



## ARTICLE

## Application of Digital Technologies in Plastic Waste Research in the Con Co Island Area (Vietnam)

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## ABSTRACT

Small island environments are highly vulnerable to plastic and microplastic pollution due to constant exposure to ocean debris and limited waste management. Con Co Island in the Gulf of Tonkin is a prime example. Despite its rich marine ecosystem, the island faces severe environmental stress from household activities, commercial fishing, shipping, and tourism. To monitor the distribution of plastic waste across ecological zones, this study employed a comprehensive, multi-method approach. The methodology combined drone (UAV) imagery analyzed with the ResUNet50 deep-learning model, SCUBA diver seabed surveys, domestic water testing, and Delft3D-Part numerical simulations. The findings revealed that plastics account for over 90% of coastal solid waste, with an estimated total accumulation of 8,379 t (an average density of 1.4 kg/m). Underwater surveys showed that plastic litter covers between 1.0% and 31.25% of the seabed, primarily concentrated near residential areas and the local harbor. Furthermore, microplastics were detected in every single domestic water sample tested, with concentrations ranging from 0.34 to 2.75 ng/L. Simulation data also indicated distinct

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seasonal variations in microplastic dispersion, heavily driven by local currents, monsoons, and eddy formations. Unlike previous studies that relied on single-method assessments, this integrated approach merges surface, benthic, water, and hydrodynamic data to offer a unified perspective. These insights provide a robust scientific foundation for developing better pollution mitigation strategies and managing marine protected areas in small island settings.

**Keywords:** Plastic Pollution; Environment Protection; Maritime Law

## 1. Introduction

Tiny island territories face immense risks from plastic debris owing to constrained size, inadequate trash disposal infrastructure, heavy reliance on ocean goods, and relentless bombardment by current-driven refuse. Both macroplastics and microplastics jeopardize aquatic habitats, travel industries, fishing operations, drinking water, and residential incomes. Typically categorized as fragments under 5 mm, microplastics trigger major alarm due to their enduring nature, ease of travel, and infiltration into drinking supplies and biological chains <sup>[1]</sup>. Contemporary investigations confirm that water dynamics heavily dictate microplastic movement, and heavier polymers frequently settle on the ocean floor amid complicated aquatic flows <sup>[2,3]</sup>.

Situated inside the Gulf of Tonkin, Con Co acts as a vital offshore Vietnamese territory, sheltering rich aquatic biomes like fragile coral networks and coastal nesting grounds. Rising visitor numbers, fishing yields, shipping traffic, and everyday chores spark distinct worries regarding how plastic trash spreads and builds up across adjacent waters. To combat this intensifying contamination, various global and domestic programs currently advocate for greener refuse handling and oceanic safeguarding <sup>[4–6]</sup>. Even so, data detailing plastic dispersion across isolated island contexts is quite sparse, especially lacking holistic works merging visual top-layer tracking, underwater floor checks, tap water testing, and computer modeling. Consequently, an extensive contamination evaluation encompassing Con Co is strictly required to aid ecological supervision and preservation tactics.

Through a research lens, scholars have created diverse analytical techniques to scrutinize plastic degradation within ocean settings. Computational fore-

casting frequently serves to replicate how tiny plastics travel amid fluctuating water dynamics. McCormack et al. <sup>[7]</sup> validated the Delft3D particulate framework via direct outdoor measurements, whereas Faruk et al. <sup>[8]</sup> utilized the MIKE 21 system to track synthetic flow throughout river networks. Troost et al. <sup>[1]</sup> investigated biological consequences via the DELFT3D-GEM architecture. Alongside mathematical models, distance-based scanning and drone instrumentation are progressively employed to chart garbage. Aerial drone surveillance reliably pinpoints shoreline refuse across varying geographic scopes <sup>[9]</sup>, while merging flying sensors with submerged vehicles significantly boosts discovery rates and financial viability within shallower maritime zones <sup>[10]</sup>.

Within Vietnam, scientific inquiries tackling plastic and microplastic contamination are somewhat scarce, heavily leaning toward isolated ecological zones or singular procedural strategies. Past literature effectively harnessed Delft3D-PART for mimicking micro-synthetic drift across river mouths alongside ocean borders <sup>[11,12]</sup>. Nevertheless, those endeavors leaned heavily on virtual computer frameworks rather than integrating concurrent physical checks detailing synthetic buildup across beaches, oceanic bottoms, and local household plumbing infrastructures. By the same token, drone-centric literature validates how well distant scanning mechanisms spot beachside trash <sup>[13]</sup>, yet such tools primarily observe upper layers, completely failing to outline deeper subsurface gathering patterns. Consequently, the dynamic relationship linking top-water drifting, bottom sediment settling, alongside distinct human health risks remains poorly understood, especially regarding diminutive island ecosystems.

Such shortcomings emphasize a crucial investigative void regarding exactly how synthetic refuse

originates, travels, pools, and shifts throughout diverse ecological spheres, most notably around smaller island regions. The exact interplay linking top-level gathering, seafloor settling, and water-driven movement functions remains poorly mapped out today. Meanwhile, the infiltration of microplastics into household plumbing continues to see minimal focus, disregarding its immediate connection to biological human consumption. Consequently, erecting a unified methodology that heavily blends geographic charting, active field inspections, clinical lab testing, alongside advanced mathematical simulations is absolutely vital to properly grasp these highly complicated ecological events.

Bridging these informational deficits clearly demands blending cooperative measurement and computational strategies equipped to track synthetic pollution traversing distinct ecological domains. Merging drone photography with the ResUNet50 artificial intelligence framework yields a potent instrument to pinpoint and chart synthetic trash spanning vast shorelines. Furthermore, underwater SCUBA inspections facilitate

firsthand monitoring of polymer buildup across ocean floors alongside coral structures, which airborne cameras simply miss. Alongside this, the Delft3D-Part application permits users to replicate microplastic travel and scattering amidst shifting water currents and seasonal weather patterns, just as tap water examinations yield crucial insights regarding imminent human ingestion risks. Ultimately, merging these specific tactics yields an exhaustive blueprint for probing synthetic contamination across compact island habitats, thereby supplying empirical foundations to guide ecological oversight and remedial actions inside safeguarded oceanic territories.

## 2. Materials and Methods

### 2.1. Data

#### 2.1.1. Survey Locations

The survey sites for assessing plastic waste pollution on Con Co Island are illustrated in **Figure 1**, **Tables 1** and **2**.

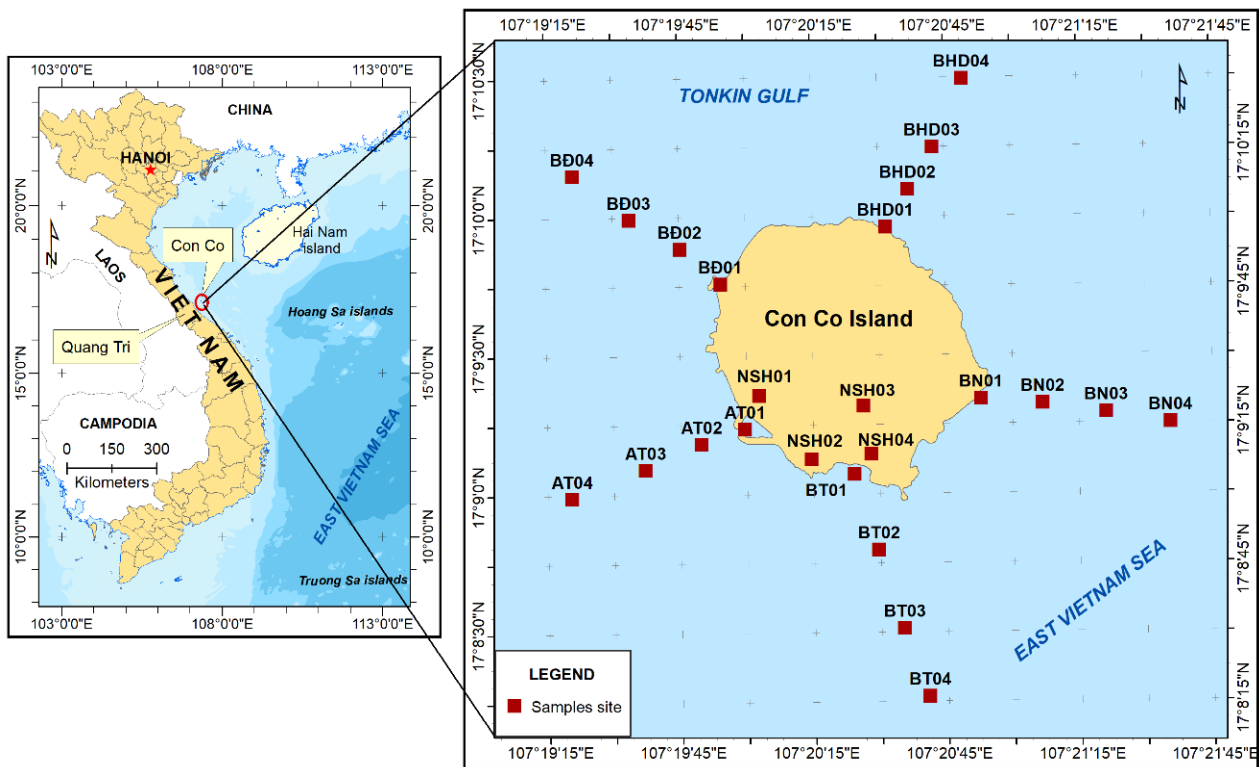


**Figure 1.** Schematic map showing the survey transects and sampling locations for plastic waste assessment in the Con Co Island area.

**Table 1.** Geographic locations of transects and sampling points used for the collection and assessment of plastic and micro-plastic waste in the Con Co Island study area.

| Line | Survey Locations | Coordinate       |                  | Time of Survey |           | Note                                                                                       |
|------|------------------|------------------|------------------|----------------|-----------|--------------------------------------------------------------------------------------------|
|      |                  | Latitude (North) | Longitude (East) | Nov. 2023      | Apr. 2024 |                                                                                            |
| 1    | AT01             | 17° 9'14.03"     | 107°19'59.64"    | +              | +         | 04 points on the survey cross-section, sampling in the coastal area of the roadstead.      |
|      | AT02             | 17° 9'9.27"      | 107°19'48.60"    | +              |           |                                                                                            |
|      | AT03             | 17° 9'4.91"      | 107°19'36.47"    | +              |           |                                                                                            |
|      | AT04             | 17° 9'0.14"      | 107°19'22.92"    | +              |           |                                                                                            |
| 2    | BT01             | 17° 9'1.17"      | 107°20'24.83"    | +              | +         | 04 points on the survey cross-section, sampling in the coastal area of the Ben Tranh area. |
|      | BT02             | 17° 8'47.64"     | 107°20'29.44"    | +              |           |                                                                                            |
|      | BT03             | 17° 8'34.42"     | 107°20'34.61"    | +              |           |                                                                                            |
|      | BT04             | 17° 8'20.99"     | 107°20'41.00"    | +              |           |                                                                                            |
| 3    | BN01             | 17° 9'19.22"     | 107°20'56.78"    | +              | +         | 04 points on the survey cross-section, sampling in the coastal area of Ben Nghe.           |
|      | BN02             | 17° 9'17.11"     | 107°21'10.10"    | +              |           |                                                                                            |
|      | BN03             | 17° 9'15.04"     | 107°21'24.94"    | +              |           |                                                                                            |
|      | BN04             | 17° 9'12.62"     | 107°21'39.09"    | +              |           |                                                                                            |
| 4    | BHD01            | 17° 9'58.24"     | 107°20'36.19"    | +              | +         | 04 points on the survey cross-section, sampling in the coastal area of Ben Ha Dong.        |
|      | BHD02            | 17°10'7.23"      | 107°20'44.35"    | +              | +         |                                                                                            |
|      | BHD03            | 17°10'15.32"     | 107°20'52.55"    | +              | +         |                                                                                            |
|      | BHD04            | 17°10'23.36"     | 107°21'0.84"     | +              | +         |                                                                                            |
| 5    | BDD01            | 17° 9'46.73"     | 107°19'49.61"    | +              | +         | 04 points on the survey cross-section, sampling in the coastal area of Ben Da Den.         |
|      | BDD02            | 17° 9'53.75"     | 107°19'36.36"    | +              | +         |                                                                                            |
|      | BDD03            | 17°10'1.26"      | 107°19'25.97"    | +              | +         |                                                                                            |
|      | BDD04            | 17°10'9.90"      | 107°19'13.24"    | +              | +         |                                                                                            |

Note: "+" represents that sampling was conducted during the corresponding survey period.

