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ORIGINAL RESEARCH ARTICLE

Modeling river-to-sea plastic waste dynamics using OpenDrift: A case study in Thanh Hoa, Vietnam

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Abstract: Plastic pollution in aquatic ecosystems represents a significant and escalating global environmental crisis, demanding urgent scientific and policy attention. This study examines the transport and accumulation patterns of plastic waste originating from the Ma, Lach Bang, and Len Rivers in Thanh Hoa province, Vietnam. To simulate these dynamics, we employed the OpenDrift modeling framework, which integrates high-resolution environmental parameters such as wave action, wind patterns, ocean currents, temperature, and salinity. Simulations were conducted across four seasonal scenarios (winter, transitional periods, and summer) and were validated against unmanned aerial vehicle imagery, demonstrating strong spatial concordance in accumulation patterns. The results reveal marked seasonal variability: winter conditions, dominated by the Northeast monsoon and reduced river discharge, led to localized accumulation along southern coastal zones, whereas summer conditions, characterized by intensified river flow and Southwest monsoon winds, facilitated extensive offshore dispersion. These findings unveil critical, previously overlooked patterns of plastic waste dynamics, guiding precise risk mapping and strategic interventions for sustainable marine management in Thanh Hoa and beyond.

Keywords: Waste transportation; Plastdrift; Seasonal scenarios; Marine environments

1. Introduction

Plastic waste accumulation in aquatic environments poses a multifaceted and escalating threat to biodiversity and ecosystem integrity.[1] In marine ecosystems, plastic pollution disrupts biological communities and trophic interactions,[2] with numerous studies reporting mortality among marine fauna, including mammals, birds, fish, and turtles, due to ingestion, entanglement, and exposure to microplastic particles.[3] These impacts are not limited to pelagic zones; coastal and intertidal habitats, such as mangrove forests, are also increasingly vulnerable to plastic contamination.[4-6]

Rivers serve as critical pathways for transporting plastic waste from terrestrial sources to marine environments.[7-10] Freshwater streams often generate stratified currents that extend beyond river mouths, altering local hydrodynamic conditions and influencing the drift trajectories of plastic debris.[11-13] However, the extent to which fluvial inputs directly shape the spatial dispersion of plastic waste in marine systems remains insufficiently understood, prompting further investigation into the complex interactions between riverine and oceanic processes.[11,14,15] In this context, Thanh Hoa province – with its diverse and dynamic river networks – offers a representative case study for examining plastic waste transport from inland waterways to coastal and offshore zones.[16]

The East Sea and its surrounding waters exhibit complex plastic transport dynamics, primarily governed by atmospheric and ocean circulation patterns.[17-19] As a semi-enclosed basin, the East Sea is strongly influenced by the Asian monsoon system, characterized by northeasterly winds in winter and southwesterly winds in summer.[20,21] These seasonal regimes generate distinct surface circulation patterns, with stronger vortices and wind speeds of 8 – 10 m/s in winter and weaker flows averaging 4 – 5 m/s in summer. Wind forcing, combined with geostrophic currents and tidal oscillations, produces wind-driven drift that significantly affects the dispersion of floating plastic debris.[22-24] This drift is typically modeled as a fraction of wind speed – ranging from 1% to 6% – with a coefficient of 2 – 3% commonly applied for plastic particles, resulting in enhanced transport during winter when wind intensity is greater.[21,25-27]

Against this backdrop, the present study investigates the transport trajectories and dispersion patterns of plastic waste originating from three major rivers in Thanh Hoa province: the Ma, Lach Bang, and Len Rivers. Using the OpenDrift modeling framework – a robust tool for simulating buoyant particle movement – we simulate plastic transport under varying seasonal conditions. The model integrates key environmental drivers, including ocean currents, wind fields, river discharge, and flow velocity, to capture the complex hydrodynamic interactions influencing plastic dispersion. This comprehensive approach enables the identification of spatial and temporal variability in plastic transport, highlighting accumulation zones and potential pollution hotspots in marine environments.

2. Study sites

The study area is located in the coastal zone of Thanh Hoa province, Vietnam, encompassing a 102 km arc-shaped shoreline along the East Sea (Figure 1). This region receives freshwater input from three major rivers: the Ma, Lach Bang, and Len Rivers. Each river exhibits distinct hydrological characteristics in terms of scale, flow regime, and seasonal variability.[16,28] These rivers play a vital role in supporting agricultural, industrial, and domestic water demands across their basins. However, they are increasingly subjected to anthropogenic pressures such as urban expansion, deforestation, and agricultural runoff, which contribute significantly to plastic waste discharge into aquatic systems. The convergence of these rivers into the coastal zone makes Thanh Hoa an ideal location for investigating land-to-sea plastic transport mechanisms. The combination of diverse riverine inputs and dynamic coastal hydrodynamics provides a representative setting for analyzing the spatial and temporal variability of plastic waste movement and accumulation. By focusing on this region, the study aims to capture the influence of river discharge, ocean currents, and wind patterns on plastic dispersion, thereby identifying potential accumulation zones and informing strategies for marine pollution mitigation.

3. Research methods and data sources

3.1. Drift model selection

OpenDrift is an open-source Lagrangian particle-tracking framework developed by the Norwegian Meteorological Institute (MET Norway).[29] It has been widely applied in various environmental studies. For example, it was used to model plastic drift from the Mekong River,[30] support search and rescue operations in Korea,[31] assess oil spill risks in Cuba and the Barents Sea,[32,33] and study microplastic dispersion in the Mediterranean Sea.[34,35] The model was selected for its robustness, flexibility, and ability to integrate diverse environmental datasets such as ocean currents, wind fields, and river discharge.[29-31,36-38] In this study, five modules were configured to reflect the hydrodynamic conditions of the region. These modules simulate key processes influencing plastic transport, and their interrelationships are illustrated in Figure 2. This modeling approach enables a detailed analysis of seasonal variability and spatial patterns of plastic waste movement from riverine sources to marine environments.

