Modeling-Based Seasonal Evaluation of Plastic Waste Dispersion at Nhat Le Estuary, Quang Binh

4.1. Purpose

This study aims to evaluate how plastic waste disperses from the Nhat Le estuary (Quang Binh, central Vietnam) under different seasonal conditions using numerical modeling. Nhat Le is a crucial estuary connecting inland waterways to the sea, with significant plastic inputs from urban areas, fishing activities, and tourism. There is limited existing research on how plastics travel and accumulate in this area, yet controlling pollution is vital to protect the region's coastal environment and burgeoning tourism. The project's objective is to simulate and analyze plastic waste dispersion during the two dominant monsoon seasons – Northeast (NE) and Southwest (SW) – and to compare dispersion patterns from two key source points (the Nhat Le fishing port and a nearby seafood market). By doing so, the study seeks to identify dispersion pathways, accumulation zones, and seasonal differences, providing scientific insight to inform plastic pollution management in the estuary.

4.2. Methods

Data Sources: The study utilized field surveys and external datasets. Bathymetric data of Nhat Le River was obtained from CEFD surveys. Hydrodynamic and wave conditions were characterized using in-situ observations from May 2018 (NE monsoon) and December 2019 (SW monsoon), alongside DTU16 (tide), CMEMS (wave), and HYCOM (current) models.

Model Setup: The DHI MIKE 21/3 FM model was used in 2D mode, coupling Hydrodynamic (HD), Spectral Wave (SW), and Lagrangian Particle Tracking modules. The domain covered 7 km north, 9 km south, and 4.5 km offshore, with 15,817 mesh elements (20–30 m resolution nearshore, coarser offshore). Boundary conditions included river inflow (Quan Hau Bridge) and ocean forcing (tidal, wave, current data).

Plastic Dispersion Simulation: The model simulated five plastic types (PE, PP, PVC, Nylon, PET) based on literature and VAST project CSCL 10.01/22–22. Plastic release was modeled as continuous discharge from two sources: (1) Fishing port (near estuary mouth) and (2) Seafood market (northwest riverbank), with dispersion analyzed for both monsoon seasons.

Model Calibration and Validation: The hydrodynamic-wave model was calibrated using May 2018 data, adjusting parameters to match observed water levels, currents, and wave heights. Performance metrics showed good agreement (NSE = 0.80 for wave height, 0.60 for currents/wave direction). The model was then validated with December 2019 data, achieving NSE = 0.74 for wave height, 0.73 for direction, confirming its reliability in simulating estuarine hydrodynamics across seasons. These results provide confidence for plastic dispersion modeling.

4.3. Results

Plastic dispersion at Nhat Le Estuary is driven by monsoonal currents. During the Northeast (NE) monsoon, currents flow southward, while in the Southwest (SW) monsoon, they move northward. Tidal currents also influence particle movement near the estuary.

- **Fishing Port Source – Northeast Monsoon:** Plastic from the fishing port is quickly flushed seaward along the river's main flow during the NE monsoon. Strong currents carry most debris southward along the coast, forming a narrow plume offshore. Minimal accumulation occurs near the estuary as plastics are primarily transported away.