**Table 2.** Locations of domestic water sampling sites on Con Co Island.

| Line | Survey Locations | Coordinate       |                  | Time of Survey |           | Note                                                                  |
|------|------------------|------------------|------------------|----------------|-----------|-----------------------------------------------------------------------|
|      |                  | Latitude (North) | Longitude (East) | Nov. 2023      | Apr. 2024 |                                                                       |
| 1    | NSH01            | 17° 9'18.99"     | 107°20'2.40"     | +              | +         | 04 survey points, collecting domestic water samples on Con Co Island. |
|      | NSH02            | 17° 9'8.58"      | 107°20'14.95"    | +              | +         |                                                                       |
|      | NSH03            | 17° 9'16.61"     | 107°20'28.06"    | +              | +         |                                                                       |
|      | NSH04            | 17° 9'8.87"      | 107°20'26.77"    | +              | +         |                                                                       |

Note: "+" represents that sampling was conducted during the corresponding survey period.

### 2.1.2. Topographical Data of the Coastal Area of Con Co Island

The bathymetric and shoreline data for the coastal waters of Con Co Island were extracted from UTM topographic maps in the VN-2000 geographic coordinate system, with scales of 1:50,000 and 1:25,000, published by the Department of Surveying and Mapping, Ministry of Natural Resources and Environment. These data were digitized and subsequently updated using the most recent bathymetric surveys. All topographic information was transformed into the VN-2000 coordinate framework.

For the surrounding regions, including the Gulf of Tonkin, supplementary bathymetric and topographic information was obtained from global datasets. Specifically, the GEBCO 1/8° database, managed by the British Oceanographic Data Centre, and the 5-minute grid

ETOPO5 repository from the National Geophysical Data Center were utilized. The latter provides a 0.5-minute topographic dataset synthesized by merging high-resolution satellite imagery with localized, in situ bathymetric measurements obtained from previous surveys<sup>[14]</sup>.

### 2.1.3. Tides in the Coastal Area of Con Co

Water level oscillation data were integrated to refine simulation parameters and define inputs at the hydrodynamic model's open seaward frontiers. We utilized tide level shifts recorded at Con Co station to calibrate the model effectively. These specific empirical readings originated from the Con Co Meteorological Station at six-hour windows throughout 2023.

Tidal states at the outer oceanic borders were mapped using harmonic constants synthesized from extended water depth logs gathered via various initiatives spearheaded by the Center for Marine Hydromete-

orology, the Institute of Marine Mechanics, the Institute of Marine Resources and Environment, the Institute of Geography, alongside several other affiliated organizations. This approach ensures high precision for the model's overall hydrodynamic projections. The offshore boundary conditions of the hydrodynamic model were defined using 13 tidal constituents-M2, S2, N2, K2, K1, O1, P1, Q1, Mf, Mm, M4, MS4, and MN4-extracted from the TPXO-8 global tidal model with a spatial resolution of  $0.25^\circ \times 0.25^\circ$  [15].

Additionally, data archives captured through surveillance initiatives directed by entities like the Center for Marine Hydrometeorology and the Institute of Marine Resources and Environment were utilized to sharpen the characterization of open boundary parameters within the immediate nearshore coastal sectors.

#### 2.1.4. Wind Data in the Coastal Area of Con Co

Wind dynamics act as a pivotal driver of hydrodynamic behavior, specifically governing the seasonal fluctuations of the coastal regime adjacent to Con Co Island. In this research, we scrutinized prolonged wind archives from the Con Co station, gathered by the National Center for Hydrometeorology in six-hour windows. Supplemental observational readings captured at identical intervals spanning January–December 2023 were likewise integrated into the computational framework.

Furthermore, meteorological indices comprising wind velocity, barometric pressure, surface temperature, solar radiance, and cloud density throughout 2023 were acquired via the National Centers for Environmental Prediction (NCEP). These arrays feature a horizontal resolution of  $0.2^\circ \times 0.2^\circ$ , supplying essential atmospheric forcing fields required for our high-precision model simulations.

#### 2.1.5. Thermo-Salinity Data

Seawater temperature and salinity logs regarding the Con Co coastal zone originated from direct monitoring executed at the Con Co meteorological station, alongside specific measurements gathered during the project “Survey and Assessment of Microplastic Content and Their Influencing Factors in the Con Co Island Ma-

rine Reserve.” Further details concerning thermal and saline levels were acquired via the Copernicus Marine Environment Monitoring Service (CMEMS) utilizing the Global Ocean Physical Analysis and Forecast system covering 2023. This repository synthesizes computational modeling, empirical records, and orbital imagery, distributed across a uniform grid featuring a horizontal resolution of  $1/12^\circ$  (roughly 8 km) [16].

#### 2.1.6. Microplastic Density Data Measured in Coastal Areas

Microplastic concentration logs were aggregated from various initiatives previously executed throughout the targeted region. Furthermore, outcomes from specialized field assessments performed during November 2023 and April 2024 were integrated into the primary database. These inventories supplied granular microplastic density metrics, which were unified alongside historical project findings to define the essential baseline parameters required for model initialization and subsequent validation.

### 2.2. Application of Low-Altitude Unmanned Aerial Vehicles (UAVs) Method

Drones were flown to evaluate plastic pollution around the Con Co Marine Protected Area and nearby waters in Vietnam. The captured pictures were stitched into wide orthophotos spanning 20 to 30 ha, which algorithms then scanned to map trash spread across beaches and the sea. To automate tracking, researchers applied machine learning to the aerial captures. Because the photos featured extreme detail ( $3 \text{ cm}^2/\text{pixel}$ ), the ResUNet50 segmentation model accurately spotted synthetic debris across deep water, shallow coasts, and dry land. The approach even separated the region's waste into three distinct polymer groups (Nylon, PET, OPS), taking advantage of the network's sensitivity to subtle reflection differences.

Regarding flight procedures, drones operated at 150 m, securing a clarity of  $3 \text{ cm}^2$  per pixel. The study layout involved five coastal paths radiating from Con Co Island. Each path contained four checking stations separated by 500 m, alongside extra beach passes. The November 2023 trip yielded 1,200 shots, whereas the

April 2024 return brought back 1,625 pictures. These standalone frames were merged into 20 to 30-hectare maps. Because crews didn't log a strict overlap rate on-site, they verified adequate blending later. They confirmed this during software processing by evaluating point density, model stability, geometric accuracy, and seamless borders before authorizing the layouts for debris mapping.

To categorize the visuals, the team ran a ResUNet50 segmentation system paired with a ResNet50 encoder. The labeled information featured five types of litter spotted on the ground: first, rigid plastics like toys, shoes, nets, bags, and bottles; second, buoyant foam pieces; third, natural wood scraps such as logs and twigs; fourth, dumped clothes or textiles; and fifth, glass containers. In total, researchers prepared 2,825 marked pictures. They broke this collection down using a structured 80-to-20 ratio, which dedicated exactly 2,260 photos to teaching the computer model and kept the remaining 565 files to verify its accuracy.

To judge how well the system worked, researchers matched the computer's guesses against human-labeled examples using the Intersection over Union standard, alongside distinct checks for recall and precision. When looking at synthetic trash bigger than 3 cm<sup>2</sup>, the program scored above 85% in overall correctness. Most errors happened because of intense sunlight reflections, crashing waves, wet logs, or pale natural items that looked virtually identical to rigid plastics or foam on camera. The crew double-checked these confusing spots using their field notes before finalizing the charts.

Picture collection occurred under highly realistic

island weather conditions. The November 2023 time-frame fell during the northeast monsoon, bringing harsh winds, turbulent waters, and very little tourist or fishing traffic. Alternatively, the April 2024 window was a seasonal shift featuring rain, thunderstorms, and notable breezes, though many more boats were working around the island's northern edges. Factors like bright sun glare, crashing surf, and sea foam caused the biggest headaches for spotting waterborne plastics, while trash stuck on the beach remained much clearer. Because these environmental quirks make it tough to tell foam apart from pale wood or breaking waves, the team manually reviewed questionable spots before finishing.

### 2.3. SCUBA-Based Seabed Survey Method

To assess the ocean floor, researchers utilized a specialized underwater transect technique. Within every monitoring location, the team set up a pair of transects at varying depths, ensuring the extremities of both lines were distinctly indicated and assessed separately. A duo of scuba divers rolled out parallel 100-meter-long ropes, following the natural bathymetric curves at specific underwater levels. After deploying these measurement guides, the team rigorously inspected and fastened them against the ocean bottom so they would not drift away or rise upward. For precise location tracking, surface floats were tied to the extremities of every underwater rope, functioning as visible indicators for the submerged setups (**Figure 2**).

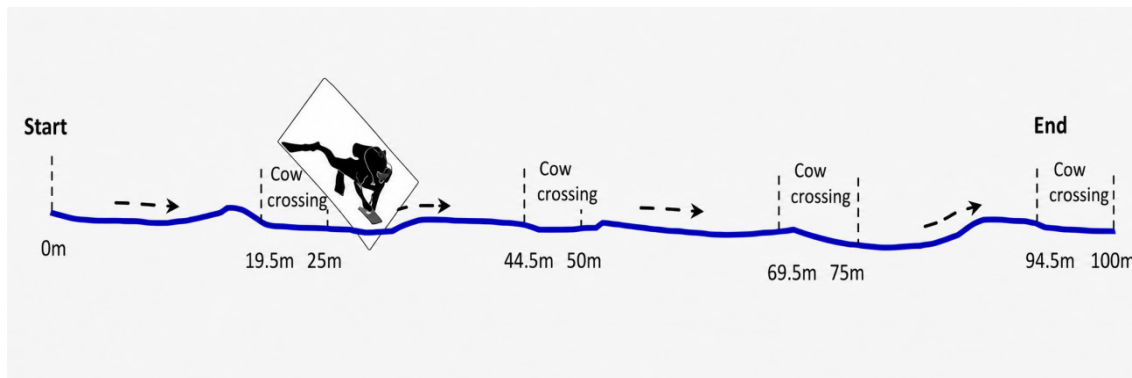


**Figure 2.** Schematic diagram of plastic pollution data recording along seabed transects lines <sup>[17]</sup>.

Large synthetic litter on the ocean floor was examined via SCUBA methods, aided by submerged camera and videography equipment. The team executed a pair of field expeditions during November 2023 and April 2024. During every expedition, researchers mapped out five distinct survey paths and explored four specific underwater stops per path to record the spread of large plastic waste. Qualified divers approximated the volume of this plastic garbage through firsthand visual evaluations while swimming underwater.

## 2.4. Method for Analyzing Microplastics in Domestic Water to Quantify Density and Extent of Impact

Examining tiny plastic fragments in household water involved a highly comprehensive laboratory sequence aimed at securing accurate samples and maximizing particle retrieval. The initial phase required finding the best liquid quantity to test, since pollution concentrations and floating debris differed widely across various collection areas. Researchers shunned extremely low quantities to preserve overall accuracy, whereas excessively massive amounts might damage filtration screens during handling. To pinpoint the perfect testing quantity, scientists utilized a scaling technique where varying trial portions (10, 20, 50, 100, 150, and 200 mL) underwent filtration. Researchers then evaluated the affected screen textures by eye to determine the absolute best liquid amount for every single specific environmental monitoring location.

To eliminate biological and natural materials that might disrupt polymer detection, the team treated specimens with a chemical breakdown utilizing 30% hydrogen peroxide ( $H_2O_2$ ). After this breakdown, the synthetic fragments were isolated via a buoyancy technique employing a newly mixed saturated sodium chloride (NaCl) fluid<sup>[17]</sup>. Before application, this mixture passed through glass-fiber screens featuring a 0.7  $\mu m$  microscopic opening to reduce baseline impurities. Afterward, the processed liquids went into glass containers, were covered firmly with aluminum wrap, and sat completely still for 2–4 h. This wait allowed gravity-driven settling alongside layer division, where heavier debris sank downward while buoyant microplastics

lingered near the topmost layer.

Researchers next meticulously extracted the buoyant layer holding potential plastic particles utilizing a glass dropper equipped with a rubber squeezer. To prevent liquid agitation and keep sunken debris completely intact, they smoothly rested the dropper's tip against the container's interior edge and gradually suctioned liquid directly from the highest level. The team duplicated this retrieval action between three and five occasions, guaranteeing thorough gathering of drifting synthetic pieces for upcoming examination.