3.1.1. Leeway module

The Leeway module was used to simulate wind-induced drift of floating plastic particles in aquatic environments. It accounts for key physical parameters such as wind resistance coefficients and the aerodynamic properties of different plastic types, which influence particle responses to surface wind forces. The module calculates the leeway drift velocity (V_{leeway}), representing the wind-driven component of particle movement. This velocity

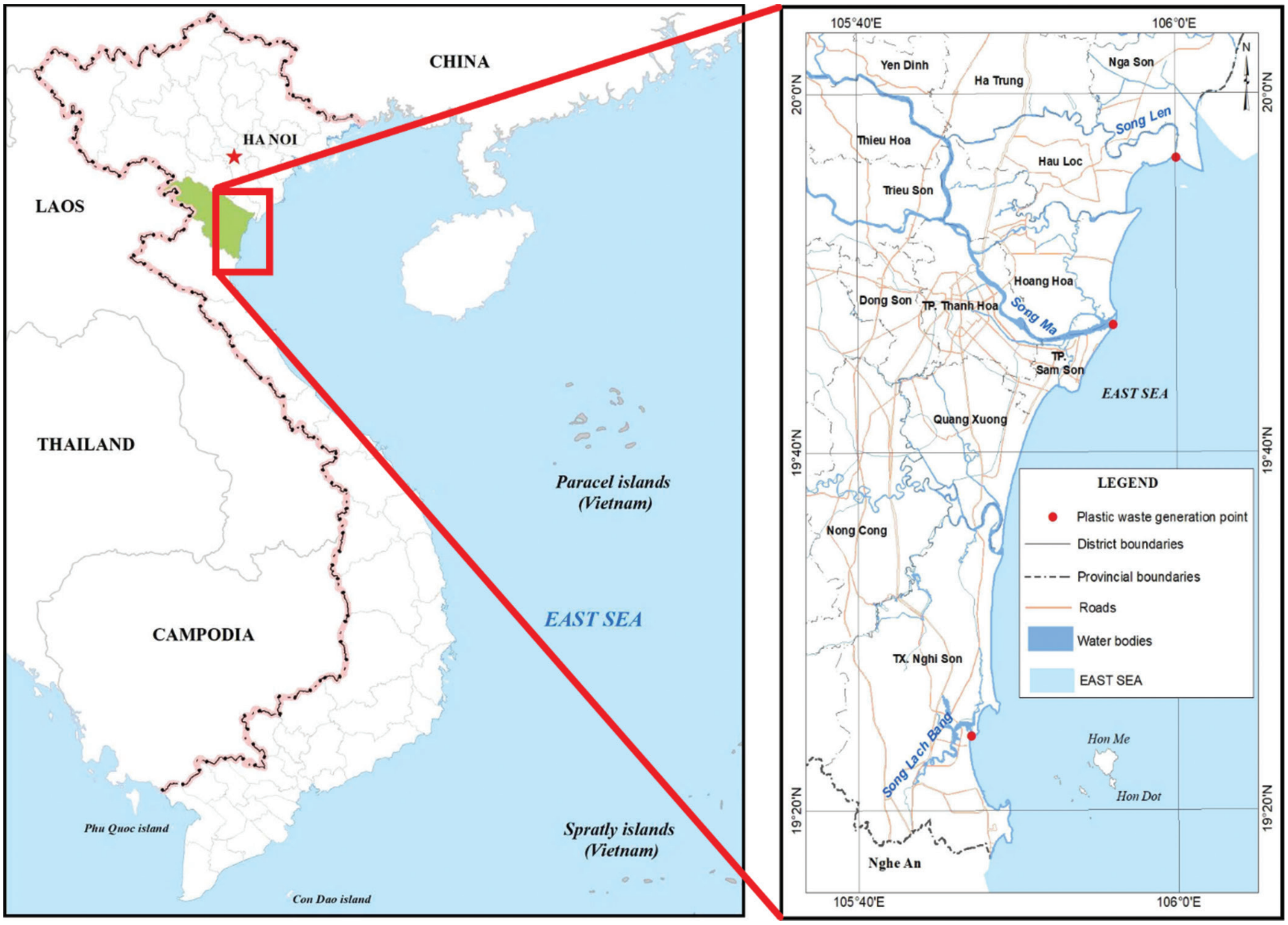


Figure 1. Study area

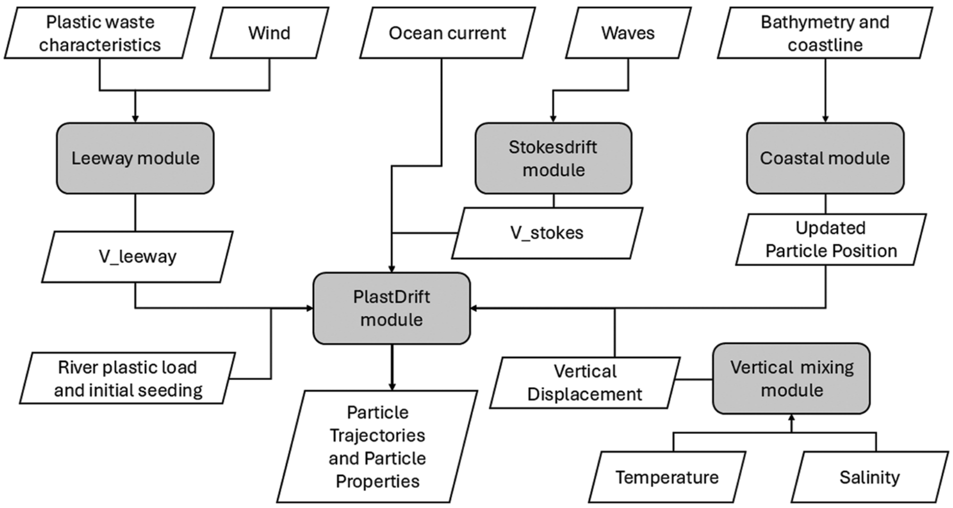


Figure 2. Modeling plastic waste transport and accumulation

is estimated using the leeway drift formula, as described in previous studies. Typically, the wind drift coefficient ranges from 1% to 6% of the wind speed, depending on the object's buoyancy, shape, and exposure. For plastic debris, a coefficient of 2 – 3% is commonly applied, resulting in stronger drift during high wind conditions. This module is essential for accurately capturing the role of wind in the dispersion of plastic waste, particularly in coastal and open-sea environments where wind forcing significantly influences transport dynamics:[39,40]

