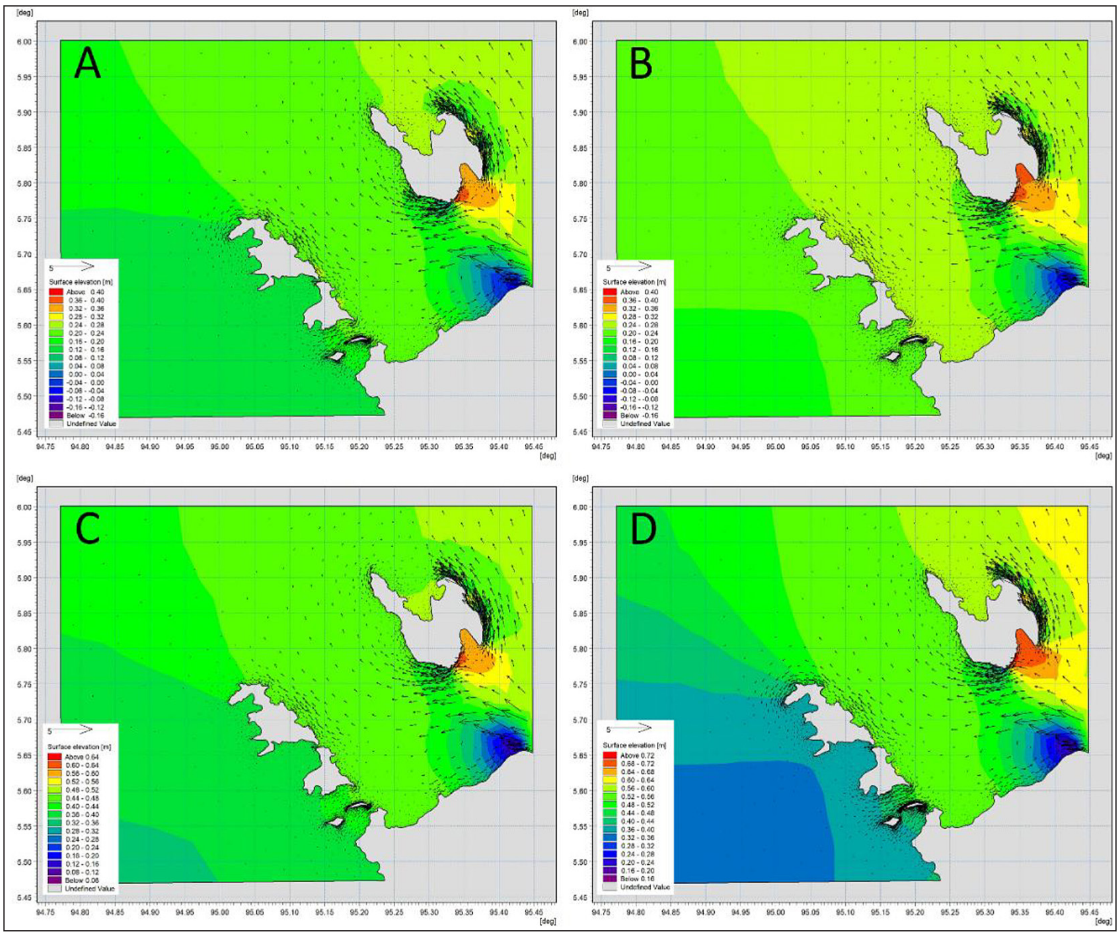

Figure 5. The direction of current in 2021: (a) January; (b) April; (c) July; (d) October

than that offshore or in other areas of coastal Weh Island. Meanwhile, the current was established along the coast and moved eastward along the north coast of the Aceh mainland until it moved northwestward when there was a conjunction of currents on the east side. The water mass on the east side of Pulo Aceh moved northwest at a relatively high speed until it weakened towards the boundary to the north and west. In July, the current along the coast of Breueh Island moved along the coastline to the west until it eventually turned south on the west coast of the island. During this period, the offshore water mass in Pulo Aceh moved northward.

