

From Riverine Transport to Legal Evidence: Coupled Hydrodynamic–Ecological Modelling of Transboundary Plastic Pollution

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Research Article

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Abstract

Transboundary rivers transport plastic pollution across political boundaries, yet the evidence base available for characterizing this movement remains dominated by concentration measurements that cannot resolve where contamination originates or how it is redistributed. This study develops and applies a coupled hydrodynamic-ecological modeling framework for a major transboundary river system, integrating field observations with discharge-controlled particle transport to evaluate how microplastic contamination moves from upstream catchments toward a coastal receiving environment. Field monitoring was conducted at 12 locations across two seasons and two matrices (surface water and bed sediment). Surface-water concentrations ranged from 7.8 to 41.6 particles L⁻¹ (system-wide mean 19.7 ± 8.9 particles L⁻¹), increasing from 15.1 ± 6.2 particles L⁻¹ in the dry season to 24.3 ± 9.8 particles L⁻¹ during the monsoon (approximately 61%). Sediment concentrations ranged from 74 to 386 particles kg⁻¹ dry weight. The hydrodynamic model reproduced observed discharge with an R² of 0.87 and a Nash-Sutcliffe efficiency of 0.81. Coupling concentration data with discharge substantially changed the interpretation of contamination patterns: reach-scale particle flux ranged from 1.4 × 10⁸ to 9.8 × 10⁹ particles day⁻¹ in the dry season and 5.6 × 10⁸ to 4.2 × 10¹⁰ particles day⁻¹ during the monsoon, producing a system-wide annual export on the order of 10¹² particles yr⁻¹. Source apportionment indicated that upstream boundary loading accounted for approximately 28% to 39% of the modeled annual downstream load, while locally introduced sources accounted for approximately 61% to 72%, with a combined-model mean absolute percentage error of 16.8%. Monte Carlo simulation produced a 95% prediction interval of 0.8 × 10¹² to 2.7 × 10¹² particles yr⁻¹ for annual export, and validation against withheld observations yielded an R² of 0.74. The framework converts physical transport into a mass-balance representation of contamination that can inform assessments of transboundary movement, contribution, causal pathways, and environmental exposure, while demonstrating that detection at a boundary alone is insufficient for attribution.

1. Introduction

Plastic pollution is now recognized as a planetary-scale environmental problem, and freshwater systems occupy a central position within it. Rivers serve as the dominant conduits through which land-based plastic waste reaches the ocean, and global assessments converge on the conclusion that most marine plastic debris originates from terrestrial sources delivered through river networks (Lebreton et al., 2017, p. 15611; Meijer et al., 2021). Lebreton and colleagues estimated that between 1.15 and 2.41 million tonnes of plastic waste enter the ocean from rivers each year, with more than 74% of this emission occurring between May and October, which indicates a strong hydrological control on the timing of riverine plastic export (Lebreton et al., 2017, p. 15611). Later work refined the global picture, showing that more than 1000 rivers account for approximately 80% of annual riverine plastic emissions, which range between 0.8 million and 2.7 million metric tons per year (Meijer et al., 2021). Projections of future emissions remain severe, with annual plastic waste entering aquatic ecosystems potentially reaching 53 million metric tons by 2030 under current commitments (Borrelle et al., 2020). These figures establish rivers not merely as passive channels but as active, seasonally modulated engines of plastic transport.

Microplastics, conventionally defined as plastic particles smaller than 5 mm, form a particularly difficult component of this load because they are dispersed across multiple compartments, transported at different rates according to size and density, and exchanged repeatedly between the water column, the riverbed, and adjacent floodplains. The mismatch between modeled riverine plastic export and observed marine inventories has been described as a missing sink problem, and riverine loads remain poorly constrained because sampling strategies, conversion factors, and model structures introduce very large uncertainty (Roebroek et al., 2022; Weiss et al., 2021, p. 111). This uncertainty is not a purely technical concern. It directly limits the ability of regulators, negotiators, and courts to attribute contamination to particular sources or jurisdictions.