## 2.5. Modeling of Microplastic Dispersion Using Delft3D-Part under Hydrodynamic and Monsoonal Forcing

### 2.5.1. Model Selection

The movement, spreading, and flow of tiny plastic debris within water bodies depend heavily on fluid dynamics, which tie directly into ocean current motions. During this research, scientists utilized the Delft3D modeling platform to replicate vital fluid parameters, such as flow, warmth, and saltiness, around the Con Co Island territory. Initially created by Deltares (previously known as the Delft Hydraulics Institute, Netherlands), Delft3D serves as an advanced three-dimensional, process-driven simulation toolkit mapping various shoreline and river mouth interactions. Its compartmentalized framework contains specific modules handling fluid movement (Delft3D-Flow), wave actions (Delft3D-Wave), sediment flow (Delft3D-Sed), water purity (Delft3D-Waq), biological activities (Delft3D-Eco), alongside particulate tracking (Delft3D-Part). This combined architecture proves perfectly appropriate for investigating fluid circulation habits, particle settling and lifting, substance movement, and overall ecological health across nearshore zones<sup>[18]</sup>.

Inside the overarching Delft3D ecosystem, researchers utilize the specific Delft3D-Part package as their primary tool for tracing synthetic fragments, allowing detailed examination of particle drift and scattering throughout both two-dimensional (2D) and three-dimensional (3D) aquatic spaces. This tracking package relies completely on data produced via the flu-

id dynamics simulator (Delft3D-Flow), which similarly functions in 2D or 3D. The system calculates individual fragment pathways across a three-dimensional grid as time progresses, continuously adapting to shifting densities.

The framework heavily relies on predictable interactions while introducing unpredictable fluctuations via the randomized swapping of tracking units during every calculated interval. The underlying logic utilizes a random-walk theory, effectively mapping synthetic travel probabilities with a predetermined quantity of tracked units. This specific technique perfectly accommodates the dynamic mimicking of changing polymer quantities across numerous fluid states typical throughout bays, nearshore, and ocean environments.

Pollution origins might be configured as either constant or sudden releases, detailing distinct attributes like thickness, weight, alongside other crucial structural properties. Moving pathways remain heavily impacted by shifting weather drafts, surface breeze friction, and comparable outside forces. Essential simulated actions involve bottom settling (particles sinking onto the ocean floor), lifting (debris returning into the fluid layers), and gradual degradation. Around any monitored zone, three major forces dictate fragment action: fluid-driven pushing, random scattering, plus ongoing sinking-and-rising cycles.

The settling velocity of individual particles at a given time step is estimated using Stokes' law<sup>[19]</sup>:

$$V_s = \frac{2(\rho_{particle} - \rho_{fluid})}{9\mu} g R^2. \quad (1)$$

In which,  $V_s$  is the settling (dispersion) velocity [m/s];  $\rho_{particle}$  is the particle density [kg/m<sup>3</sup>];  $\rho_{fluid}$  is the water density;  $\mu$  is the kinematic viscosity [kg/(s·m)];  $g$  is the gravitational acceleration [m/s<sup>2</sup>]; and  $R$  is the particle radius [m]. The density of seawater is influenced by surrounding environmental conditions, particularly temperature and salinity.

The equation can also be reformulated to estimate the median grain size ( $D_p = 50$ ) by expressing it in terms of the particle radius squared:

$$V_s = \frac{(\rho_{particle} - \rho_{fluid}) D_p^2}{19\mu}. \quad (2)$$

In which  $D_p$  is the diameter of particles.

### 2.5.2. Hydrodynamic Model Setup

The fluid dynamics simulation mapping the coastal waters of Con Co Island was built utilizing a curved, right-angled grid. This calculation boundary encompasses the ocean spaces circling the territory, stretching roughly 82 km across the northwest-southeast trajectory and 68 km across the northeast-southwest line. This specific boundary represents a total liquid surface area of roughly 5,634 km<sup>2</sup> (ignoring landmass portions). Inside this boundary, the grid is split into 321 × 386 calculation nodes, featuring lateral cell dimensions varying from 12.3 m around coastal sectors to 1,901.5 m across deeper zones (**Figure 3**).

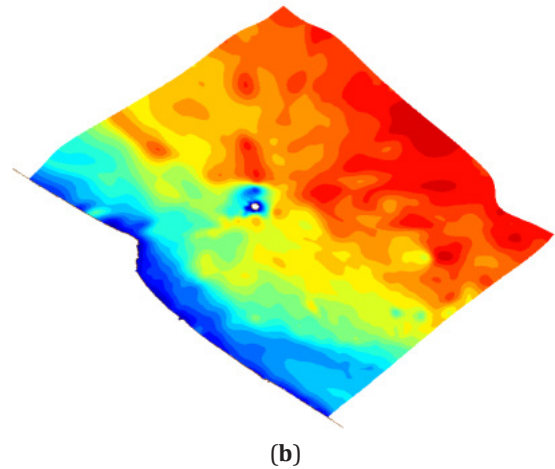
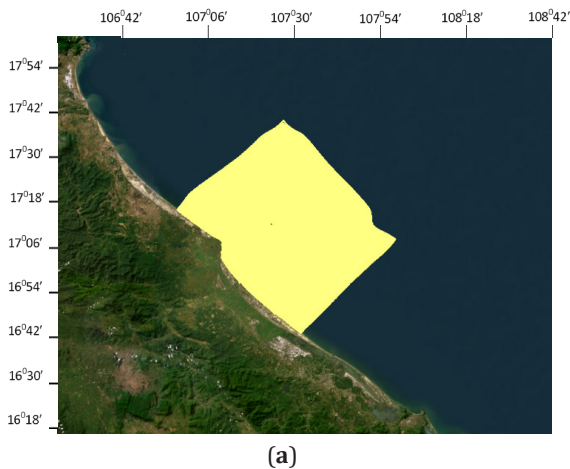


Figure 3. Cont.

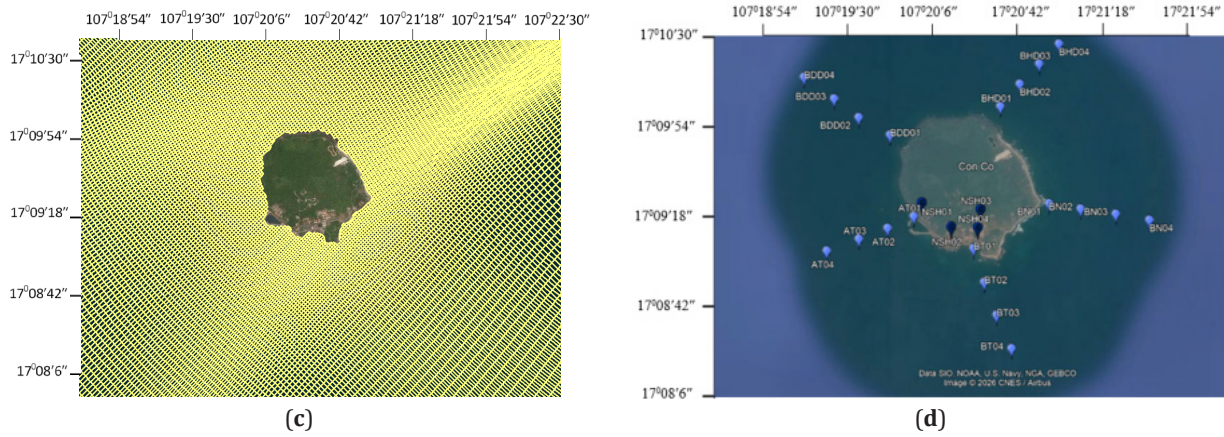


**Figure 3.** (a) Research area; (b) Bathymetry; (c) Mesh generation; (d) Plastic sample collection location.

The depth-based division relied entirely on a  $\sigma$ -coordinate framework. Every analyzed coordinate was split into eight distinct levels, where each section comprised 12.5% of that area's total depth, ultimately guaranteeing an even downward spacing from the waves to the seafloor.

Underwater elevation details for this simulation originated from refined topographical collections that experts integrated throughout the grid creation phase. This information underwent enhancement and evaluation via QUICKIN programming, while the resulting seafloor map was encoded into simulation starting documents, clearly displayed in **Figure 3**.

The integrated framework built for the coastal margins of Con Co Island was properly arranged and run for distinct seasonal phases during 2023. Outcomes from the initial month of each trial were discarded, subsequently utilized to build the starting baseline for the rest of that specific computational timeframe, thus guaranteeing simulation steadiness and dependability. The time step for fluid and particle tracking computations was fixed at 0.5 min, ensuring adequate precision to record rapid shifts across tidal flows and wind-influenced mechanics.

The digital architecture was structured as a unified combination of primary fluid circulation and wave mechanics. Core variables incorporated encompass salt levels and heat distributions, surface breeze stress, alongside wave movements. The architecture functions utilizing an active simultaneous connection between liquid flow and wave spread, ultimately facili-

tating highly accurate modeling regarding stream-wave crossings throughout the Con Co shore sector. This setup empowers the program to document the combined impacts of tide pulls, wind friction, and wave-driven streams on the synthetic fragment scattering and overall travel patterns.

The outer edge parameters governing the hydrodynamic system were established applying lunar harmonic elements. Altogether, thirteen primary tidal variables were integrated, specifically M2, S2, K2, N2, O1, K1, P1, Q1, Mf, Mm, M4, MS4, and MN4. These rhythmic factors were pulled and refined through the LEGOS FES2014 worldwide tide directory<sup>[20]</sup>. Incorporating this information ensures exceptionally detailed and dependable lunar inputs along the exposed sea edges, which remain vital for precisely mirroring tidal behaviors and their subsequent impact on particle drifting around the Con Co regional coastal marine waters.

Within Delft3D, the beginning condition of the framework might be configured utilizing resume documents created during prior processing sessions. Concerning the Con Co research zone, the starting states for every scenario were formulated via the findings of an initial one-month warm-up phase. This technique guarantees that the program receives sufficient duration to balance and that all subsequent evaluations commence from a fluidly stable current baseline. This specific preparation boosts computational firmness while significantly upgrading the accuracy of extended assessments regarding stream and polymer drifting routines within this coastal domain.

This investigation integrates weather influences, covering breezes, ambient heat, alongside barometric pressure, inside the calculated architecture. Air current files were acquired via the National Centers for Environmental Prediction (NCEP) utilizing a resolution of  $0.2^\circ$  [16]. Gathered every three hours, this vital information provided fundamental parameters driving flow and synthetic-drifting tracking performance evaluations.

Beyond just wind power, the setup calculates the impacts of barometric weight alongside atmospheric warmth shifts. Regional grid arrays containing drafts, atmospheric pressure, climate warmth, sun exposure, and cloud density, each carrying a time frequency of three hours, were utilized to characterize meteorology. Adding these metrics enables an incredibly authentic representation of the intertwined atmospheric and aquatic forces directing microplastic travel across the surrounding Con Co Island nearshore marine territory.

The surf simulator in this research was programmed to run via active linkage connecting both the fluid movement package and the Delft3D-Part synthetic drift tracker. During every sixty-minute interval, the Surf framework absorbed variables generated by the fluid environment, notably the mathematical mesh, gale currents, underwater topography, tide heights, and flow velocity. Exterior edge rules governing swell assessments were mapped implementing localized surf weather predictions for the test zone throughout 2023 [21]. The surf program utilized the JONSWAP frequency structure alongside a drag factor measuring 0.067 to characterize floor friction. To measure swell alteration across shallow depths, the Battjes and Janssen (B&J) formula [22] got implemented, yielding accurate representations of realistic wave shattering effect results.

This configuration generated a fluidly linked framework able to record the mixed consequences of lunar streams, wind pushes, and swell behaviors on the travel and scattering of microplastics throughout Con Co shore regions. During this assessment, the trustworthiness of these measurements was appraised applying the Bravais-Pearson correlation metric alongside the recognized Nash and Sutcliffe formula as the primary

comparative markers.

The Bravais-Pearson correlation coefficient is determined by the following formula:

$$r^2 = \left( \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \right)^2 \quad (3)$$

In which:  $O_i$ : observed, measured value;  $\bar{O}$ : average observed value;  $P_i$ : calculated, forecasted value;  $\bar{P}$ : average forecasted value;  $r$  is in the range of 0–1. The forecasted calculation results will be best when  $r$  approaches 1, and the reliability will be lowest when  $r$  approaches 0 [23].

Another index to evaluate the reliability of the model is the forecasting efficiency index—Nash and Sutcliffe index. This index evaluates the number of forecasts that ensure the allowable reliability.

$$E = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (4)$$

As the  $E$  value nears 1, the accuracy of the forecast results reaches its optimal level; conversely, when  $E$  approaches 0, the reliability of the forecasts diminishes significantly. Furthermore, when  $E$  is negative, the average characteristics derived from the observational data yield superior forecasting outcomes compared to the model [23].

In addition, current speed data, including both magnitude and direction, recorded in the Con Co coastal waters were used for calibration in the same two seasonal periods. The findings revealed strong alignment between calculated and recorded measurements. Regarding current strength, the  $R^2$  indicator spanned from 0.65 to 0.78, whereas the  $E$  metric fluctuated between 0.62 and 0.64. For the current trajectory, the  $R^2$  metrics spanned from 0.63 to 0.73, alongside matching  $E$  values between 0.59 and 0.60 (**Figures 4 and 5**).