$$V_{leeway} = V_{wind} \times (a + b.r) \quad \text{(I)}$$

where V_{mind} represents the wind speed at a height of 10 m; a is the intercept coefficient, accounting for the portion of drift that is not linearly dependent on wind speed; b is the linear coefficient, representing the portion of drift that is proportional to wind speed; and r is the random noise coefficient, introduced to model uncertainties in the drift. The coefficients a and b are empirically determined and specific to the type of drifting object.

3.1.2. Stokes drift module

This module simulates the effect of ocean waves on the transport of floating particles by calculating the net drift resulting from wave-induced orbital motion. Stokes drift is a critical factor in modeling the movement of plastic debris, especially in coastal and offshore environments where wave activity is significant. The module accounts for the cumulative displacement of particles caused by wave motion, which contributes to long-range transport. To quantify this effect, the Stokes Drift module applies a mathematical formula that estimates the drift velocity based on wave parameters such as amplitude and frequency, as described in previous studies.[40,41] This component enhances the accuracy of trajectory simulations by incorporating wave-driven transport mechanisms into the overall particle movement model:

$$v_s(z) = \frac{a^2 wk}{2} e^{2kz} \quad \text{(II)}$$

where a is wave amplitude; k *is* wave number, calculated as $2\pi/\lambda$ (where λ is the wavelength); ω is the angular frequency, calculated as $2\pi/T$ (where T is the wave period); z is depth (negative when moving downward into the water column); and v_s (z) is the Stokes drift velocity at depth z.

The Stokes drift velocity is highest near the surface (z = 0) and diminishes with increasing depth.

3.1.3. Vertical mixing module

This module is designed to simulate the dynamic vertical distribution of particulate matter within the aquatic column. It incorporates key physical processes, including turbulent diffusion, buoyant forces, and stratification driven by density gradients. This module plays a critical role in accurately representing the vertical transport and fate of plastic debris, which may exhibit variable buoyancy characteristics – either ascending, remaining suspended, or descending – depending on environmental conditions such as temperature, salinity, and biofouling.

The OpenDrift model specifically employs the Langevin equation to simulate vertical diffusion, as follows:[42,43]

$$dz = w.dt + \sqrt{2K_z dt}.R \quad \text{(III)}$$

where dz is the change in depth; w is the settling/rising velocity (buoyancy or sinking velocity); Kz is the vertical diffusivity coefficient; dt is the time step; and R is a standard random number drawn from a normal distribution, Normal (0,1).

In this modeling framework, seawater temperature and salinity are utilized as primary inputs to compute the buoyant velocity of plastic debris within the marine environment. These parameters are integrated into the Thermodynamic Equation of Seawater 2010 (TEOS-10), which is implemented in the Vertical Mixing module of the OpenDrift modeling system. The relative density contrast between plastic particles and the ambient seawater – determined by TEOS-10 – governs their vertical displacement. This vertical motion significantly influences the transport pathways and spatial accumulation patterns of plastic waste in the ocean, particularly in stratified water columns where density gradients are pronounced.

3.1.4. Coastal module

This module was integrated to robustly simulate the interaction between plastic debris and coastal environments, encompassing shoreline dynamics and nearshore processes. The module uses logical conditions and geospatial checks to handle the behavior of particles when they encounter land. It accounts for mechanisms such as particle washout, refloating due to wave action, and entrapment within coastal features (e.g., estuaries, mangroves, and tidal zones). By resolving these processes, the module enables a high-resolution representation of plastic waste transport, retention, and redistribution in coastal regions, which are critical zones for accumulation and ecological impact.

3.1.5. PlastDrift module

The PlastiDrift module is not a standalone module; it is a specialized version of OpenDrift designed for plastic waste simulation. In this research, PlastDrift serves as the integrative core of the modeling system, synthesizing input parameters from four specialized submodules to generate scenario-specific outputs based on seeded data. Within the designated study area, plastic waste originating from riverine sources is introduced into the model and subsequently advected through the marine environment under the combined influence of ocean currents, wind forcing, wave dynamics, and vertical mixing processes. The module dynamically tracks the trajectory and transformation of plastic particles, enabling comprehensive simulations of their transport pathways. In addition, the coastal interaction module was employed to resolve shoreline-related processes, including accumulation, retention, and redistribution of plastic debris. This integrated approach facilitated a detailed understanding of plastic waste behavior across both open ocean and coastal zones, supporting assessments of environmental impact and mitigation strategies.

3.2. Environmental scenarios and their influence on plastic waste dispersion

Variations in environmental conditions – particularly wave and wind regimes – play a pivotal role in shaping the transport trajectories and dispersion patterns of plastic debris in the marine environment. These dynamic forces not only influence the movement of particles but also contribute to the formation of new accumulation zones or the redistribution of existing hotspots.[44,45]

In the coastal region of Thanh Hoa, a long-term climatological analysis spanning 30 years (1992 – 2022) reveals that both wave and wind regimes exhibit bidirectional characteristics. Specifically, the wave regime is dominated by northeast and southeast directions, with average significant wave heights ranging from 0.7 to 1.2 m (Figure 3). Similarly, the wind regime shows two principal directions – northeast and southeast – as illustrated in the wind rose diagram (Figure 4).

Based on these environmental patterns, four representative simulation scenarios were developed to reflect distinct seasonal and transitional phases. Each scenario integrates key environmental drivers – such as wind direction, river discharge, and temperature – to evaluate their combined influence on plastic waste behavior and distribution.