The transboundary dimension of the problem sharpens these difficulties. Large international rivers integrate the activities of multiple states within a single hydrological unit, so that contamination detected at a border cannot, by itself, be assigned to any upstream or downstream actor. The Ganga-Brahmaputra-Meghna system, which drains more than 1.5 million km² across India, Nepal, Bhutan, China, and Bangladesh, is a clear illustration (Hossain et al., 2023, p. 3). It has been reported to release between 1 and 3 billion microplastic particles into the Bay of Bengal every day, making it one of the most significant single riverine sources of microplastic to the ocean (Hossain et al., 2023, p. 3). Schmidt and colleagues ranked the combined Meghna, Brahmaputra, and Ganges system among the highest-emitting river basins in the world (Schmidt et al., 2017, p. 12250). Contamination generated in one jurisdiction therefore becomes an exposure experienced in another, often at a considerable distance and after complex in-river processing.

This physical reality has begun to attract attention in the legal and governance literature. Tanaka argued that land-based marine plastic pollution may be attributable to multiple states simultaneously, producing situations of shared state responsibility in which the threshold for invoking responsibility is higher than in single-source cases (Tanaka, 2023). Guggisberg showed that sovereignty operates as a double-edged sword, limiting the adoption of binding global standards for land-based sources while simultaneously enabling unilateral trade-related measures that can reduce plastic waste leakage (Guggisberg, 2023). Duvic-Paoli demonstrated that the prevention principle struggles to accommodate plastics because their life cycle involves numerous operators across many borders, making identification of a state of origin difficult (Duvic-Paoli, 2020, p. 196). Bai and Wang addressed the resulting accountability gap directly, proposing that evidence collection should rely on chemical fingerprinting and oceanographic drift modeling and that causation could be reconstructed through pollution contribution ratios (Dan & Tao, 2026). Vito and colleagues similarly concluded that transboundary plastic waste management remains poorly understood because monitoring methodologies are fragmented, and they called for integrated monitoring that combines sampling, remote sensing, and oceanographic models (Vito et al., 2025).

A consistent theme across these strands is that attribution and assessment require more than the detection of particles. They require a quantitative account of how particles move, how much of a downstream burden is inherited from upstream, and how confidently those quantities can be stated. Hydrodynamic and transport models can supply precisely this kind of information, but they have rarely

been framed as evidentiary instruments for transboundary assessment. This study responds to that gap by developing a coupled hydrodynamic-ecological modeling framework for a transboundary river system, calibrating it against field observations, apportioning downstream contamination between transboundary and local inputs, and quantifying the uncertainty that surrounds the resulting estimates. The aim is not to assign legal responsibility to any state but to demonstrate that physical transport can be expressed as a defensible mass-balance relationship capable of informing downstream assessments of movement, contribution, causal pathway, and exposure.

2. Literature Review

2.1 Rivers as pathways and the global emission budget

The recognition of rivers as primary plastic pathways emerged from a series of global modeling studies that combined waste management data, population density, and hydrological information. Lebreton and colleagues produced one of the earliest calibrated estimates, reporting annual riverine plastic emissions of 1.15 to 2.41 million tonnes with more than 74% occurring between May and October and with the top 20 polluting rivers, mostly in Asia, contributing 67% of the global total (Lebreton et al., 2017, p. 15611). Schmidt, Krauth, and Wagner independently estimated riverine plastic debris export and placed the combined Meghna, Brahmaputra, and Ganges system among the largest contributors (Schmidt et al., 2017, p. 12250). Meijer and colleagues subsequently showed that emissions are distributed across far more rivers than earlier assessments suggested, with more than 1000 rivers accounting for roughly 80% of annual emissions and small urban rivers emerging among the most polluting (Meijer et al., 2021). Borrelle and colleagues framed the trajectory of the problem, estimating that between 19 and 23 million metric tons, or about 11%, of plastic waste generated globally in 2016 entered aquatic ecosystems and that emissions could reach 53 million metric tons per year by 2030 (Borrelle et al., 2020).

Counterbalancing these emission estimates is a persistent mass-balance discrepancy. Weiss and colleagues investigated the fate of riverine microplastics and found that estimates of global flux vary enormously depending on the sampling techniques and mass conversion factors applied, yielding values ranging from 129 kt yr⁻¹ to several thousand kt yr⁻¹ for the same conceptual budget (Weiss et al., 2021, p. 111). Roebroek and colleagues quantified this uncertainty systematically, showing that model structure and parameter uncertainty alone can span up to four orders of magnitude, that the homogenization of field observations adds a further three orders of magnitude, and that correlations between river discharge and plastic flux are never above 0.5 and vary strongly between catchments (Roebroek et al., 2022). Zhang and colleagues narrowed the range of global ocean emissions using observed seawater concentrations, converging on approximately 1.5 orders of magnitude of uncertainty (Zhang et al., 2023, p. 1377). Sonke and colleagues projected global dispersal under policy scenarios and estimated a total marine plastic pool of 263 teragrams with land-to-sea transport of 14 Tg per year, noting that microplastic concentrations remain elevated after 2060 because of continued fragmentation of legacy waste (Sonke et al., 2025). Collectively, this literature establishes both the magnitude of riverine contributions and the fragility of the estimates that describe them.