Such verification results confirm that this fluid framework accurately duplicated tidal heights and circulation behaviors across both monsoon periods, consequently establishing a solid foundation for upcoming polymer drift calculations.

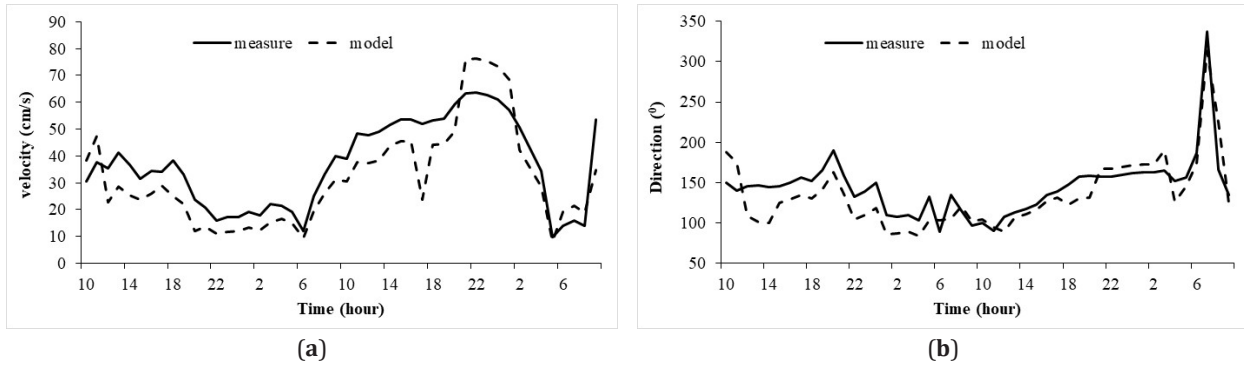


**Figure 4.** Comparison of observed and simulated current at Con Co in August 2023: (a) Speed ( $R^2 = 0.78$ ,  $E = 0.62$ ); (b) Direction ( $R^2 = 0.73$ ,  $E = 0.59$ ).

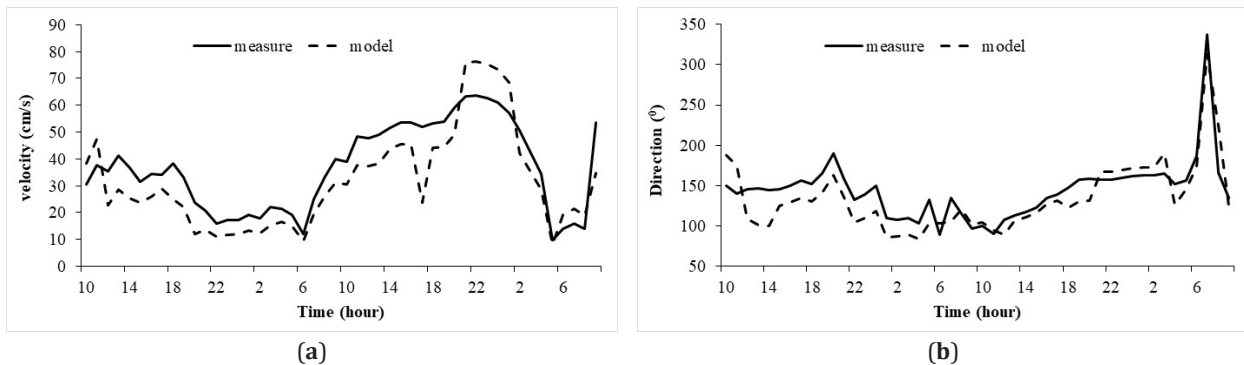


**Figure 5.** Comparison of observed and simulated current at Con Co in August 2023: (a) Speed ( $R^2 = 0.65$ ,  $E = 0.64$ ); (b) Direction ( $R^2 = 0.63$ ,  $E = 0.60$ ).

### 2.5.3. Microplastics Model Setup

Polymer specimens were gathered across four typical transects, each containing five extraction locations (**Figure 3d**). Laboratory findings revealed climatic variations: throughout the northeast monsoon, fragment totals spanned from 4 to 122, while during the southwest monsoon, quantities spanned from 14 to 73 fragments per specimen. The Delft3D-Part model was driven by calibrated hydrodynamic fields generated from the Delft3D-FLOW and Delft3D-WAVE modules. Model inputs included water levels, current velocities, wave conditions, bathymetry, wind forcing, seawater temperature, and salinity obtained from the available environmental datasets<sup>[19,21]</sup>. Microplastic particles were represented as passive Lagrangian tracers, and their transport was governed by advection, turbulent diffusion, and gravitational settling. This configuration enabled the simulation of seasonal transport and redistribution of microplastics around Con Co Island (**Figure 6**).

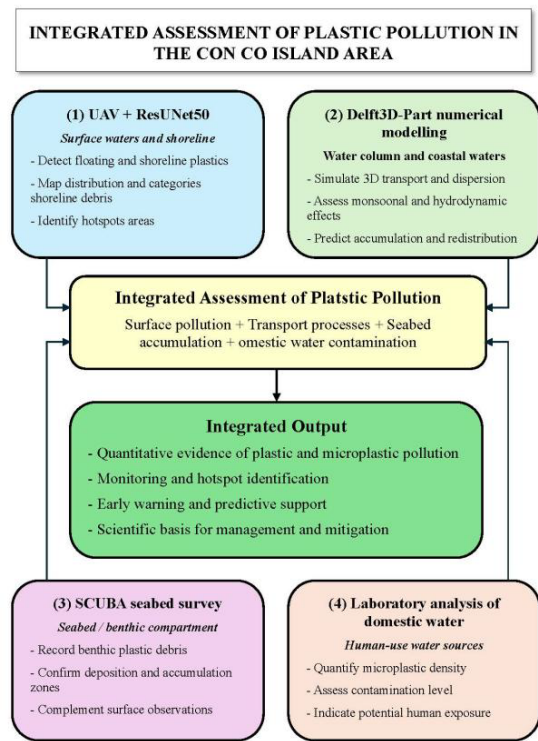


**Figure 6.** Diagram of linkage among the four complementary approaches.

### 3. Results

#### 3.1. Survey Results of Plastic Waste Pollution in the Coastal Zone of Con Co Island

UAV-supported assessments performed along five littoral cross-sections of Con Co Island during dual tracking intervals (November 2023 and April 2024) established that synthetic debris formed the prevailing segment of bulk solid litter within the analyzed sector, accounting for roughly 90% of the total weight. Among these, rigid plastics (incorporating containers, toys, footwear, packaging, and fishing nets) made up an average of 57.5%, followed by foam buoys at 32.5%, whereas substitute types of detritus, including wood, textiles, and glass, contributed strictly minor fractions (**Table 3**).

The zones holding the maximum synthetic litter density were mostly located across the northern, northwestern, northeastern, and southeastern sections of the territory, where vast rocky edges and shore defense structures, including seawalls and also breakwaters, tended to catch and hold floating detritus, encouraging its localized gathering. Upper waters bordering the

coast throughout the cold season displayed reduced quantities of drifting debris because the winter time-frame is defined by fewer gales and lessened visitor activities, culminating in decreased volumes of trash penetrating the nearshore environment.

Drawing upon on-site examinations, questionnaires from native inhabitants, vacationers, eateries, lodgings, alongside bureaucratic bodies across this land-mass, the projected volume of gathered synthetic debris along the Con Co beachfront reached 8,379 kg, representing 90% of the overall littoral solid rubbish mass measuring exactly 9,310 kg. This translates into a mean concentration yielding 1.4 kg per meter of beachfront and 0.04 kg/m<sup>2</sup> concerning littoral space (**Table 4**).

Forecasting trends in population growth, tourism, services, and maritime transport on Con Co Island in line with the island's development plan for 2021–2030 and the vision toward 2050, the total volume of plastic waste generated is projected to reach approximately 14.3 t by 2030. In particular, coastal plastic waste is expected to continue accumulating at high levels unless effective mitigation and collection measures are implemented (**Table 5**).

**Table 3.** Composition of solid waste in the coastal and surface waters of the Con Co Island Marine Protected Area across two survey periods.

| No. | Plastic Waste Type                                                                            | Rate (%)  |           |         | Distribution                                                                                                                                                                                                                                                                 |
|-----|-----------------------------------------------------------------------------------------------|-----------|-----------|---------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     |                                                                                               | Nov. 2023 | Apr. 2024 | Average |                                                                                                                                                                                                                                                                              |
| 1   | Bottles, toys, footwear, bags, plastic packaging for construction materials, fishing nets     | 55        | 60        | 57.5    | Plastic debris was scattered along the island's shoreline, with concentrations primarily observed in areas with rocky beaches and seawalls. Higher accumulations were recorded in the northern, northwestern, northeastern, eastern, and southeastern sectors of the island. |
| 2   | Floating Styrofoam                                                                            | 35        | 30        | 32.5    | Plastic debris was scattered along the island's shoreline, with concentrations primarily observed in areas with rocky beaches and seawalls. Higher accumulations were recorded in the northern, northwestern, northeastern, eastern, and southeastern sectors of the island. |
| 3   | Tree branch, tree stump, wood                                                                 | 8         | 7         | 7.5     | Plastic debris was scattered along the island's shoreline, with higher concentrations observed on rocky coastal areas located to the north, northwest, east, and northeast of the island.                                                                                    |
| 4   | Fabric, old clothes                                                                           | 1.5       | 2         | 1.75    | Plastic debris was scattered along the island's shoreline, with higher concentrations primarily observed in areas with rocky beaches and seawalls.                                                                                                                           |
| 5   | Glass bottles and jars                                                                        | 0.5       | 1         | 0.75    | Plastic debris was distributed along the shoreline of the island, with higher concentrations primarily observed in areas with rocky beaches and seawalls.                                                                                                                    |
| 6   | Other debris (coral fragments, seashells, snails, etc.)—Not included in statistical analysis. |           |           |         |                                                                                                                                                                                                                                                                              |

**Table 4.** Current status of accumulated and dispersed plastic waste volume along the coastal zone of Con Co Island.

| No. | Plastic Waste Type                                                                        | Rate (%)       |                |         | Amount of Plastic Waste              |                             |                         |                             |                               |                             |                         |                             |
|-----|-------------------------------------------------------------------------------------------|----------------|----------------|---------|--------------------------------------|-----------------------------|-------------------------|-----------------------------|-------------------------------|-----------------------------|-------------------------|-----------------------------|
|     |                                                                                           |                |                |         | Beach Area 2 (Few)                   |                             | Beach Area 2 (Few)      |                             | Beach Area 3 (There are Many) |                             | Beach Area 3 (Many)     |                             |
|     |                                                                                           |                |                |         | Length of Coastline (m)              | Average Waste Volume (kg/m) | Length of Coastline (m) | Average Waste Volume (kg/m) | Length of Coastline (m)       | Average Waste Volume (kg/m) | Length of Coastline (m) | Average Waste Volume (kg/m) |
|     |                                                                                           | Survey Phase 1 | Survey Phase 2 | Average | 2,100                                | 0.05                        | 840                     | 0.5                         | 1,790                         | 3.5                         | 1,260                   | 2.0                         |
| 1   | Bottles, toys, footwear, bags, plastic packaging for construction materials, fishing nets | 55%            | 60%            | 58%     | 60.4                                 |                             | 241.5                   |                             | 3,602.4                       |                             | 1,449.0                 |                             |
| 2   | Floating Styrofoam                                                                        | 35%            | 30%            | 33%     | 34.1                                 |                             | 136.5                   |                             | 2,036.1                       |                             | 819.0                   |                             |
| 3   | Tree branch, tree stump, wood                                                             | 8%             | 7%             | 8%      | 7.9                                  |                             | 31.5                    |                             | 469.9                         |                             | 189.0                   |                             |
| 4   | Fabric, old clothes                                                                       | 1.50%          | 2%             | 2%      | 1.8                                  |                             | 7.4                     |                             | 109.6                         |                             | 44.1                    |                             |
| 5   | Glass bottles and jars                                                                    | 0.50%          | 1%             | 1%      | 0.8                                  |                             | 3.2                     |                             | 47.0                          |                             | 18.9                    |                             |
|     | Other waste (iron, steel, animal bones, coral, shells, snails, etc.)                      |                |                |         | Not included in statistical analysis |                             |                         |                             |                               |                             |                         |                             |
|     | Total amount of waste in 4 coastal areas of Con Co Island:                                | 100%           | 100%           | 100%    | 105,0                                |                             | 105.0                   |                             | 420.0                         |                             | 6,265.0                 |                             |