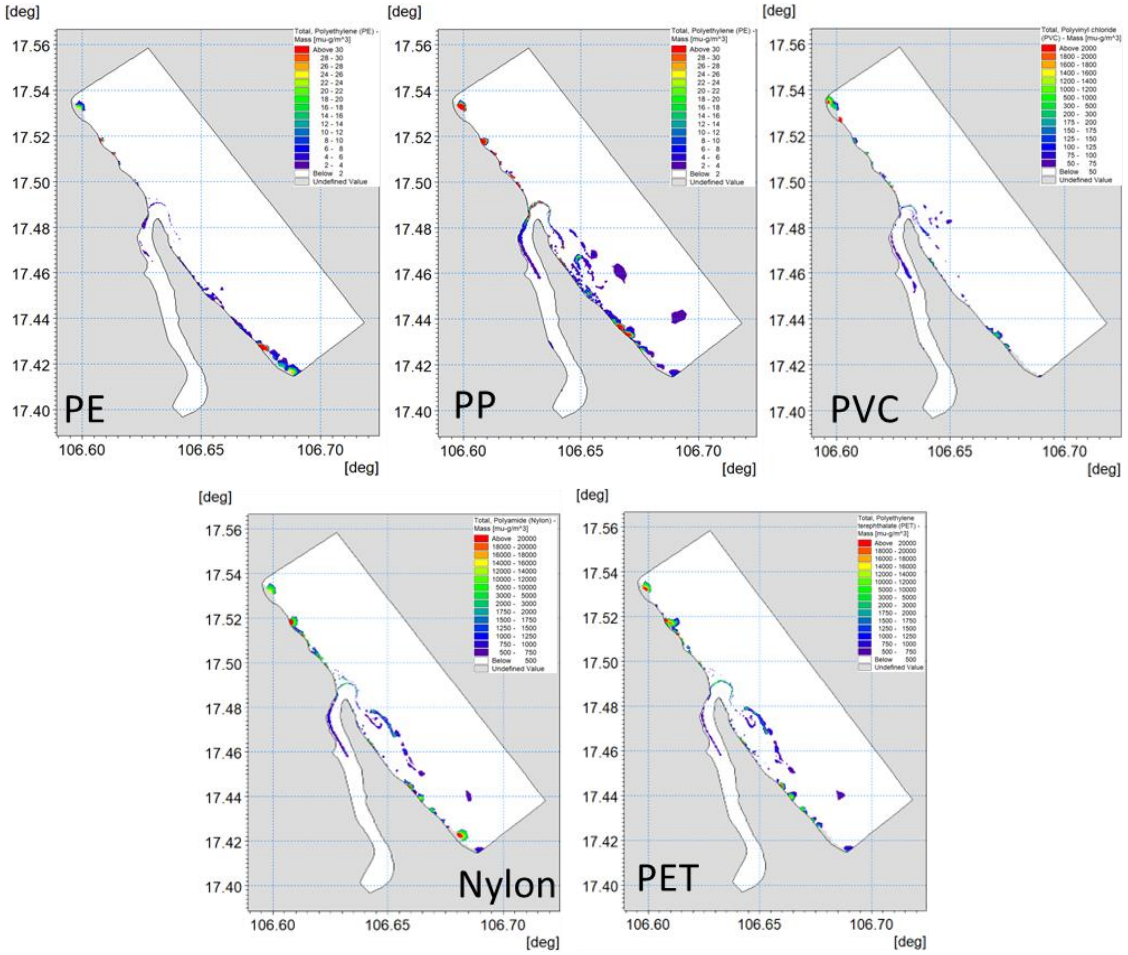

Figure 1: Results of Fishing Port source – Northeast monsoon scenario

- **Fishing Port Source – Southwest Monsoon:** During the SW monsoon, weaker flows result in wider plastic dispersion from the fishing port, with some accumulation on both estuary banks. Tidal currents spread debris nearshore, while the northward alongshore current carries plastics offshore toward northern Quang Binh beaches, forming a diffuse plume.
- **Seafood Market Source – Northeast Monsoon:** Plastic from the seafood market (left bank) follows the north riverbank during the NE monsoon, with most debris accumulating inside the estuary and along the northern shoreline. Some plastics drift across the mouth to the south bank, while the southward alongshore current carries escaped debris offshore.