In general, the movement of water masses in the northern waters of Aceh is strongly influenced by the transport of water masses originating from the Strait of Malacca and Andaman Sea (Setiawan et al., 2018). As explained earlier, the seasonal influence on the circulation of water masses in this area was insignificant, with minor corrections produced for different seasons. The model results generally showed that the water mass entered the boundary area from the southeast and then flowed out of the boundary toward the northwest. This circulation was consistent throughout the season owing to the influence of the global circulation, gyres, and wind forcing (Rizal et al., 2012). The movement of the current on the southeast side was also due to the conjunction of water masses originating from the Strait of Malacca and the Andaman Sea, which deflected into the narrow channel separating Banda Aceh and Sabang, combined with shallow water bordered by the coastline, to produce fairly strong currents (Rizal et al., 2010).

Notably, the direction of the current in the western waters around Breueh Island and Nasi Island exhibits seasonal variability (Setiawan et al., 2018). The western waters of Pulo Aceh showed current flow with relatively low velocities compared with the eastern side. Current velocities in the western waters of Pulo Aceh during the simulation time ranged from 0.2 m/s to 0.4 m/s. Owing to the geographical contingencies of the islands in the area, the movement of currents disperses in all directions, generating radial currents that are influenced by changes in the topography, wind conditions, and terrestrial morphology. For example, in January, the water mass north of Breueh Island moved westward until it turned southward along the coast of the island. Conversely, during July, strong winds from the west pushed the mass of water from the Indian Ocean towards Pulo Aceh, which weakened the currents on the west and north sides of Pulo Aceh, producing weak currents to the north.

Particle trajectories

This study employed particle tracking to illustrate the distribution of debris particles originating from four potential sources within an area. Particle movement typically aligns with the prevailing currents in the region, and the initial distribution for each period is depicted on Day 5 (Fig. 6).

In January, particles from sources 1 and 3 demonstrated distinct movement patterns. Particles from Source 1 (Krueng Aceh) and Source 3 (near Sabang) generally moved northward, driven by prevailing currents. In contrast, the particles from Source 4, located in the Andaman Sea, exhibited southward drift. Source 2, near Pulo Aceh, initially showed a slow northward movement, before shifting southward during the simulation. By the end of the simulation, some particles had reached the western coast of Breueh Island, indicating that trash particles could potentially wash ashore, likely originating from Source 2. A similar pattern emerged during the April period, with particles from various sources spreading out but ultimately a few remaining near the coasts by the end of the simulation. In particular, on the western side of Breueh Island, a few particles were observed, which were likely linked to the waste originating from Pulo Aceh via Source 2.

In July, the particle movement pattern shifted significantly. The particles from Source 1 primarily moved westward, leading to their accumulation along the coast of Banda Aceh. As the simulation progressed, a substantial number of particles from this source were observed north of Banda Aceh City and along the eastern side of Breueh Island. Based on the simulation results, particles from Source 2 during the July period were mainly found on the western side of Breueh Island. In contrast, the particles from sources 3 and 4 moved out of the simulation boundary, heading north and southwest, respectively. The October period showed similar patterns as July, although by the end of the simulation, there were fewer particles near the coastal waters.

During January, the particles from Source 1 initially moved westward at relatively low velocities. Over time, these particles shifted direction, drifting eastward and then northwestward. Eventually, they converged with particles from Source 3 in the waters surrounding Sabang, Banda Aceh,