2.2 Microplastics in South Asian and GBM river systems

Regional studies provide the empirical foundation for understanding contamination in the GBM system and its receiving waters. Alam, Shammi, and Tareq sampled the Ganges River Basin through to the Meghna Estuary and reported average microplastic concentrations of 50.9 ± 24.4 particles L^{-1} in upstream water and 64.1 ± 26.3 particles L^{-1} in downstream water, with sediment concentrations of 2953.49 ± 1670.52 particles kg^{-1} upstream and 4014.66 ± 1717.59 particles kg^{-1} downstream (Alam et al., 2023). Hossain and colleagues provided the first observations for the Meghna estuary itself, recording surface-water abundances from 33.33 to 316.67 items m^{-3} with a mean of 128.89 ± 67.94 items m^{-3} and a morphology dominated by fibers at 87% (Hossain et al., 2023). Banik and colleagues compared five major estuaries along the northern Bay of Bengal and found that the Meghna showed the least contamination in both surface water (150.00 ± 65.62 items m^{-3}) and sediment (30.56 ± 9.34 items kg^{-1}) among the systems examined, while classifying all five estuaries at hazard level V according to polymer risk (Banik et al., 2023). Rakib and colleagues characterized sediments of the Karnaphuli River estuary, reporting a fiber-dominated assemblage with most particles below 0.5 mm (Rakib et al., 2022, p. 8581). Neelavannan and colleagues examined the Hooghly distributary of the Ganga through to the Sundarbans Biosphere Reserve, recording mean concentrations of 718 ± 244 items m^{-3} in water and 428 ± 266 items kg^{-1} dry weight in sediment, with a polymer assemblage dominated by high-density polyethylene at 33% (Neelavannan et al., 2023).

The broader waste-management context in the region is equally relevant. Mosaddek and Khanam estimated that Bangladesh generates approximately 9.8 million tons of plastic waste annually, of which only about 14% is recycled, with the remainder entering landfills, open dumps, rivers, and the ocean (Mosaddek & Khanam, 2025, p. 10). The combination of high emission potential, large transboundary inflow, and dense downstream exposure makes the GBM system a critical setting for applied transport research.

2.3 Drivers of spatial and seasonal variability

A recurring finding across fluvial studies is that plastic abundance is strongly structured by hydrology. Van Emmerik and colleagues demonstrated in the Saigon River that macroplastic transport varies by up to a factor of five within a measurement period and that rainfall, discharge, and the presence of organic material are associated with transport variation (Emmerik et al., 2019, p. 13549). Bai and colleagues reviewed the controlling factors of riverine microplastic flux and noted that as much as 74.5% of the total plastic load emitted from rivers occurs between May and October, with studies attributing higher wet-season concentrations to increased land-river connectivity and others attributing lower wet-season concentrations to dilution by increased discharge (Bai et al., 2021, p. 69). Amrutha and colleagues reported that monsoonal flushing transported microplastics from the Western Ghats catchment toward the Arabian Sea, with higher rainfall in 2019 associated with increased export and shortened residence times under high-energy conditions (Amrutha et al., 2022, p. 32310). Rolf and colleagues connected flooding frequency and floodplain topography to microplastic abundance in Rhine alluvial soils, reporting

25,502 to 51,119 particles per kg dry soil in the top 5 cm and demonstrating that local topography governs accumulation (Rolf et al., 2022). Munkhbat and colleagues showed that repeated movement of plastic debris between surface water and the floodplain, driven by water-level change and turbulence, alters surface properties and degradation in the Tuul River system (Munkhbat et al., 2024, p. 65555). Together these studies indicate that the same hydrological signal can produce opposing concentration responses depending on whether mobilization or dilution dominates locally.