**Table 5.** Projected status of accumulated and dispersed plastic waste volume along the coastal zone of Con Co Island.

| No.                      | Sources of Plastic Waste Emissions                                                                                                  | Unit                 | Average Amount of Plastic Waste Emitted (kg/day) | Forecast of Changes in Emission Sources and Expected Volume of Plastic Waste Emitted by 2030 (kg/year) |                         |                            |                                                                                                                                     | Remark                                                                                                                                                                                                                    |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------|----------------------|--------------------------------------------------|--------------------------------------------------------------------------------------------------------|-------------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                          |                                                                                                                                     |                      |                                                  | Year of 2023–2024                                                                                      |                         | Year of 2025–2030          |                                                                                                                                     |                                                                                                                                                                                                                           |
|                          |                                                                                                                                     |                      |                                                  | Number of Emission Sources                                                                             | Amount of Plastic Waste | Number of Emission Sources | Amount of Plastic Waste                                                                                                             |                                                                                                                                                                                                                           |
| I                        | Volume of household plastic waste                                                                                                   |                      |                                                  | 23,619.2                                                                                               |                         | 5,966.6                    | By 2025: Agencies, organizations, residential areas, and tourists will use over 80% eco-friendly materials to replace plastic bags. |                                                                                                                                                                                                                           |
| 1                        | Residents on the island and workers arriving support activities including infrastructure, construction, afforestation, and tourism. | Person               | 0.06                                             | 110.0                                                                                                  | 2,435.8                 | 154.0                      | 682.0                                                                                                                               | Operating time in the year: 365 days                                                                                                                                                                                      |
|                          | Tourist                                                                                                                             | Person               | 0.02                                             | 8,681.0                                                                                                | 347.2                   | 13,022.0                   | 104.2                                                                                                                               | Average time of year: 2 days                                                                                                                                                                                              |
|                          | Administrative units, schools, military units, border guards                                                                        | Unit                 | 2.20                                             | 20.0                                                                                                   | 11,440.0                | 22.0                       | 2,516.8                                                                                                                             | Operating time during the year: 5 days/week (260 days/year)<br>● 05 guest houses; 06 homestays<br>● Operating time in the year: 100 days (mainly during the tourist season and scattered on weekends throughout the year) |
|                          | Guest house, Homestay                                                                                                               | Business Household   | 7.00                                             | 11.0                                                                                                   | 7,700.0                 | 12.0                       | 1,680.0                                                                                                                             |                                                                                                                                                                                                                           |
|                          | Fishing vessels are regularly anchored at the port.                                                                                 | A                    | 0.20                                             | 5.0                                                                                                    | 365.0                   | 6.0                        | 87.6                                                                                                                                | Operating time in the year: 365 days                                                                                                                                                                                      |
|                          | Means of transport by ship and boat to the island to serve people's activities and tourism                                          | Number of ships/year | 3.20                                             | 416.0                                                                                                  | 1,331.2                 | 1,400.0                    | 896.0                                                                                                                               | Operating time in the year: 02 ships to the island 04 times/ship/week: 416 times                                                                                                                                          |
| II                       | The amount of plastic waste concentrated along the coast of Con Co Island                                                           |                      |                                                  |                                                                                                        | 8,379.0                 |                            | 8,379.0                                                                                                                             |                                                                                                                                                                                                                           |
|                          | Total                                                                                                                               |                      |                                                  |                                                                                                        | 31,998.2                |                            | 14,345.6                                                                                                                            |                                                                                                                                                                                                                           |
| Amount of waste treated: |                                                                                                                                     |                      |                                                  |                                                                                                        |                         |                            |                                                                                                                                     |                                                                                                                                                                                                                           |
|                          | Household plastic waste:                                                                                                            |                      |                                                  |                                                                                                        | 21,257.3                |                            | 0                                                                                                                                   | By 2025: Collect over 80% of coastal waste, and 100% of household waste is collected and treated.                                                                                                                         |
|                          | Plastic waste along the coast of Con Co Island                                                                                      |                      |                                                  |                                                                                                        | 2,513.7                 |                            | 6,703.2                                                                                                                             |                                                                                                                                                                                                                           |

### 3.2. Survey Results of Plastic Waste Pollution on the Seabed of the Con Co Island Marine Protected Area

Outcomes derived from two distinct examination stages conducted across 10 cross-sections within the Con Co Island Marine Protected Area demonstrated a substantial prevalence of synthetic trash scattered between stony ridges and coral structures. The most frequent classes of rubbish included synthetic pouches, polystyrene meal boxes, pieces of flexible polymers, plastic wrappers, plastic bands, solid synthetic fragments, and also abandoned angling equipment (**Figure 7**).

The assessment outcomes similarly revealed distinct variations regarding the rate of synthetic litter presence across the analyzed locations. Deepwater zones held extremely minimal synthetic detritus across the ocean floor, featuring merely infrequent discoveries of drifting meal wrappers, synthetic sacks, or discarded angling equipment. Conversely, the most prevalent forms of synthetic rubbish—encompassing polymer

flasks, tins, synthetic sacks, and Styrofoam boxes—were extensively documented, blanketing coral formations and stony beds, featuring notably intense densities within coastal belts. Such accumulations remained exceptionally prominent throughout the Ben Tranh and Roadsteads districts, where concentrated inhabitants, multiple restaurants, and mooring routines of fishing vessels drive heightened volumes of synthetic refuse (**Table 6**).

The findings derived from the dual assessment stages additionally illustrated that the extent of synthetic litter across stony ridges and coral foundations in the Con Co Island Marine Protected Area varied between 1% and 31.25%. The maximum distribution was documented across two coastal locations, Ben Tranh alongside Roadsteads, featuring corresponding figures of 26.87% and 12.5% during November 2023, plus 31.25% and 13.75% during April 2024. Conversely, alternate investigated zones displayed substantially diminished benthic polymer spread, featuring metrics fluctuating between 1% and 9% (**Figure 8**).

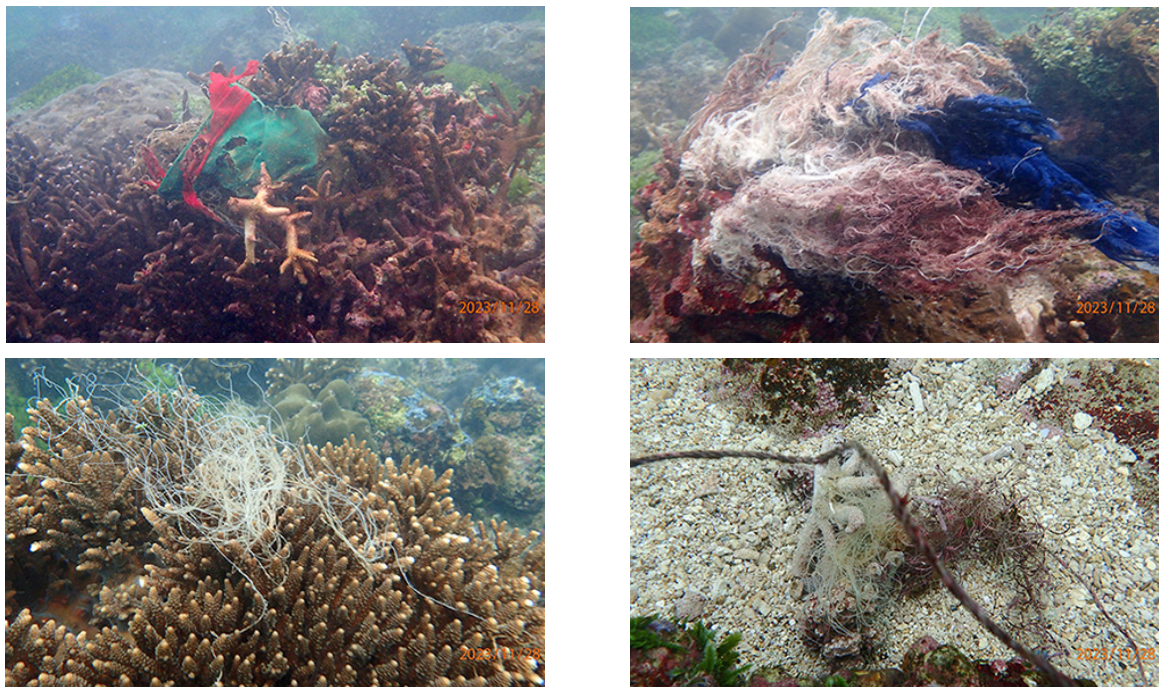
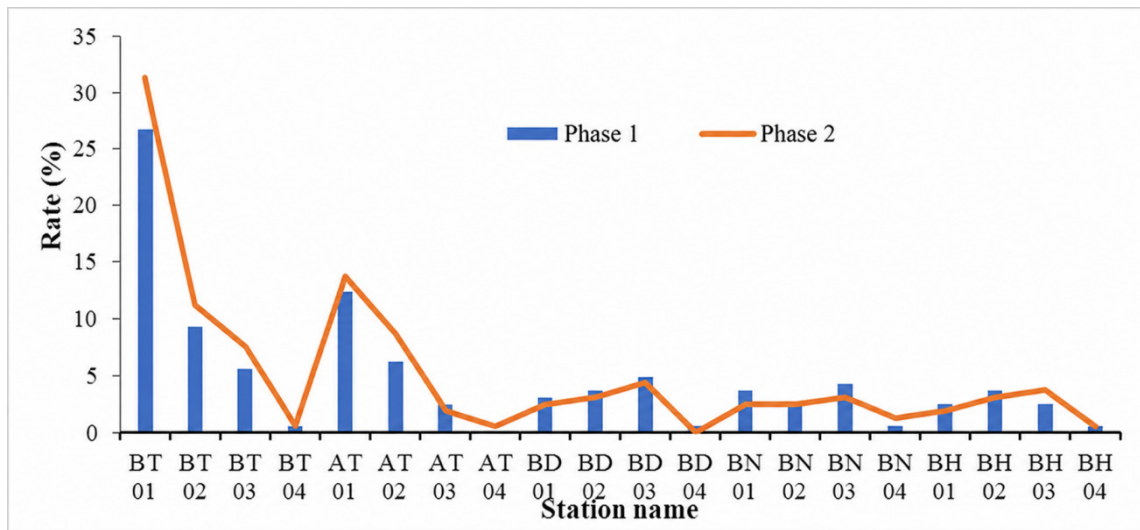


**Figure 7.** Photographs of plastic waste on the seabed in the Con Co Island Marine Protected Area.

**Table 6.** Frequency of plastic waste occurrence in the Con Co Island Marine Protected Area.

| No. | Section Symbol | Station Symbol | Frequency of Occurrence |
|-----|----------------|----------------|-------------------------|
| 1.  |                | BT 01          | 4                       |
| 2.  | BT             | BT 02          | 2                       |
| 3.  | (Ben Tranh)    | BT 03          | 2                       |
| 4.  |                | BT 04          | 1                       |
| 5.  |                | AT 01          | 4                       |
| 6.  | AT             | AT 02          | 1                       |
| 7.  | (Roadsteads)   | AT 03          | 1                       |
| 8.  |                | AT 04          | 1                       |
| 9.  |                | BD 01          | 3                       |
| 10. | BD             | BD 02          | 2                       |
| 11. | (Ben Da Den)   | BD 03          | 1                       |
| 12. |                | BD 04          | 1                       |
| 13. |                | BN 01          | 3                       |
| 14. | BN             | BN 02          | 1                       |
| 15. | (Ben Nghe)     | BN 03          | 1                       |
| 16. |                | BN 04          | 1                       |
| 17. |                | BH 01          | 3                       |
| 18. | BH             | BH 02          | 1                       |
| 19. | (Ben Ha Dong)  | BH 03          | 1                       |
| 20. |                | BH 04          | 1                       |

Note: "1" very few; "2" few; "3" many; "4" abundant.

**Figure 8.** Plastic waste coverage in the Con Co Island Marine Protected Area.

### 3.3. Analysis Results of Microplastic Pollution in Domestic Water on Con Co Island

The assessment was executed during dual stages: November 2023 (Phase 1) alongside April 2024

(Phase 2), encompassing a total of four testing locations for household water. The outcomes stand as follows:

- Stage 1 (Nov. 2023): Polymer quantities fluctuated between 10 and 55 fragments per specimen,

equating to concentrations from 0.50 ng/L to 2.75 ng/L, yielding an average metric of 1.23 ng/L. Specimen NSH-02 registered the maximum density (2.75 ng/L), whereas specimen NSH-03 displayed the minimum (0.50 ng/L).