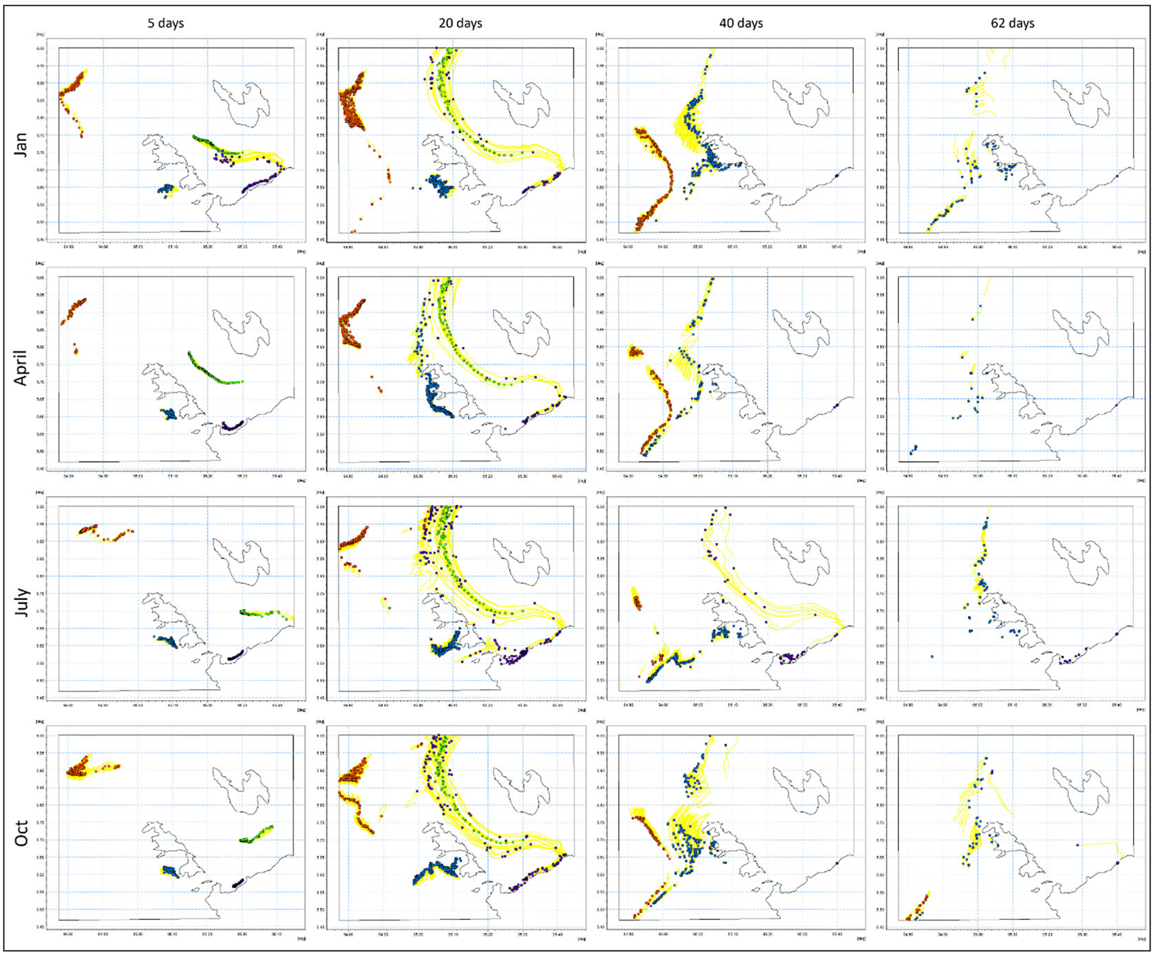

Figure 6. Simulated trajectories of debris released from four sources around Pulo Aceh in January, April, July, and October. The trajectories represent 5, 20, 40, and 62 days after discharge. Some particles are transported towards the Andaman Sea, while others follow coastal streams, indicating that they may be stranded on nearby coastlines.

and Nasi Islands. The particles from source 3 exhibited rapid dispersion, with most crossing the northern boundary within the first 40 d of the simulation. This swift movement suggests that, despite their initial trajectory, particles from Source 3 were unlikely to contribute significantly to coastal pollution as they quickly exited the simulation area.