2.4 Numerical modeling of microplastic transport

Numerical transport modeling offers a means of resolving these competing effects. Pilechi and colleagues developed CaMPSim-3D, a Lagrangian three-dimensional particle-tracking model coupled to an Eulerian hydrodynamic system, and showed that the choice of advection scheme can change predicted residence times by up to 100% (Pilechi et al., 2022). Atwood and colleagues modeled coastal accumulation of microplastics emitted by the Po River and found that the quantity of particles discharged was only semi-coupled to beaching rates, which were strongly mouth dependent and concentrated within the first ten days (Atwood et al., 2019). Duan and colleagues coupled a distributed hydrology model with an estuarine ocean model and demonstrated that including the estuary substantially altered estimates of microplastic discharge to the ocean because of salinity-induced retention in Delaware Bay (Duan et al., 2026). Zhou and colleagues simulated river- and urban-related microplastic pollution in the northern Gulf using a regional ocean model forced by major river discharges (Zhou et al., 2025, p. 8). Alvarez Barrantes and colleagues used a hydromorphodynamic model with an active riverbed to show that deposited microplastics increase the erosive capacity of flow, producing deeper channels and larger bars, and that suspended load concentrates in the channel thalweg (Barrantes et al., 2025). These studies collectively establish the methodological toolkit on which the present framework draws.

2.5 Source apportionment, uncertainty, and mass balance

Attribution requires that transport models be paired with source apportionment. Strokhal and colleagues modeled river export of macro- and microplastics from urban and waste-management sources worldwide and performed sensitivity analysis showing that river export of microplastics is somewhat sensitive to wastewater treatment removals while remaining weakly sensitive to per-capita inputs from many diffuse sources (Strokhal et al., 2023, p. 4848). Unice and colleagues applied integrated geospatial transport models to tire and road wear particles in the Seine watershed and concluded that mass balance assessments of microplastics are an important component of risk characterization (Unice et al., 2018, p. 1648). Roebroek and colleagues reinforced the centrality of uncertainty, showing that the yearly plastic load in rivers remains poorly constrained and that most global models assuming a discharge-driven flux are not well supported by observations (Roebroek et al., 2022). The lesson from this body of work is that a defensible apportionment must be accompanied by an explicit uncertainty budget rather than a point estimate.

2.6 Polymer and particle characteristics as diagnostic tracers

Particle characteristics provide independent lines of evidence that complement hydrological and concentration data. Klein and colleagues analyzed river shore sediments of the Rhine and Main and found that polyethylene, polypropylene, and polystyrene together accounted for more than 75% of identified polymer types (Klein et al., 2015). Nguyen and colleagues reported polymer compositions along the Red River to the Gulf of Tonkin of 19.7% polyethylene, 26.7% polypropylene, 25.8% polyethylene terephthalate, and 9.3% polyvinyl chloride in water, with 17.6%, 39.7%, 14.2%, and 10.4% respectively in sediment, and attributed the dominance of low-density polymers to their widespread distribution in aqueous systems (Nguyen et al., 2024, p. 177784). Strady and colleagues established a baseline for a developing Southeast Asian country and identified polyethylene and polypropylene as the most common polymers among characterized particles (Strady et al., 2020, p. 111872). Rami and colleagues confirmed eight polymer types in surface water and sediment of the Zayandeh-rud River using infrared spectroscopy (Rami et al., 2023, p. 211). Karing and colleagues reported polyethylene as the dominant polymer in two Malaysian rivers, followed by polystyrene, polycarbonate, and polyethylene terephthalate (Karing et al., 2023, p. 8). Because polymer type and morphology reflect both source and transport history, they are valuable diagnostic tracers when concentration data alone are ambiguous.

2.7 Transboundary governance and evidentiary standards

The governance literature clarifies what kinds of evidence would actually be useful in a transboundary setting. Tanaka concluded that because marine plastic pollution may be attributable to multiple states, shared responsibility raises the barrier for invocation and proposed elaborating due diligence obligations, strengthening compliance procedures, and interlinking regimes governing the marine environment and international watercourses (Tanaka, 2023). Guggisberg emphasized that effective binding commitments on land-based sources are rare because of the sensitive nature of territorial sovereignty, while the Basel Convention regime offers a widely ratified framework for reducing trade in hard-to-recycle plastics (Guggisberg, 2023). Duvic-Paoli showed that life-cycle complexity obscures the state of origin, complicating application of the prevention principle (Duvic-Paoli, 2020, p. 196). Bai and Wang proposed evidence collection and sharing protocols based on chemical fingerprinting and oceanographic drift modeling, alongside reconstructed causation through pollution contribution ratios (Dan & Tao, 2026). Vito and colleagues reviewed monitoring methodologies for transboundary plastics and concluded that no single technology is sufficient, recommending an integrated approach that supports more effective decision-making (Vito et al., 2025). Read together, this literature indicates that evidentiary utility depends on quantifying contributions and their uncertainty, not merely on detecting contamination.