To comprehensively assess seasonal variability, the scenarios are defined as follows: (i) Scenario 1 represents winter conditions, dominated by the northeast monsoon. This period is characterized by lower temperatures and reduced river discharge, which affect the vertical movement and localized accumulation of plastic debris. The simulation spanned from January 1 to January 31, 2021; (ii) Scenario 2 captures the transitional phase from winter to summer, marked by a gradual shift in wind direction and increasing river flow. Simulations were conducted for April 2022 and April 2024, each lasting 1 month, to analyze interannual variability and the emergence of new transport pathways; (iii) Scenario 3 simulates summer monsoon conditions, featuring intensified southwest winds, elevated precipitation, and high river discharge. These factors enhance long-distance dispersion and introduce additional plastic waste from land-based sources via surface runoff. The simulation covered July 2021 and July 2024; (iv) Scenario 4 reflects the transition from summer to winter, characterized by declining river discharge and shifting wind regimes. Conducted in September 2021, this scenario provides insights into redistribution mechanisms and the formation of new hotspots during seasonal change.

Collectively, these scenarios offer a comprehensive framework for understanding the spatiotemporal dynamics of plastic waste in response to monsoonal variability and coastal hydrodynamics.

3.3. Data sources

3.3.1. Wave, wind, and ocean current data

To evaluate the dispersion of marine litter in the coastal waters of Thanh Hoa, this study employed a combination of statistical analysis and numerical modeling. Specifically, long-term wave and wind regime data were analyzed to define computational scenarios and to construct the corresponding input datasets for the simulation model.

Central to the modeling framework is the integration of high-resolution oceanographic data. Ocean current velocity, temperature, and salinity are derived from the Regional Ocean Modeling System (ROMS) and satellite-based observations. The data sources include: (i) ROMS: A widely recognized and rigorously validated ocean modeling system that synthesizes multiple oceanographic datasets to produce high-resolution simulations of ocean dynamics; and (ii) satellite-derived data: Remote sensing products from the National Oceanic and Atmospheric Administration and Moderate Resolution Imaging Spectroradiometer were utilized to calculate temperature and salinity parameters within the study area (project code: ĐTDL.CN.55/20).

By combining these datasets with long-term wave, wind, and ocean current records specific to the Thanh Hoa coastal region, a comprehensive set of input conditions was constructed. These inputs correspond to four distinct seasonal and transitional scenarios, as detailed in Table 1, and serve as the foundation for

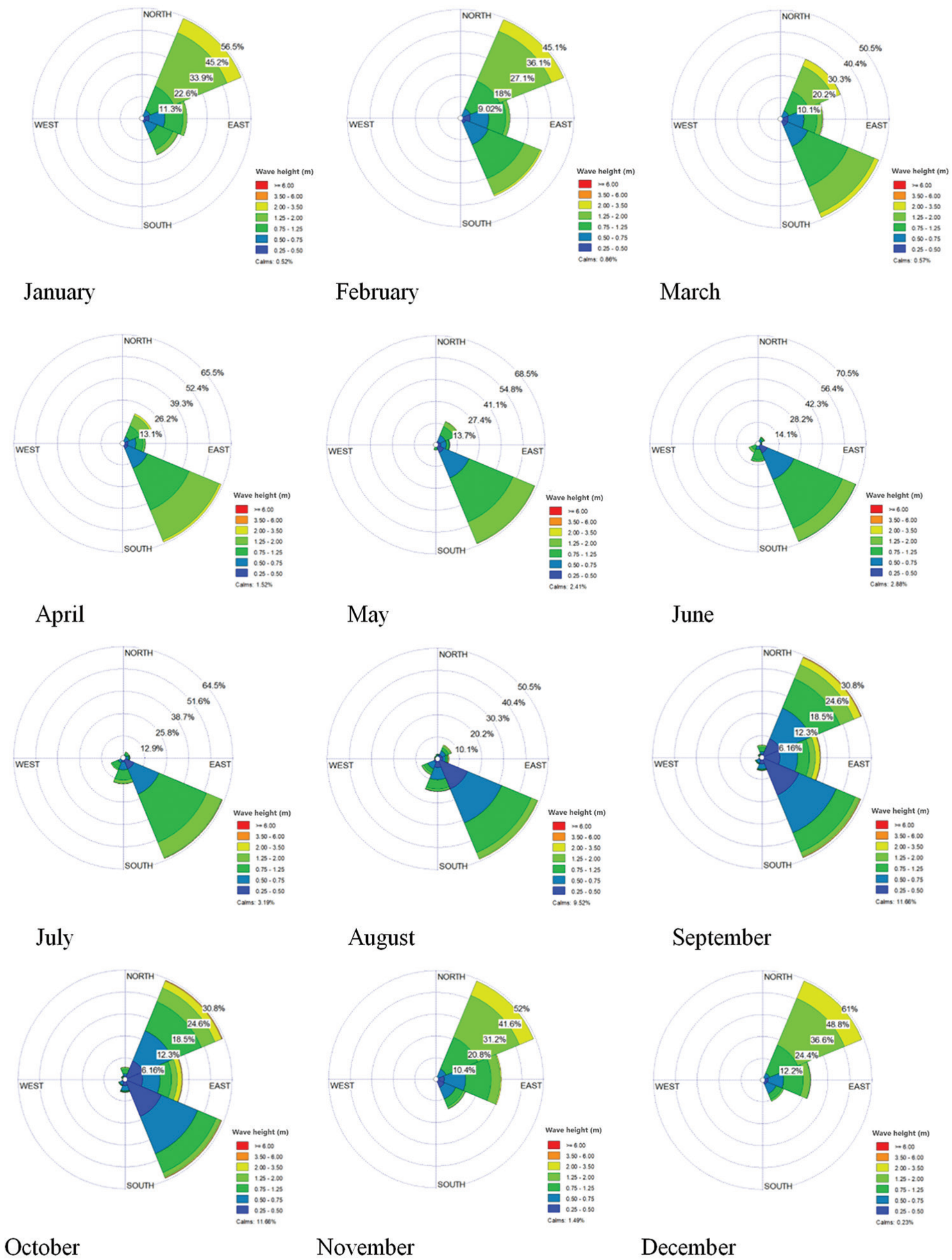


Figure 3. Twelve-month wave pattern characteristics in the coastal area of Thanh Hoa

simulating plastic waste transport and accumulation under varying environmental conditions.