Source 1, which represents debris from Krueng Aceh, is recognized as the primary terrestrial input of debris along the coast of Banda Aceh. During July, the potential for particle deposition was particularly high in the northern Banda Aceh region, leading to a noticeable buildup on the western coast of the city, with some particles reaching Nasi Island by day 20. By the end of July, particles from Source 1 were deposited on the west coast of Breueh Island. This highlights the significant impact of local waste from Banda Aceh City on the coastal regions of Breueh and Nasi Islands. Conversely, source 2 demonstrated the greatest potential for depositing waste originating from Pulo Aceh waters. By the end of January, particles from this source had accumulated on the western side of Breueh Island, likely influenced by the prevailing currents at that time. However, by the end of July, these particles had shifted closer to Nasi Island and the western side of Breueh Island, indicating that localized debris from Pulo Aceh waters were likely the primary source of pollution in these areas.

In contrast, particles from Source 3 did not show a distribution pattern conducive to coastal accumulation, despite initial concerns regarding their potential impact. The strong northward currents carried most of the particles from this source beyond the simulation boundary, reducing their likelihood of affecting coastal regions. Similarly, particles from source 4, initially considered a potential contributor to debris in Pulo Aceh from international shipping lanes, were primarily transported outside the boundary toward the southwest. Although some movement toward the Pulo Aceh waters was observed around day 40, the overall pattern showed that particles from this source remained mostly outside the area of concern, indicating a limited impact on local pollution.

Assessment of Stranded Debris

Field data were collected to assess the presence and distribution of the waste particles. This was performed to validate the type and origin of waste in the monitored area. The results from the two monitoring stations on Nasi Island, specifically Nipah and Alue Riyeung, are shown in Figure 7. The data show that the prevalence of plastic waste is very high compared with that of other types of waste. Although other materials such as rubber, wood, metal, glass, and cloth were also detected, the amount of these materials was relatively low at both sites. This finding is supported by the concentration data, which indicates that plastic waste has the highest concentration of all waste types, as shown in Figure 8.

The origin of the collected waste was determined by analyzing the packaging materials. The results revealed that the majority of waste originated locally. However, waste from international sources, including Malaysia and Thailand, was also found on Nasi Island. The presence of international waste on the beaches of Alue Riyeung and Nipah is detailed in Table 3. Notably, Nipah Beach, located on the eastern side of Nasi Island, showed a slightly higher concentration of foreign debris, indicating the influence of water mass transport from the east, such as from the Strait of Malacca and Andaman Sea.

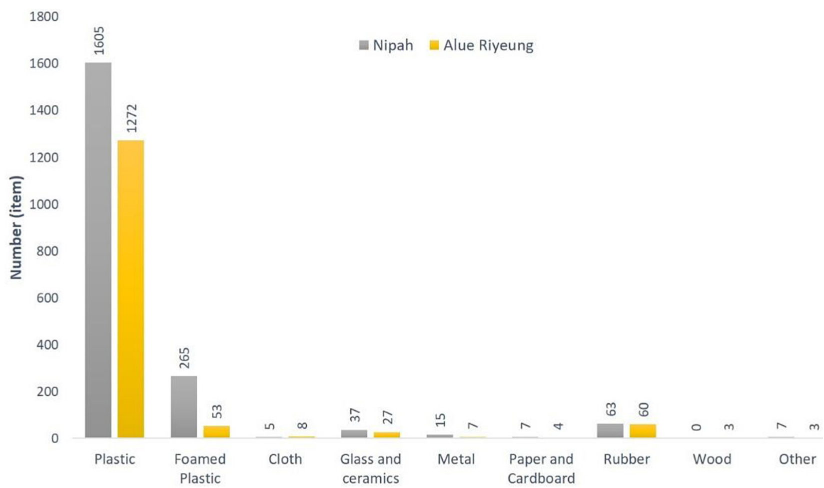

Figure 7. Distribution of debris (number per category) in Nipah and Alue Riyeung beaches