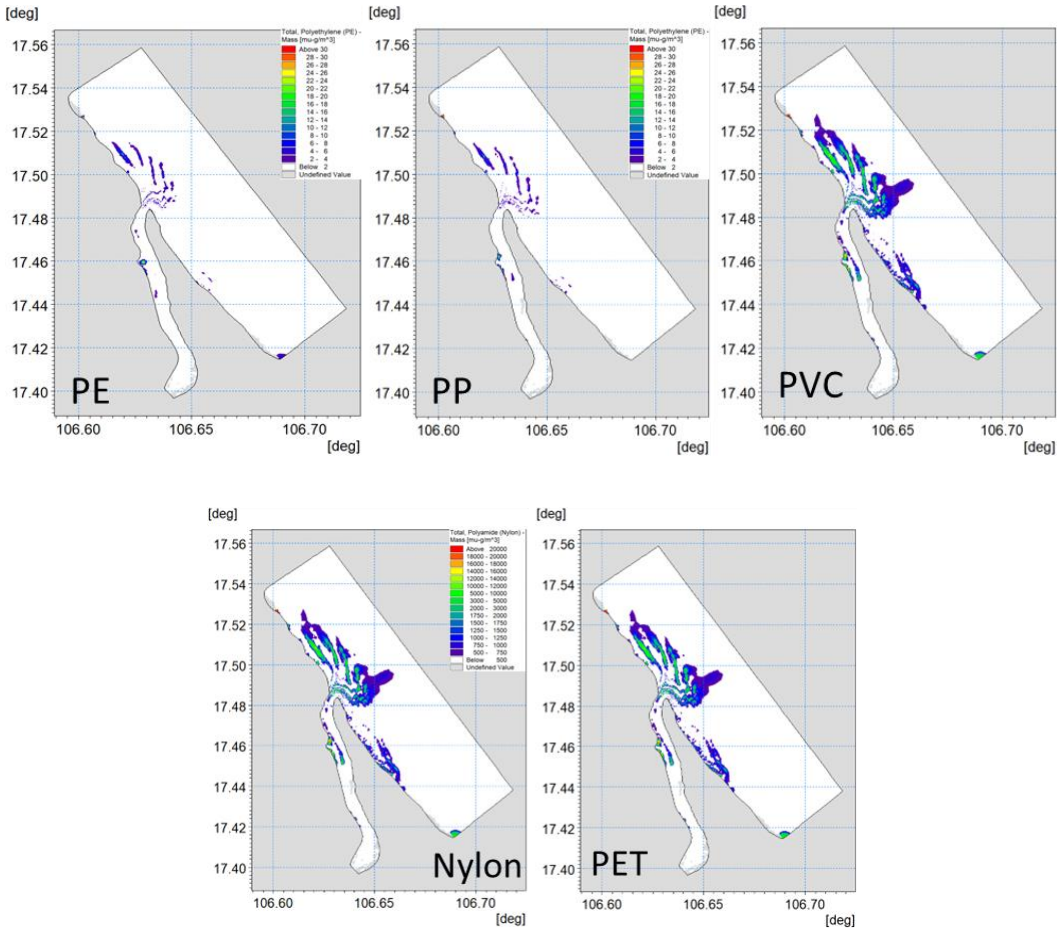

Figure 2: Results of Fishing Port source – Southwest monsoon scenario

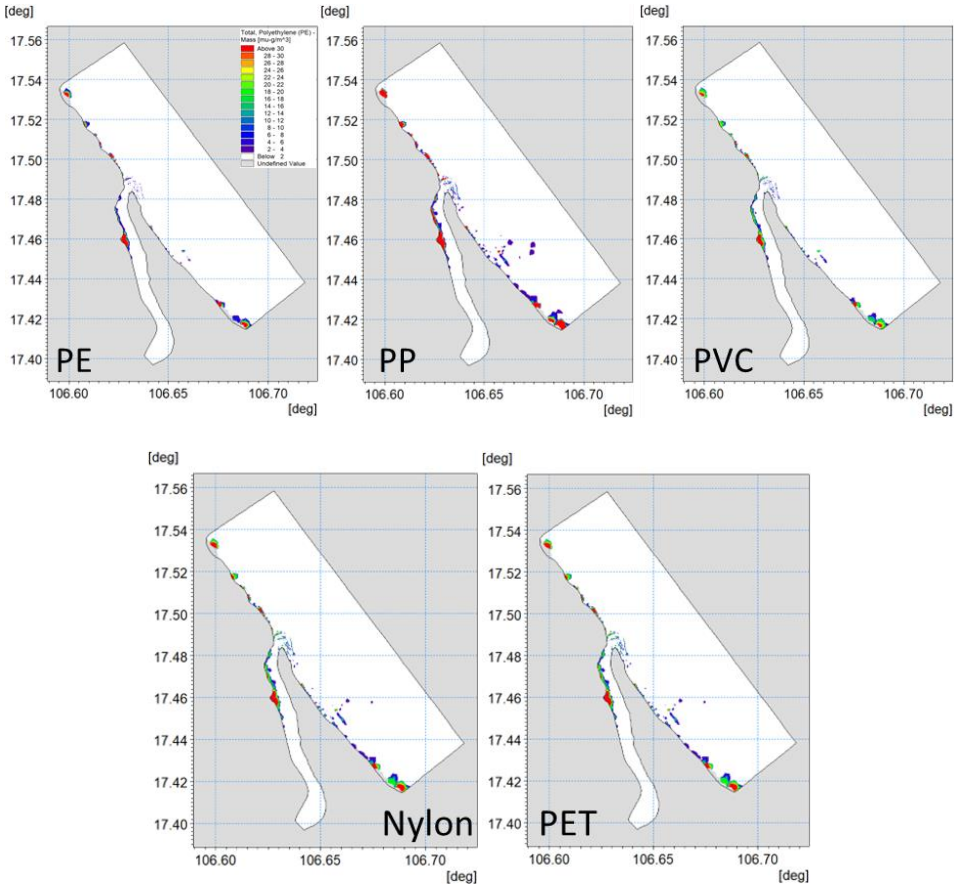

Figure 3: Results of Seafood Market Source – Northeast monsoon scenario

- **Seafood Market Source – Southwest Monsoon:** During the SW monsoon, weaker flows cause plastic from the seafood market to spread widely, with significant accumulation along the left bank inside the estuary and near the mouth. Tidal action disperses some debris to the right bank, while the northward alongshore current carries plastics offshore in a diffuse plume.