3.3.2. Plastic waste data

To establish accurate initial conditions for the simulation model, observational data on plastic waste were systematically collected from three major rivers in the study area: the Ma, Lạch Bạng, and Lèn Rivers. Sampling campaigns were conducted over two distinct periods – from June 2021 to May 2022, and from July to September 2024 – to capture both seasonal and interannual variability.

The collected data include detailed information on the types, quantities, composition, size, and density of plastic debris present in the river systems. These parameters serve as critical inputs for the model, ensuring that it accurately reflects the diversity and distribution of plastic waste entering the marine environment. A summary of the observed characteristics is presented in Table 2.

3.3.3. River flow data

To accurately model the input and dispersion of plastic waste from riverine sources, daily water flow

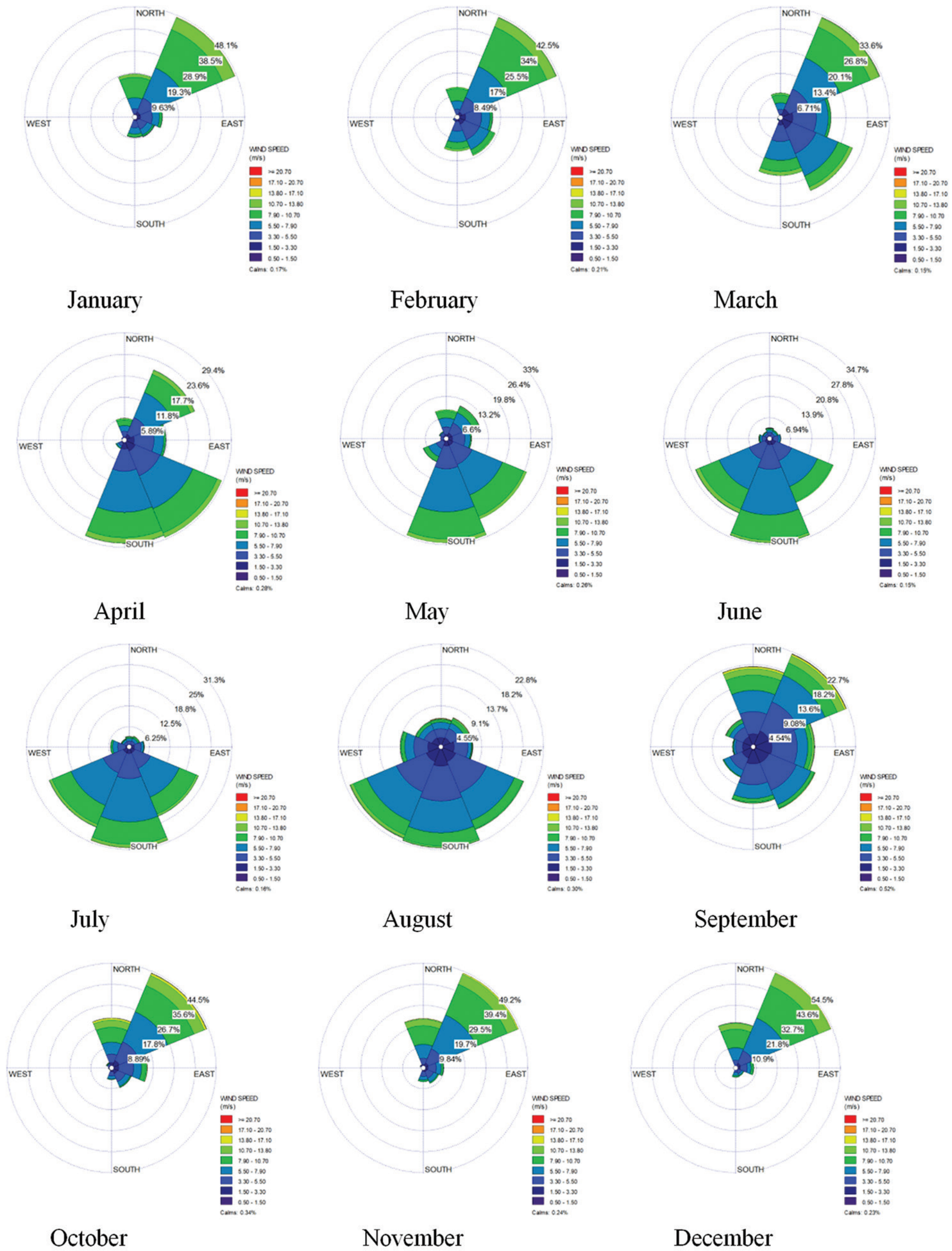


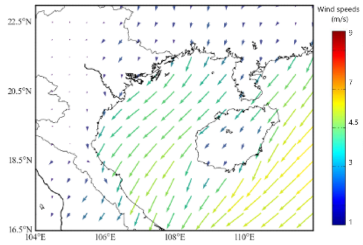
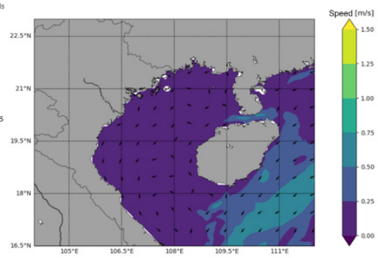
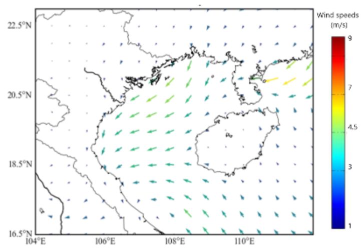
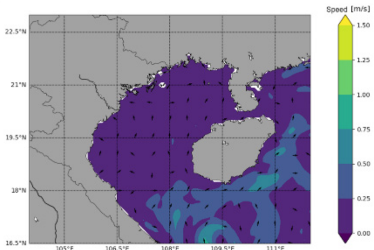
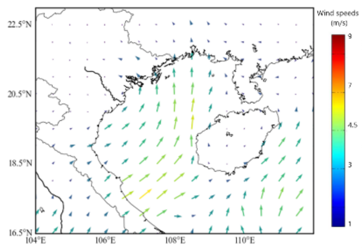
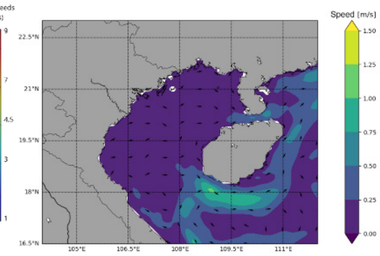
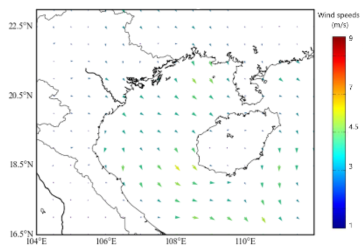
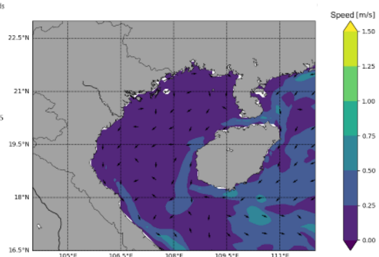
Figure 4. Twelve-month wind rose characteristics of the Thanh Hoa coastal area

measurements were collected over a 1-year period from the Ma, Lạch Bạng, and Lèn Rivers. These measurements provide essential hydrological data for quantifying the transport potential of plastic debris from inland waterways to the coastal marine environment. In particular, daily average flow data corresponding to four representative months – April, July, September, and December – were obtained from the General Department of Hydrometeorology. These months align with the seasonal scenarios defined in the study and reflect key phases in monsoonal transitions and hydrological variability. By integrating this flow data into the simulation model, the study ensured a realistic representation of plastic waste input dynamics and dispersion behavior across different seasonal conditions. The spatial and temporal distribution of riverine plastic input is illustrated in Figure 5, highlighting its role in shaping coastal accumulation patterns.

3.4. Simulation setup and analysis