- Stage 2 (Apr. 2024): Polymer quantities fluctuated between 17 and 61 fragments per specimen, equating to concentrations from 0.34 ng/L to 1.22 ng/L, yielding an average metric of 0.86 ng/L. Yet again, NSH-02 presented the maximum density (1.22 ng/L), while NSH-04 registered the mini-

mum (0.34 ng/L).

These discoveries prove that synthetic pollutants remain active inside residential water supplies utilized by native inhabitants, which primarily comprise groundwater alongside precipitation gathered and contained within household reservoirs. Significantly, NSH-02 uniformly displayed elevated synthetic concentrations relative to all alternate testing locations throughout both assessments. The mean accumulation during Stage 1 reached 1.43 times greater than that of Stage 2 (**Table 7**).

**Table 7.** Microplastics in domestic water on Con Co Island.

| No. | Station Symbol | Sample Type    | Phase 1               |                | Phase 2               |                |
|-----|----------------|----------------|-----------------------|----------------|-----------------------|----------------|
|     |                |                | Microplastic Quantity | Density (ng/L) | Microplastic Quantity | Density (ng/L) |
| 1   | NSH-01         | Domestic water | 28                    | 1.40           | 38                    | 0.76           |
| 2   | NSH-02         | Domestic water | 55                    | 2.75           | 61                    | 1.22           |
| 3   | NSH-03         | Domestic water | 10                    | 0.50           | 55                    | 1.10           |
| 4   | NSH-04         | Domestic water | 19                    | 0.95           | 17                    | 0.34           |

### 3.4. Hydrodynamic Simulation Results

#### 3.4.1. Current Distribution in the Northeast Monsoon Season

The hydrodynamic system governing Con Co Island is defined through an intricate circulation network, illustrating the synergistic impacts of tidal actions, wind-generated flows, alongside regional topographic constraints. Throughout the northeast monsoon, fluid speeds routinely fluctuate between 0.1 and 1.0 m/s. Two dominant stream orientations become apparent: one stretching from northwest to southeast, and another moving from southeast to northwest. Whenever the northwest-bound flow hits Con Co Island, this stream separates into dual unique pathways, one migrating northwestward and the second southeastward, before reuniting across the southeastern maritime zone of this landmass. Stream speeds remain broadly elevated across the northeastern and southwestern territories, featuring metrics frequently fluctuating between 0.5 and 1.0 m/s. Conversely, zones bordering the landmass plus those across the southeast typically undergo diminished velocities, largely under 0.5 m/s. Fur-

thermore, the southeastern division of this landmass remains distinguished by the manifestation of eddies: clockwise currents developing across the east-southeast, alongside counterclockwise rotations emerging across the south-southeast. Stream speeds inside these eddy zones stay comparatively minimal, primarily under 0.4 m/s (**Figure 9**, left).

The southeast-directed stream, upon arriving at Con Co Island, divides into dual separate pathways: one drifts toward the northeastern district, whereas the second pivots southwest. Such branches subsequently recombine together inside the landmass's northwestern maritime areas. Fluid velocities remain broadly intensified across the southwestern alongside northeastern sections, occasionally surpassing 1 m/s. Conversely, the northwestern littoral boundary remains routinely distinguished through diminished flows, yielding speeds frequently under 0.5 m/s. Furthermore, the dominant southeast-northwest movement triggers the creation of a clockwise gyre, wherein flow rates remain comparatively sluggish, typically measuring less than 0.3 m/s near the rotation center (**Figure 9**, right).

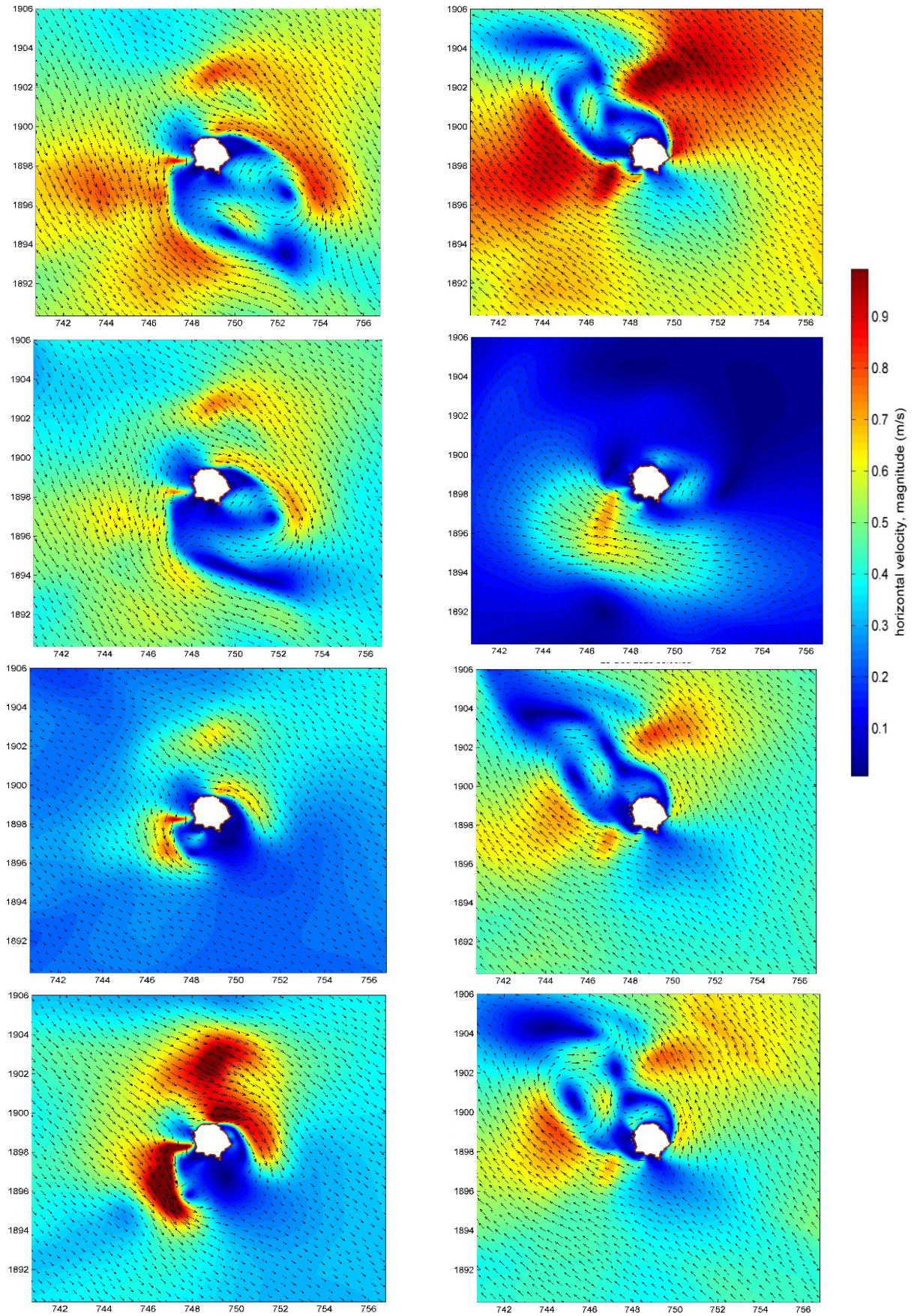


**Figure 9.** Surface current distribution in the northeast monsoon season.

### 3.4.2. Current Distribution in the Southwest Monsoon Season

Akin to the northeast monsoon, the hydrodynamic environment surrounding Con Co Island throughout the southwest monsoon is regulated through an intricate composite stream influenced by tidal movements, wind pressure, and regional topography. Fluid speeds during this period remain broadly reduced compared against those documented during the northeast monsoon, frequently staying under 0.9 m/s. The movement remains dictated through two primary stream orientations: northwest–southeast alongside southeast–northwest. Whenever the northwest-bound flow nears Con Co Island, it separates into dual separate pathways, one redirected northwestward and the other southeastward, before reuniting within the southeastern maritime boundaries of the landmass. Alternatively, streams emerging from the southeast divide upon accessing the landmass, with one pathway drifting northeast and an-

other southwest, ultimately reuniting within the northwestern territory.

Throughout the southwest monsoon, fluid speeds generally display a more uniform dispersion throughout varied districts when contrasted against the northeast monsoon, excluding the coastal domains. Elevated speeds, fluctuating between 0.4 and 0.9 m/s while periodically surpassing 1 m/s, remain recorded across the northeastern alongside southwestern divisions. Fluid mechanics throughout this period additionally produce both clockwise and counterclockwise gyres across the southeastern seas, linked to the northwest–southeast offshoot. Concurrently, the southeast–northwest stream routinely triggers clockwise eddies across the northwestern section of the landmass, featuring an extra clockwise gyre manifesting across the northeast. Stream speeds inside these gyres progressively diminish from the boundary toward the interior, attaining their minimum metrics near the core, usually under 0.3 m/s (**Figure 10**).