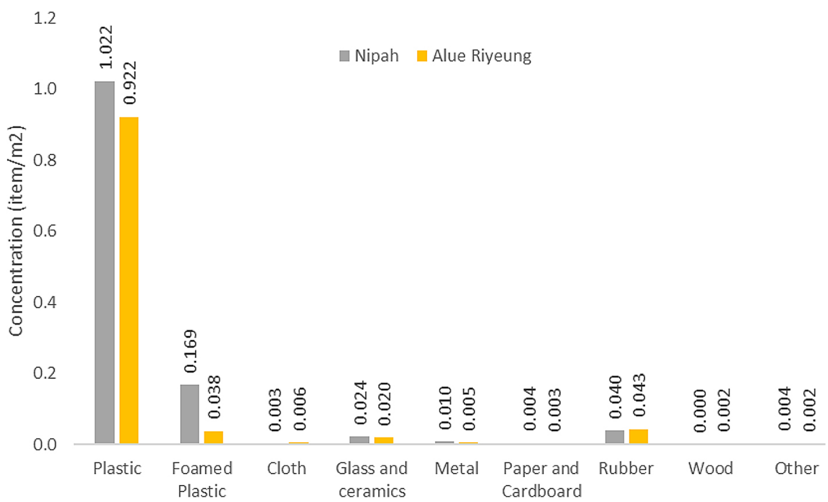

Figure 8. The concentration of marine debris found in Nipah and Alue Riyeung beaches

Table 3. Proportion of waste sources found on Nasi Island

Sources	Nipah	Alue Riyeung
Local	64.4%	67.5%
International		
Malaysia	4.4%	0.7%
Singapore	0.3%	-
Thailand	0.6%	0.2%
China	0.7%	0.5%
Myanmar	0.1%	-
Sri Lanka	0.1%	-
Abu Dhabi	0.1%	-
Emirates/ Middle East	0.1%	-
India	-	0.2%
Vietnam	0.1%	-
N/A	29.3%	30.9%

The particle tracking model employed in this study indicated a low probability of significant particles from Source 3 stranding on the Pulo Aceh coast, particularly on Nipah Beach. Source 3, situated in northern Aceh waters between Sabang, Pulo Aceh, and Banda Aceh, was intended to evaluate the potential of international debris from the Strait of Malacca and the Andaman Sea to enter northern Aceh waters. However, the model results suggest that particles released from Source 3 are unlikely to reach Pulau Nasi. Nevertheless, these projections are consistent with field observations, which show that international debris is present in smaller percentages than local waste.

On the other hand, the model indicated a tendency for some local particles from Source 1 to approach the eastern side of Pulau Nasi, emphasizing the significant contribution of local debris to the coastline. This discrepancy highlights the limitations of the model in accurately predicting the movement of international debris. Although the presence of stranded international debris on Nasi Island's coast is relatively small, it underscores the need for a comprehensive marine debris management strategy that addresses both domestic and regional sources. The complex interactions between local and international debris sources highlight the importance of a multifaceted approach to effectively address this issue.

CONCLUSIONS

The simulation results for the marine debris particles from January to December 2021 revealed distinct movement patterns. Some particles were carried northward towards the Andaman Sea, while others followed a southwestward trajectory, eventually moving beyond the simulation boundaries. In addition, certain particles remained close to the coastline, indicating their potential for stranding along the shore. Our analysis suggests that Source 1 (Krueng Aceh River) and Source 2 (nearshore waters of Pulo Aceh) are likely the primary contributors to debris particles that are ultimately stranded in Pulo Aceh waters, as evidenced by the presence of particles near the coastlines of Nasi and Breueh Islands. In contrast, particles originating from open waters (Sources 3 and 4) tended to be transported away from the simulation area. Notably, in January, a significant accumulation of particles was observed on the west side of Pulo Aceh, particularly from Source 2, likely owing to local activity.

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