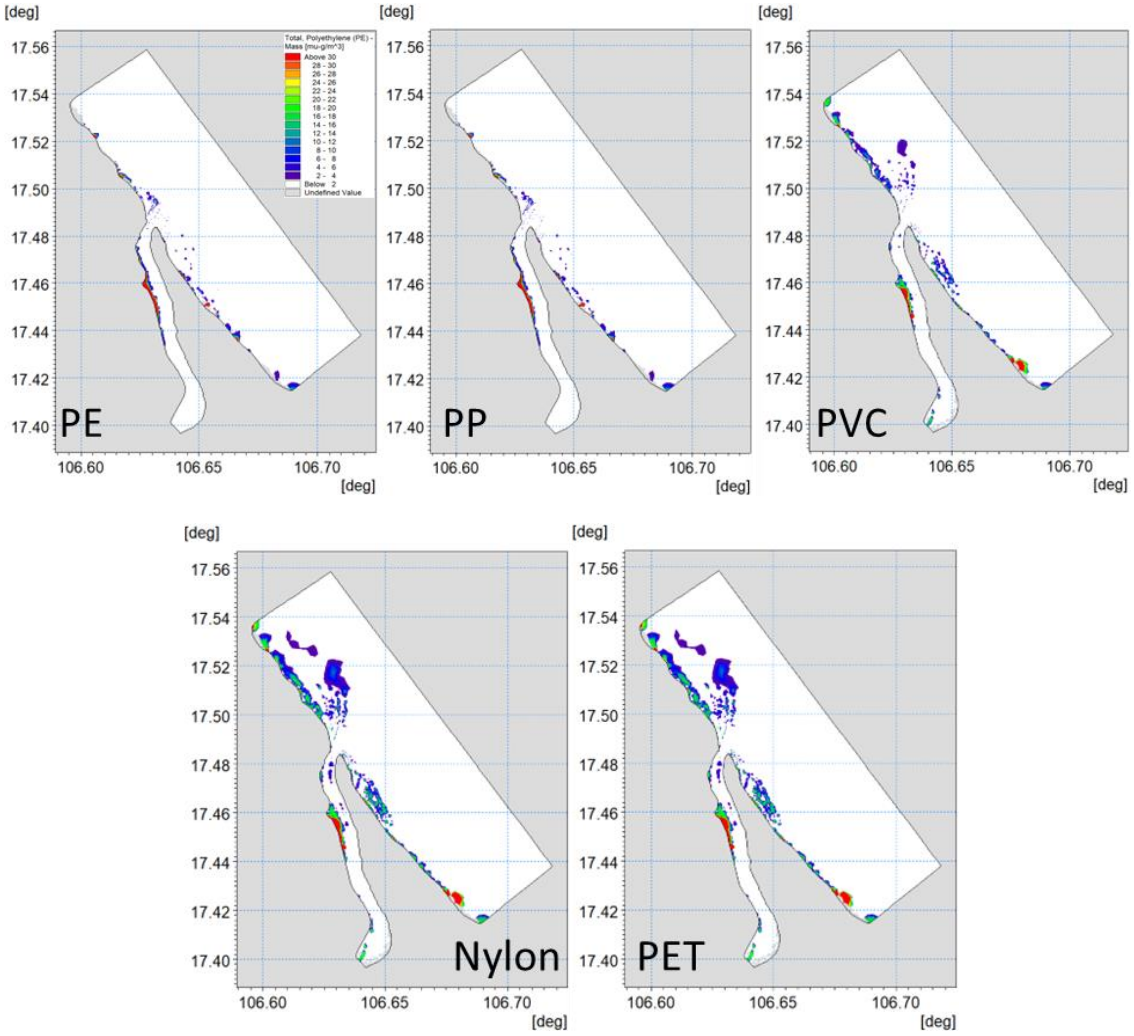

Figure 4: Results of Seafood Market Source – Southwest monsoon scenario

Key Findings: Despite differences in source location, a common trend is that **Northeast monsoon conditions produce a stronger, more directed outflow** (with debris largely flushed out and carried southward), whereas **Southwest monsoon conditions lead to weaker outflow and more local accumulation** (with debris spreading in the estuary and drifting northward once offshore). The fishing port source (near mid-channel) more effectively expels plastics to the ocean, whereas the seafood market source (bank side) leads to greater onshore retention and shoreline pollution on the source side. Both sources, however, show that some fraction of plastics will wash onto nearby beaches under the influence of waves and tides, highlighting the risk of local shoreline contamination year-round. These modeled patterns can help local authorities anticipate where clean-up or mitigation efforts might be most needed in each season (e.g., southern coast during NE monsoon, northern coast during SW monsoon, and the immediate estuary banks especially near the seafood market source).

4.4. Future Challenges

While the modeling provides useful insights, the study faced several limitations and points to areas for future improvement:

- **Data Limitations:** The study relies on assumed continuous plastic discharge due to the lack of real-world data on waste input variations. Plastic pollution likely fluctuates daily and seasonally, influenced by floods or waste dumping. More field surveys are needed to refine model inputs and better understand plastic behavior, including degradation and sinking rates.
- **Modeling Assumptions:** The **DHI MIKE 21/3 FM** model treats plastics as passive floating particles, excluding wind effects, vegetation interactions, or human removal. The 2D approach does not capture vertical mixing, which may impact microplastic transport. Future studies should explore 3D modeling and more advanced particle behavior simulations.
- **Calibration and Validation Gaps:** While the hydrodynamic model performed well, direct validation of plastic transport is limited by the lack of observed plastic dispersion data. Deploying **GPS-tracked drifters** or conducting shoreline debris surveys would improve model accuracy.
- **Collaboration Needs:** Multi-institution collaboration is crucial for data sharing and field validation. Future work aims to integrate real waste discharge measurements and advanced monitoring techniques with support from local agencies and research institutions.

In conclusion, this research has successfully demonstrated a modeling-based approach to understand seasonal plastic waste dispersion in the Nhat Le estuary. It highlights critical areas (both spatial and temporal) where plastic debris tends to accumulate under different monsoon conditions. The insights are expected to aid in developing targeted mitigation strategies, such as seasonal clean-up efforts or improved waste management at key sources. Moving forward, addressing the noted data and modeling challenges will be important to refine these results.