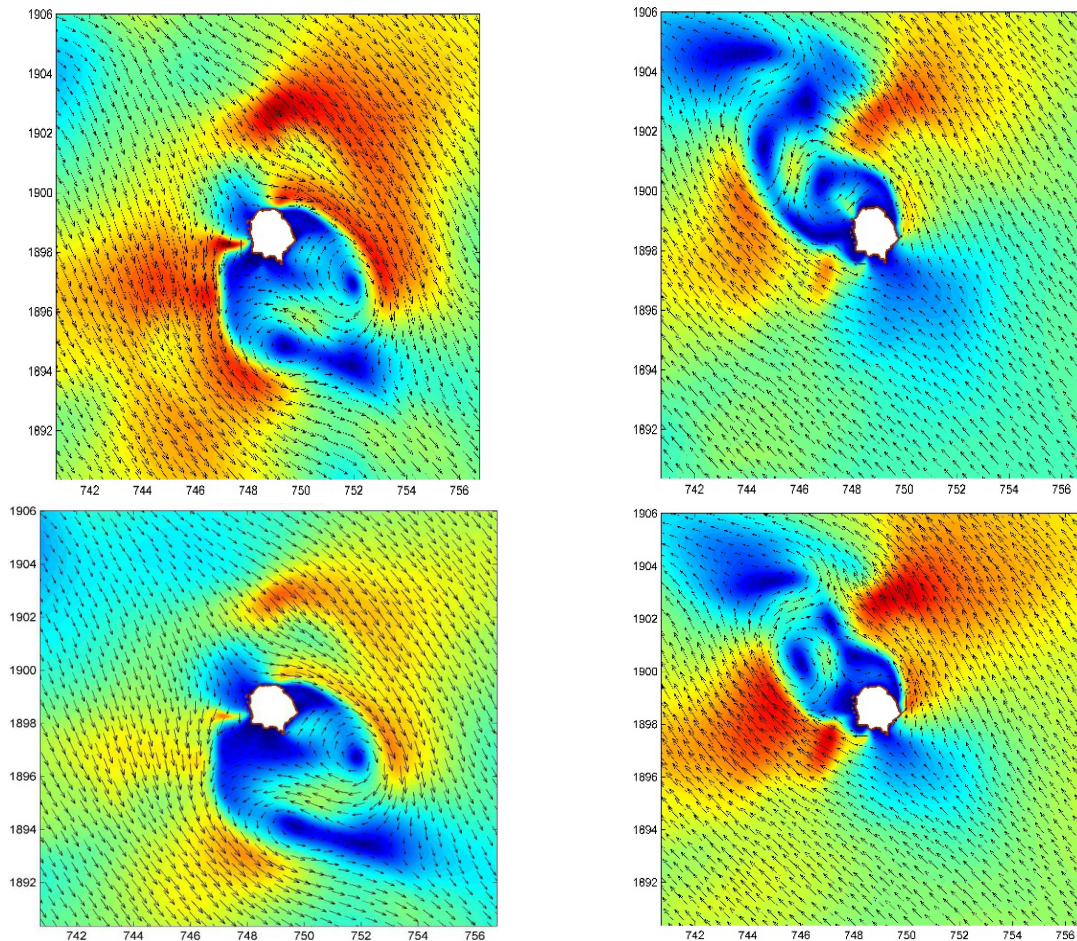


Figure 10. *Cont.*

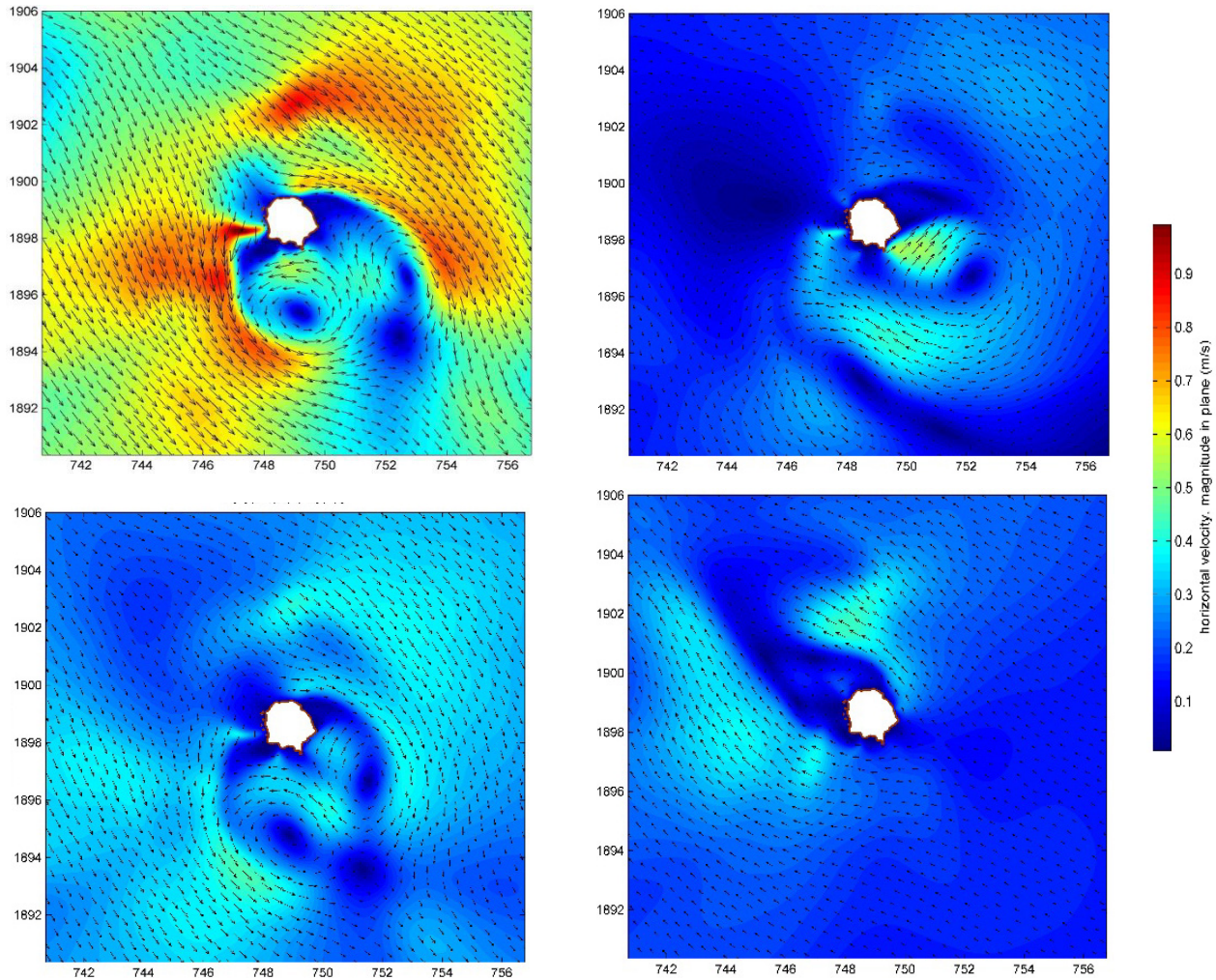


Figure 10. Surface current distribution in the southwest monsoon season.

### 3.5. Simulation Results of Microplastic Distribution

#### 3.5.1. Microplastic Distribution in the Northeast Monsoon Season

Figures 11 and 12 display the modeled dispersion of microplastics surrounding Con Co Island across the superficial stratum throughout the northeast monsoon period. Polymer densities were projected to fluctuate between 10 and 100 particles. The scattering configuration remains heavily dictated by dominant stream orientation and speed. The coastal zones bordering the landmass presented the maximum accumulations, featuring a peak of 50 particles documented (Figure 11a).

This highly concentrated zone directly aligns with populated regions, as plastic debris from local housing, farming, and factory operations constantly moves off the

mainland and enters ocean ecosystems. Furthermore, the interaction between northeast and southwest ocean tides plays a major role in pushing tiny plastic fragments from neighboring locations straight into the marine habitats closely surrounding Con Co Island, intensifying regional water pollution levels quite significantly.

The distribution and migration pathways of microplastics appeared most pronounced in the upper stratum of the marine ecosystem. Due to their comparatively minimal buoyancy, polymer fragments tended to drift and aggregate within this superficial layer. These elements are scattered across a geographical extent stretching from coastal areas to zones outside the specified research boundary. Furthermore, synthetic remnants carried oceanward through tidal movements and winds from continental zones integrated with microplastic inputs stemming from Con Co Island. Since

coastal stream speeds remain broadly sluggish ( $<0.1$  m/s), entrapment and regional settling of microplastics are routinely witnessed along the coastline. The scat-

tering configuration predominantly tracked dual major vectors: northwest–southeast alongside southeast–northwest.

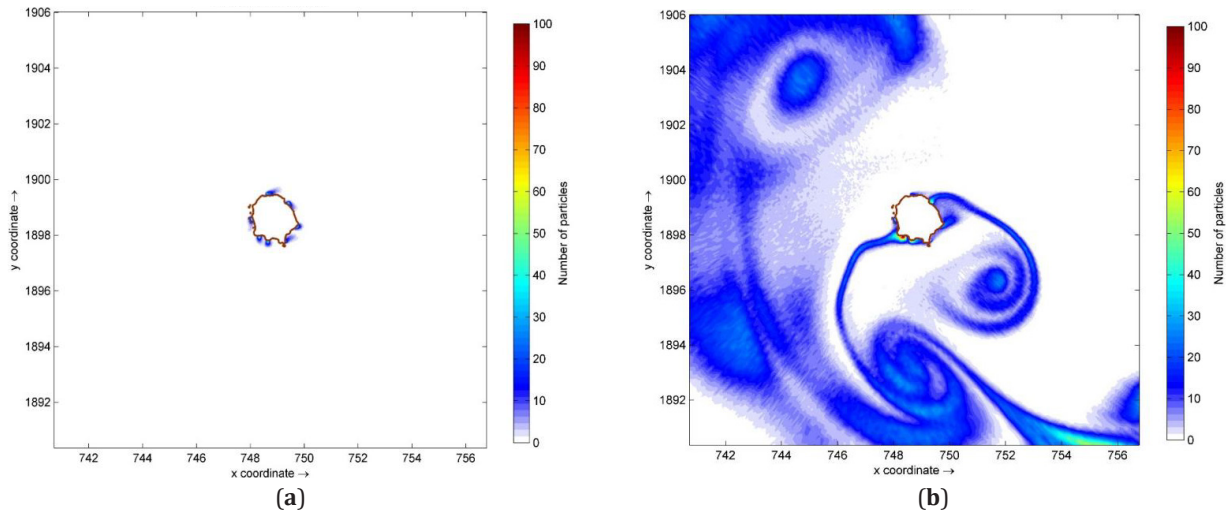


**Figure 11.** Surface microplastic distribution after (a) 1 day; (b) 5 days of northeast monsoon season.

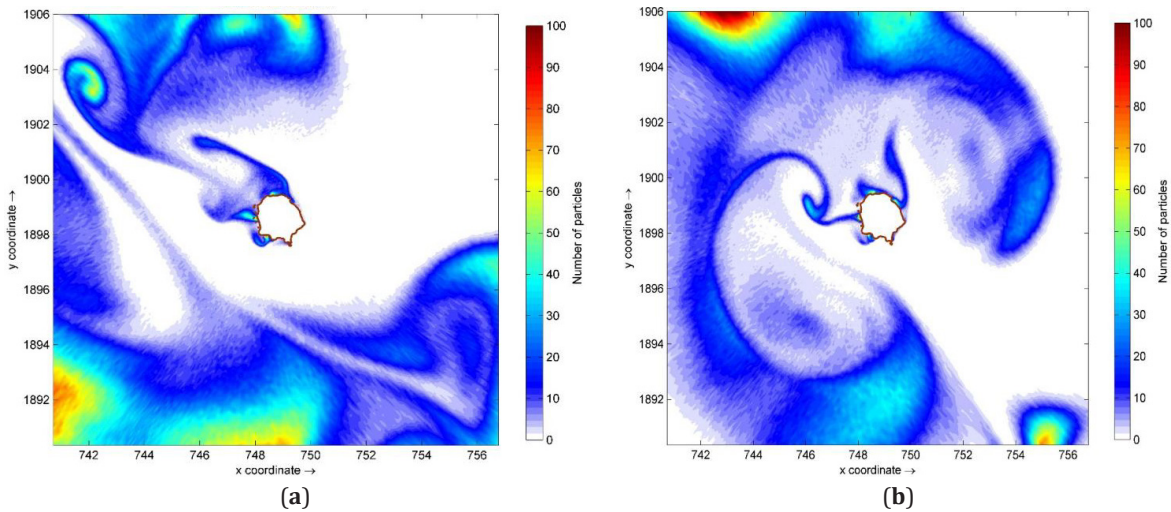


**Figure 12.** Surface microplastic distribution after (a) 25 days; (b) 41 days of northeast monsoon season.

Starting from the fifth day of modeling, uniquely on 29 November 2023, microplastics were dispersed extensively throughout the investigation zone, preserving a comparatively fixed footprint until roughly the ninth day. Throughout this timeframe, the peak aggregation zone contracted, with densities falling to 10–50 particles (**Figure 11b**). By the thirteenth day, peak accumulations resurfaced inside the research domain, climbing up to 100 particles. From the eighteenth day forward, the modeled outcomes indicated an inflation in microplastic presence across the aquatic column, as

fragments were transported into the zone through external hydrodynamic pressure (**Figure 12**).

### 3.5.2. Microplastic Distribution in the Southwest Monsoon Season

**Figures 13 and 14** portray the modeled scattering of microplastics across seas encircling Con Co Island within the superficial stratum throughout the southwest monsoon. The simulated polymer trails distinctly mirror the dominant flow framework, featuring scattering trajectories oriented along the northwest–

southeast and southeast–northwest axes.

During the initial modeling day, the coastal seas—specifically the southwestern division of the landmass heavily impacted by anthropogenic operations—displayed the peak aggregation, wherein densities reached

up to 90 particles within a comparatively restricted zone. Owing to their minimal compactness, microplastics mostly stayed afloat, prompting aggregation to appear most pronounced across the superficial stratum.