To simulate the horizontal dispersion of plastic waste, this study incorporated two key physical drivers: ocean currents and wind forcing. Wind influence is typically parameterized as a fraction (1 – 6%) of the

Table 1. Typical wave, wind, and ocean current conditions in the four scenarios

Scenario no.	Wave data		Wind data	Ocean currents
	Average altitude (m)	Main direction		
1	1.2	NE		
2	1.02	SE		
3	0.87	SE		
4	0.78	NE		

Abbreviations: NE: Northeast; SE: Southeast.

wind velocity measured at 10 m above sea level. For floating particles, a coefficient of 2 – 3% is commonly applied. In the Thanh Hoa coastal area, a coefficient of 2% was determined to be optimal based on comparisons between modeled trajectories and field observations.

The simulation setup involved a structured initialization phase to ensure a realistic representation of plastic waste input from the three major rivers: Ma, Lạch Bạng, and Lèn. Initial release points were defined at the estuaries – Hoi, Lạch Bạng, and Sùng – to reflect actual discharge locations. Observational data collected during June 2021 – May 2022 and July – September 2024 provided detailed information on plastic types, quantities, sizes, and densities. These data were averaged and used to construct representative input mixtures for the model.

To capture the spatial variability of plastic waste sources, two distribution strategies were applied: (i) Point-source distribution, where particles are released at fixed estuary locations; and (ii) dispersed distribution, simulating broader pollution input by releasing particles across multiple points.

This dual approach enhances the model's ability to reflect both concentrated and diffuse plastic pollution

Table 2. Observational data on the types, quantities, composition, size, and density of plastic waste present in the Ma, Lach Bang, and Len rivers

Waste type	Lach Bang		Len		Ma	
	Quantity (pieces)	Mass (kg)	Quantity (pieces)	Mass (kg)	Quantity (pieces)	Mass (kg)
Plastic bags	186	4.50	588	11.76	1,259	45.79
Strings	45	0.97	118	2.03	387	2.28
Food bags	91	1.23	402	6.72	431	0.74
Single-use plastics	72	0.87	187	0.98	236	0.97
Hard plastics	88	1.84	170	3.84	158	2.59
Styrofoam	132	0.40	185	0.46	506	0.93
Pineapple sacks	16	1.77	26	3.55	114	8.91
Raincoats	11	0.73	12	2.05	65	5.86
Fishing-tackle	41	0.50	133	2.13	353	3.73

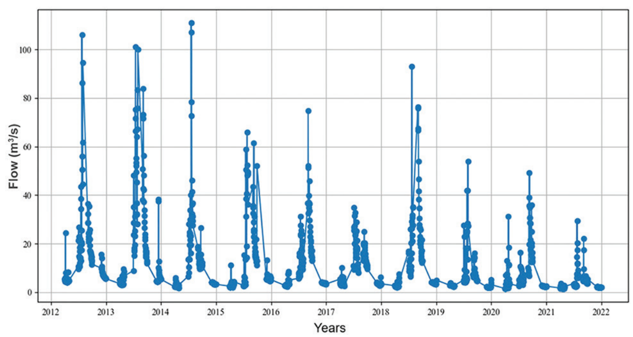


Figure 5. Average river flow in April, July, September, and December for the Ma River at Cam Thuy station