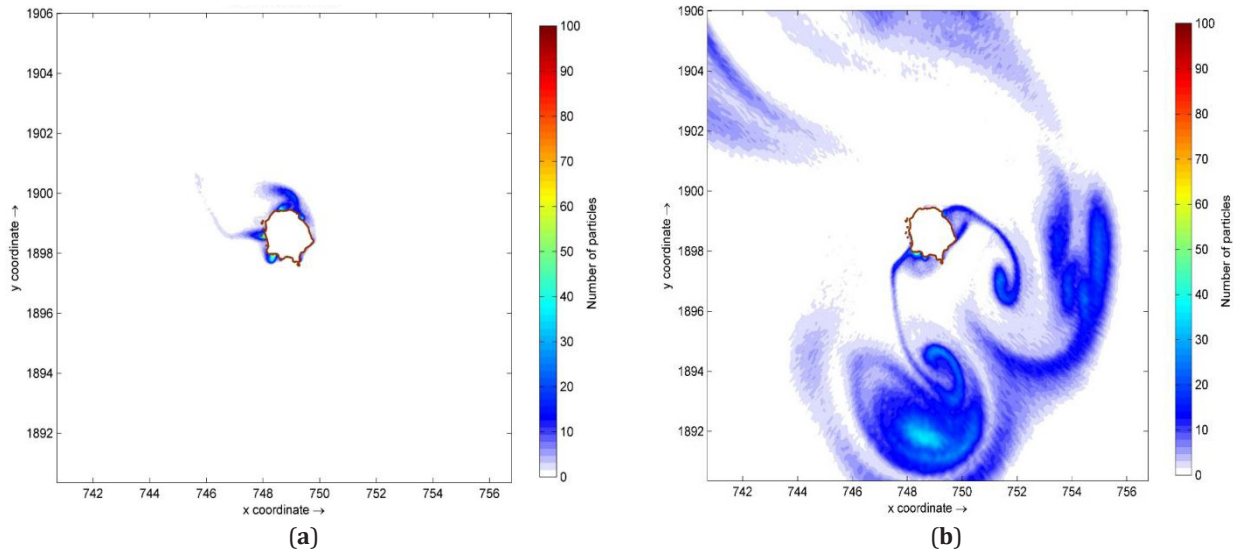


**Figure 13.** Surface microplastic distribution after (a) 1 day; (b) 6 days in southwest monsoon season.

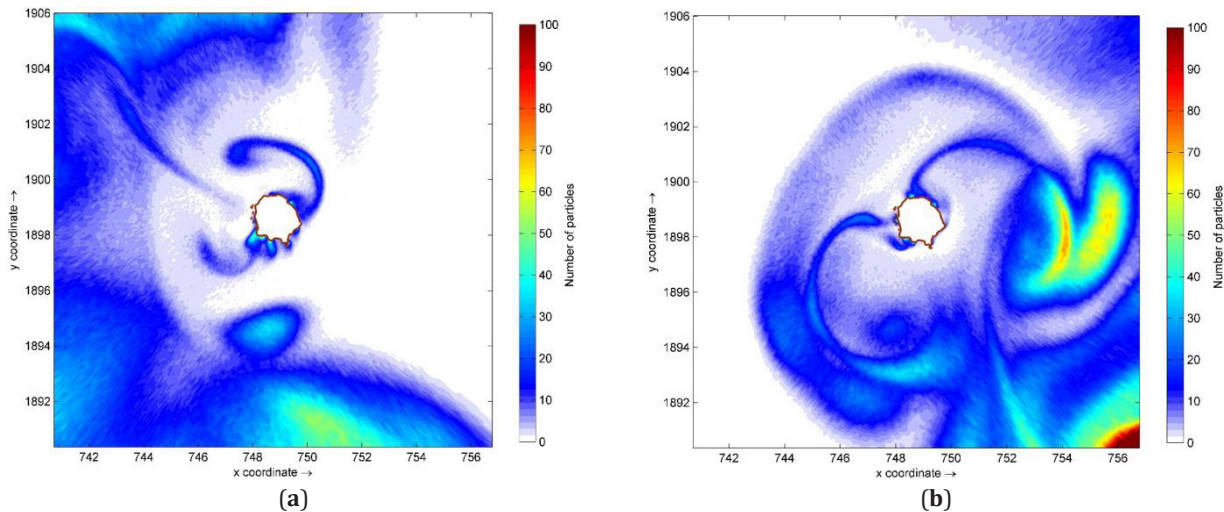


**Figure 14.** Surface microplastic distribution after (a) 24 days; (b) 43 days in southwest monsoon season.

Alongside localized regional contributions, polymer fragments carried oceanward from the continent through tidal movements and wind pressure became integrated within the circulation matrix, subsequently blending alongside those stemming from Con Co Island. Such interplay emphasizes the twin functions of domestic anthropogenic origins and external hydrodynamic conveyance in governing microplastic dispersion within

the research zone.

During the initial modeling day post-release, polymer fragments aggregated predominantly within coastal zones, presenting particle quantities fluctuating between 10 and 60 across specific localized regions (**Figure 13a**). Throughout this phase, migratory configurations suggested a broader drift toward the northeast. By the sixth day, specifically on 6 July 2023 (**Figure**

13b), synthetic debris had grown increasingly dispersed across the research boundary, whereas districts featuring heightened accumulation sustained fragment totals mostly within the 10–60 bracket. The eastern alongside southern littoral segments of this landmass exhibited the maximum densities, while the scattering reach of microplastics stemming from Con Co Island spanned up to 10 km.

From the twelfth day forward, the scattering radius broadened significantly, as the geographical dispersion proceeded to project beyond the landmass. Reaching the twenty-fourth day, on 24 July 2023 (**Figure 14a**), the peak densities documented rested marginally under 65 particles. Afterwards, driven by the impact of hydrodynamic circulation, the fragments grew progressively uniform throughout the research territory, and nearing the conclusion of the modeling timeframe, it became virtually unfeasible to distinguish regional areas of elevated aggregation (**Figure 14b**).

## 4. Discussion

Merging sophisticated tracking methodologies with computer forecasting effectively facilitated an exhaustive evaluation regarding the presence, spread, and shifting patterns characterizing plastic and microplastic contamination throughout the Con Co Island territory. By merging aerial drone surveillance alongside advanced machine learning, firsthand underwater diving inspections of seafloor debris, and fluid dynamics modeling via Delft3D-Part, our research delivers a multi-layered viewpoint concerning synthetic trash within this compact island habitat. Contemporary spatial-temporal visual-linguistic studies indicate that complicated outdoor scene translation improves whenever visible traits are examined alongside physical and chronological surroundings<sup>[24]</sup>. While that referenced paper targets roadway traffic, its core approach suits aerial drone garbage charting. Consistent monitoring across two distinct tracking phases, set pathways, and mapped beach zones delivers crucial background data separating actual lasting trash from temporary visual anomalies triggered by shifting ocean conditions or sunlight reflections.

Aerial drone inspections uncovered that synthet-

ic garbage constitutes over 90% of overall solid refuse floating on coastal and upper marine waters, featuring heavy congestion zones situated around rocky coasts alongside protective walls, mostly throughout the northern, northwestern, and northeastern regions. Total calculated shoreline plastic trash capacity hit 8,379 t, reflecting an overall density equaling 1.4 kg per coastal meter. Forecasts warn that expanding populations, the hospitality sector, and maritime operations will probably push synthetic refuse outputs toward roughly 14.3 t by 2030 unless robust mitigation tactics appear. Such an overwhelming presence of synthetic debris strongly mirrors findings from Madeira Island detailed by Bettencourt et al.<sup>[25]</sup>, wherein polymers comprised the chief portion of shoreline aquatic garbage, gathering primarily in zones impacted directly by anthropogenic actions. Across both island settings, coastal towns and vacationer industries heavily drive synthetic refuse production and localized buildup.

Submerged diving assessments revealed synthetic waste tangled among coral networks and stony ocean floors, showcasing bottom accumulation rates spanning from 1% to 31.25%. Peak concentrations appeared across shallow coastal belts, particularly around Ben Tranh and the Roadsteads, highlighting immediate consequences stemming from household chores, sightseeing, and boat mooring. Heavier, non-floating polymers born along shorelines usually gather across continental shelves, yet they might slowly drift into broader pelagic zones, occasionally hitting underwater seamounts, depending heavily on their exact distance offshore. Introducing maritime-generated trash naturally triggers a significantly broader scattering of synthetics moving outward toward deeper waters<sup>[3]</sup>. Testing local drinking water batches validated the infiltration of tiny microplastics inside municipal plumbing systems utilized by native citizens, showing density levels spanning 0.34 to 2.75 ng/L, aligning perfectly with modern investigations conducted across Mediterranean territories alongside Italian shorelines<sup>[26,27]</sup>. Such discoveries emphasize not just oceanic habitat degradation but reveal severe avenues for direct human ingestion of microplastics via daily household water utilization. Nevertheless, this current investigation merely documented baseline mi-

croplastic densities without attempting to measure individual consumption rates or linked physiological dangers. Subsequent inquiries are crucial to gauge actual human contact risks alongside their broader medical repercussions. Trustworthy forecasting applications remain incredibly pivotal for fostering a deeper comprehension regarding microplastic dynamics, vulnerability, and hazards throughout aquatic ecosystems. They streamline the pinpointing of origin points plus major congestion hubs, subsequently empowering educated policymaking meant for precise preventative measures and sweeping remediation campaigns <sup>[2]</sup>. Delft3D-Part computer trials accurately mirrored the predictable seasonal shifts dictating microplastic movement. Throughout the northeast monsoon season, fragments typically mass around northern and northeastern shorelines, driven by localized flows and swirling eddies. Conversely, the southwest monsoon produced wider and evenly distributed scattering behaviors, although heightened fragment densities remained noticeable across southern alongside southwestern coastal fringes. These outcomes emphasize the overarching power wielded by prevailing monsoon cycles, fluid motion mechanics, and seafloor terrain geometries when governing microplastic travel and eventual settling. Past scholarly outputs published by Sun et al. <sup>[28]</sup> similarly demonstrated that microplastic drift across the Gulf of Tonkin remains heavily dictated by prevailing maritime fluid environments, while indirectly reacting to shifting monsoonal winds. Moreover, Hardesty et al. <sup>[29]</sup> strongly stress the necessity of understanding and accepting the inherent unpredictability that surrounds the drifting, shifting, and resting phases characterizing human-made garbage across pelagic habitats. Matching deductions were published by Anfu-so et al. <sup>[30]</sup>, who deduced that oceanic refuse placement is heavily governed by immediate local water behaviors. The congestion pockets located surrounding Con Co Island, specifically within regions featuring sluggish currents alongside localized swirls, validate the theory asserting that calm aquatic environments function as natural catchments capturing drifting synthetic debris.

These numerical findings endorse three administrative strategies for Con Co Island. Initially, remediation efforts must target the northern, northwest-

ern, northeastern, eastern, and southeastern coastal margins, specifically rocky coastlines plus protective seawalls. This is because the steepest documented shoreline concentration categories hit 3.5 kg/m across roughly 1,790 m of beach and 2.0 kg/m spanning approximately 1,260 m of beach; combined, these heavily congested zones constitute the majority of the projected 9.31 t encompassing coastal solid refuse, wherein plastic garbage embodies nearly 8,379 t. Secondly, subsequent surveillance protocols ought to merge recurring aerial drone mapping covering the entire coast alongside five permanent beach transects, pairing them with underwater diving inspections across seafloor congestion points. Crucial locations include Ben Tranh, Roadsteads, and Ben Da Den, where bottom synthetic prevalence was logged as frequent to heavy, with polymer coverage hitting 31.25%. Finally, origin-reduction tactics must zero in on rigid plastic containers, fishing meshes, and buoyant foam, given that rigid synthetics averaged 57.5% and floating foam 32.5% among cataloged coastal trash. These initiatives must regulate residential areas, hospitality districts, boat docking zones, fishing operations, and navigation channels. Tap water supplies must remain prioritized in testing programs because documented microplastic densities varied between 0.34 and 2.75 ng/L.

## 5. Conclusions

Our research combined aerial drone inspections, underwater diving checks of ocean floors, clinical testing for microscopic plastics in tap water, and Delft3D-Part computational forecasting to deliver an extensive evaluation regarding current conditions and fluid behaviors characterizing synthetic contamination surrounding Con Co Island.

Findings verified how synthetic refuse represents the primary element among shoreline garbage, featuring congestion zones appearing across spaces prone to trapping, including stony shores alongside defensive coastal walls. Underwater, polymer trash appeared tangled amidst coral networks and solid stone foundations, displaying maximum bottom densities immediately adjoining housing zones and active boat mooring spots.

Minute plastics appeared within every tested tap water batch, heavily emphasizing looming threats directed toward oceanic habitats and general human wellbeing. Immediate administrative takeaways firmly suggest remediation efforts must target heavily congested coastal sections, while surveillance operations require consistent repetition across static drone plus diving coordinates. Furthermore, origin suppression must strictly target prevalent trash categories alongside specific human behaviors definitively pinpointed via numerical data. Connecting documented metrics alongside administrative responses reinforces how practically valuable this unified technological methodology remains regarding synthetic refuse oversight spanning entire isolated island territories.

Presently, drone technology evolves rapidly every single day. Consequently, utilizing flying cameras to map polymer contamination across isolated territories proves incredibly efficient. Yet, primary hurdles involve securing proper gear alongside skilled operators for actual execution.

Our mathematical models heavily highlighted how seasonal wind patterns, fluid flow behaviors, alongside ocean floor geometries fundamentally govern where tiny plastic particles travel and eventually settle. Such discoveries furnish an empirical foundation guiding administrative strategies, remaining easily adaptable to numerous compact Vietnamese islands and broader regional archipelagos.

Regardless, specific constraints must firmly be recognized here. This current investigation avoided scrutinizing physical shapes or categorizing exact microscopic polymer types while bypassing advanced optical spectroscopy validations entirely. Furthermore, we skipped thoroughly comparing our mathematically projected plastic densities against actual outdoor gathered samples. Subsequent academic endeavors must resolve these exact gaps, thereby enhancing both precision and dependability within future contamination appraisals.

## Author Contributions

Conceptualization, C.V.D. and L.T.N.; methodology, T.A.T.; software, N.V.D. and T.Q.N.; validation, L.T.N. and

T.A.T.; formal analysis, T.T.T.C. and T.M.B.; investigation, N.T.P.; resources, H.C.V.; data curation, T.A.T. and T.M.B.; writing—original draft preparation, C.V.D.; writing—review and editing, C.V.D., T.A.T., N.V.D. and T.T.T.C.; supervision, L.T.N. All authors have read and agreed to the published version of the manuscript.

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## Data Availability Statement

The data that support the findings of this study are available from the data curation authors, Tu Anh Tran and Tuong Manh Bui, upon reasonable request.

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## Conflicts of Interest

The authors declare they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

## AI Use Statement

During the preparation of this manuscript, the authors used Gemini solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors

take full responsibility for the integrity and accuracy of the work.

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