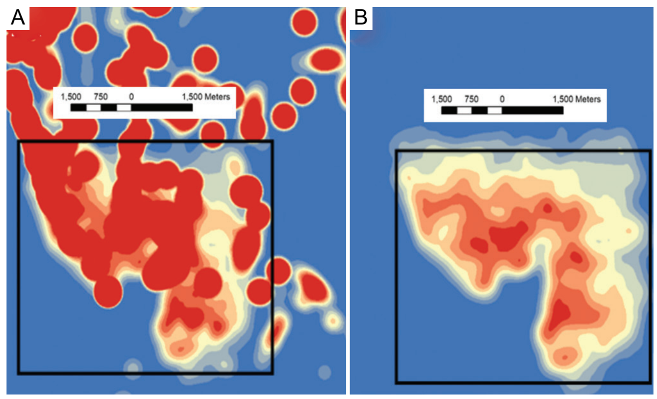


Figure 6. Comparison of marine plastic debris accumulation trends between OpenDrift model results and unmanned aerial vehicle (UAV)-derived observations in the Nghi Son bay area. (A) Simulation results for September 2024 from the OpenDrift model. (B) UAV-derived observations from imagery captured in September 2024.

patterns. Combined with hydrodynamic forcing, the setup enables accurate simulation of plastic waste trajectories and accumulation zones in the OpenDrift framework.

4. Results and discussion

4.1. Model simulation and accuracy assessment

In this study, simulation results from the OpenDrift model, run from June 2024 and forecasted through September 2024, were compared with plastic debris detection data extracted from unmanned aerial vehicle (UAV) imagery captured in late September 2024 (project code: ĐTĐL.CN.55/20). The comparison is illustrated in Figure 6, where Figure 6A shows the simulated plastic debris density under the September 2024 scenario, and Figure 6B presents plastic debris density derived from UAV-based calculations. These datasets were overlaid to evaluate the accuracy of the model in capturing plastic waste dispersion and accumulation patterns.

The results indicate that the modeled trend of plastic accumulation aligns reasonably well with observations from remote sensing data. The general pattern shows higher concentrations of plastic debris in enclosed coastal areas, gradually decreasing toward offshore regions. This suggests that the OpenDrift model provides a reasonably accurate simulation of the transport, dispersion, and accumulation of plastic debris in the Thanh Hoa marine area.

Based on these simulation results, the model was subsequently applied to the remaining scenarios to develop risk zoning maps for plastic debris accumulation.

4.2. Simulation results according to scenarios

Simulation results of plastic waste movement and accumulation in the Thanh Hoa sea area under four established scenarios are shown in Figure 7.

In Scenario 1 (winter), Figure 7A illustrates that during this season, characterized by the Northeast monsoon and lower river discharge, the simulated trajectory and dispersion of plastic waste mainly follow a coastal path from Nga Son district down to Nghi Son town, moving in a southerly and southwesterly direction. The dominant wind pattern, along with waves and ocean currents, plays a crucial role in shaping the movement of plastic waste, leading to the formation of localized accumulation areas. A notable finding is the tendency for plastic waste to concentrate in coastal communes such as Hai An, Truc Lam, and Truong Lam in Nghi Son town. In these areas, debris tends to drift ashore, leading to the highest particle density, especially in locations affected by eddies or intertwined currents, such as Truc Lam commune. These accumulation zones exhibit elevated concentrations of plastic particles, posing risks to sensitive marine habitats and adjacent coastal communities. The simulations also highlight the potential for long-distance transport of plastic waste

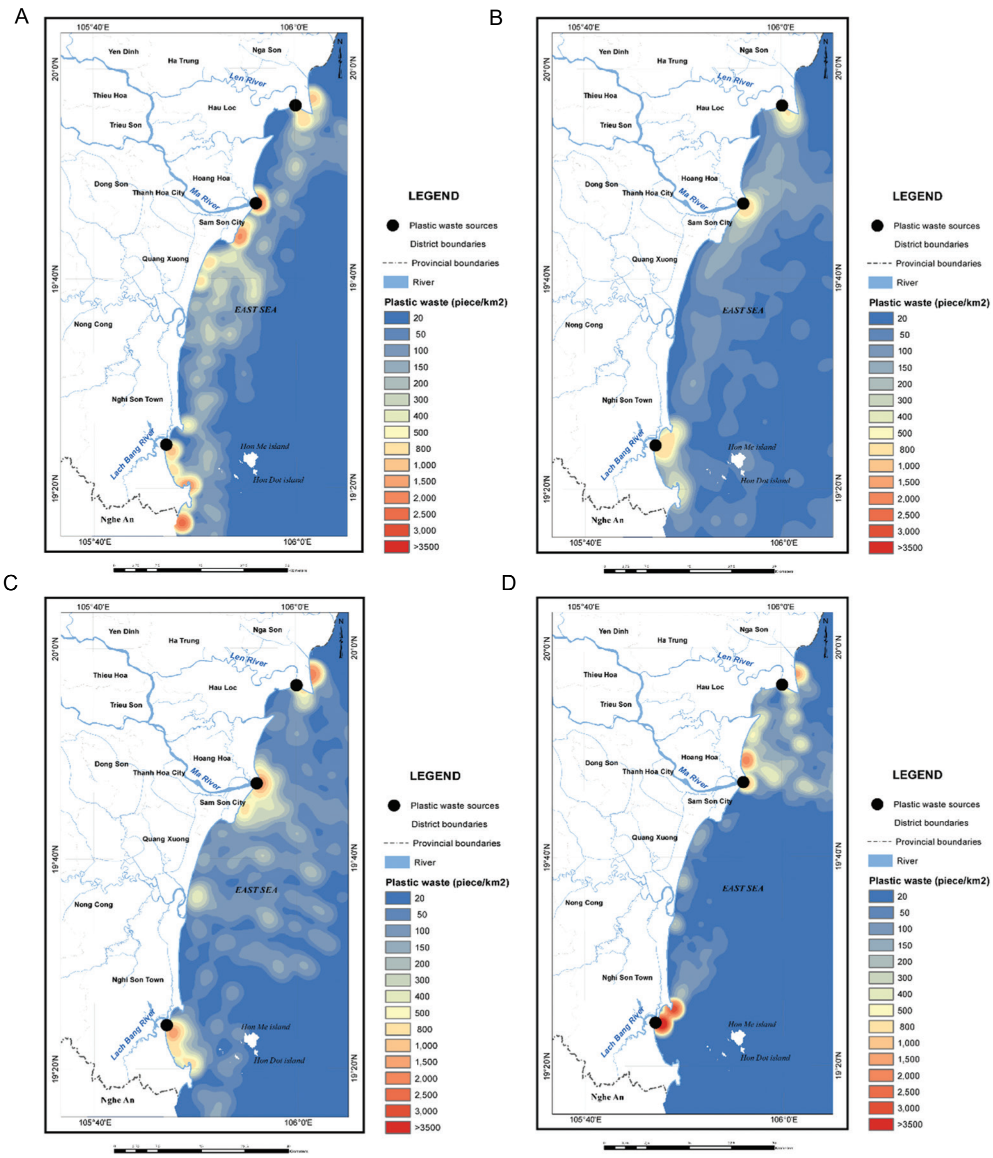


Figure 7. Simulation results of plastic waste dispersion and accumulation in the Thanh Hoa sea across four seasons, corresponding to four scenarios: (A) Northeast monsoon (January); (B) Transition from northeast to southwest monsoon (April–May); (C) Southwest monsoon (July); (D) Transition from southwest to northeast monsoon (September)

during winter. While some particles remain confined to coastal regions, others are carried by ocean currents and wind-driven processes, potentially reaching distant regions or becoming trapped in offshore eddies and gyres. Furthermore, the analysis suggests that cooler temperatures and lower river flows during winter may alter the physical behavior of plastic debris. Decreased buoyancy or increased density due to temperature changes could cause some plastics to sink, thereby modifying their trajectories and dispersion patterns.

In Scenario 2 (winter-to-summer transition: April – May), the shift from the Northeast to the Southwest monsoon is marked by dynamic environmental changes that significantly affect plastic waste dispersion. As the influence of the Northeast monsoon weakens and the Southwest monsoon begins to take effect, the simulations capture interactions among wind and wave patterns, ocean currents, and increasing river discharge. During this transitional phase, simulations indicate a potential redistribution of existing waste accumulation areas (hotspots). Waste becomes more widely dispersed, with no distinct formation of new hotspots. Plastic debris continues to drift ashore along the coastline from Nga Son district to Nghi Son town (Figure 7B). Previously confined waste may be transported to new areas due to changes in environmental conditions.

In Scenario 3 (summer: July), characterized by the Southwest monsoon and increased river discharge rates due to monsoon rains, distinct patterns emerge in plastic waste transport and dispersion. The simulations captured the combined impact of heavy rainfall, strong river flows, and distinct wind and wave patterns. As shown in Figure 7C, summer is marked by the widespread dispersion of plastic waste across both coastal and offshore areas, resulting in large accumulation zones and hotspots. These concentrations are particularly evident in regions influenced by converging currents, eddies, or coastal topography. Furthermore, the simulations highlight the potential for long-distance transport of plastic debris during this period. The interaction of strong monsoon winds, ocean currents, and high river flows facilitates the movement of plastic fragments over considerable distances.

In Scenario 4, which represents the transition period from the southwest monsoon to the northeast monsoon (September), the shift from summer to winter is accompanied by a weakening of the Southwest monsoon and a gradual decline in river discharge, resulting in significant changes in plastic waste movement. Figure 7D shows that, during this transition period, there is potential for the redistribution of existing accumulation areas and the formation of new hotspots. Plastic waste that had accumulated in certain coastal areas during the summer may be dispersed or transported to other regions due to changing environmental conditions. In general, plastic waste during this period tends to move both toward the coast and the open sea, with particle densities concentrated in the districts of Nga Son, Hoang Hoa, Sam Son, and Quang Xuong, as well as Nghi Son town. In contrast, the coast of Hau Loc district appears to be less affected.

5. Conclusion

While the OpenDrift model has been utilized in various marine pollution studies globally, this research represents its first comprehensive application specifically tailored to simulate plastic waste transport and accumulation from major river systems (Ma, Yen, and Len Rivers) to the coastal and marine environment of Thanh Hoa province, Vietnam. This regional focus provides critical insights into local pollution dynamics that were previously unquantified.

The study developed simulations for four distinct seasonal scenarios (winter, two transitional periods, and summer) based on 30 years (1992 – 2022) of wave and wind data specific to Thanh Hoa. This multi-seasonal approach, encompassing varying wind patterns, wave regimes, and river discharges, offers a nuanced understanding of how dynamic environmental conditions influence plastic waste trajectories, dispersion, and hotspot formation throughout the year. The study makes important contributions by identifying hotspots and high-risk areas for plastic waste accumulation, specifically in Thanh Hoa's coastal waters, and more broadly for similar other coastal regions in Vietnam. These findings will substantially support efforts to monitor and manage marine plastic waste and contribute to the improvement of marine environmental quality.

Due to data constraints, particularly the limited availability of observed data on the real-world drift processes of plastics from rivers to the sea, it was not possible to fully evaluate the model's accuracy in predicting or forecasting plastic waste movement.

While this study focused on Thanh Hoa province, the findings and methodology can be extended to other regions affected by plastic pollution. The integration of modeling tools such as OpenDrift with environmental datasets and field observations provides a robust framework for assessing and predicting the trajectory of plastic waste in complex marine systems. To enhance the accuracy of forecasting plastic waste movement, dispersion, and accumulation, further in-depth research is needed, particularly through the use of satellite-based positioning systems attached to plastic objects of varying sizes to track their actual drift processes. Such data would allow for more precise model calibration.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Availability of data

There are only some non-restricted data can be shared upon reasonable request to corresponding author.

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