3. Research Gap

Despite substantial progress on each individual strand of this problem, the literature has not yet integrated them into a single framework oriented toward transboundary assessment. Three specific gaps stand out.

First, global and regional emission models describe where plastic enters rivers, and hydrodynamic models describe how particles move once entrained, but these bodies of work are rarely combined to produce a source-apportioned mass balance for a specific transboundary reach. Studies that quantify riverine flux tend to report aggregate exports, while studies that model transport tend to treat upstream boundaries as given rather than partitioning downstream loads between inherited and locally generated contamination.

Second, uncertainty is acknowledged as a fundamental limitation but is seldom quantified in a form that decision makers can use. Existing analyses show that model structure, parameter choice, and observation homogenization can introduce several orders of magnitude of uncertainty, yet most applied studies still report single point estimates of flux or concentration without prediction intervals.

Third, the linkage between physical modeling and legal or governance reasoning remains largely conceptual. Contributions from the legal literature describe what would be needed for attribution, such as contribution ratios, fingerprinting, and drift modeling, but applied studies rarely produce these quantities in a form tied to actual field measurements. Consequently, the evidentiary gap identified in the governance literature persists in practice. This study addresses these gaps by coupling field observations with discharge-controlled transport modeling in a transboundary river system, apportioning downstream contamination between upstream boundary loading and local sources, and reporting the resulting estimates with explicit uncertainty bounds.

4. Research Objectives

1. To characterize the seasonal hydrodynamic regime of the study system, including discharge variability and surface-water velocity, and to evaluate how well a hydrodynamic model reproduces observed discharge.
2. To quantify the spatial and seasonal distribution of microplastics in surface water and bed sediment across the monitoring network, including particle morphology, size class, and polymer composition.
3. To estimate reach-scale and system-wide particle transport by coupling observed microplastic concentrations with modeled river discharge, and to identify where and when peak downstream flux occurs.
4. To apportion the modeled downstream particle load between transboundary upstream boundary inputs and locally introduced domestic sources, and to evaluate competing source scenarios against observed concentrations.
5. To quantify uncertainty in the export estimates through Monte Carlo simulation and model validation, and to translate the resulting mass-balance representation into a form that can inform transboundary dispute assessment without assigning legal responsibility.

5. Methodology

5.1 Study system and monitoring design

The study was conducted along a transboundary river continuum that extends from an upstream boundary through urbanized and industrialized middle reaches to a low-gradient downstream system discharging toward a coastal receiving environment. The monitoring network comprised 12 sampling locations distributed across the longitudinal gradient of the river. Sampling was conducted during two hydrological periods, the dry season and the monsoon season, in order to capture the range of discharge conditions that governs particle mobility. At each location, two matrices were sampled: surface water and bed sediment. The design is summarized in Table 1.

Table 1
Design of the field monitoring program

Component	Description
Study system	Transboundary river continuum from upstream boundary to lower reach and coastal receiving environment
Sampling locations	12 sites distributed across upstream, middle, and downstream reaches
Sampling periods	Dry season; monsoon season
Matrices sampled	Surface water; bed sediment
Hydrodynamic measurements	River discharge; surface-water velocity
Particle characterization	Morphology; size class; polymer type
Model evaluation	Withheld station observations; uncertainty simulation

5.2 Field sampling and laboratory analysis

Surface-water samples were collected from the upper water column under conditions that avoided disturbance of bed material, and were processed by sequential sieving and filtration to isolate the microplastic size fraction of interest. Bed sediment was collected from depositional and transport zones and subjected to density separation before filtration. All filters were examined under a stereomicroscope for particle enumeration and morphological classification. Recovered particles were assigned to morphological categories of fragment, fiber, film, and foam-like particle, and to size classes spanning less than 1 mm, 1 to 2 mm, and 2 to 5 mm. A subset of particles was subjected to spectroscopic polymer identification to determine the relative contribution of polyethylene, polypropylene, polyethylene terephthalate, polystyrene, and other polymers. Procedural blanks and contamination controls were applied throughout to limit background interference.

5.3 Hydrodynamic modeling

A coupled hydrodynamic-ecological modeling framework was established for the study reach. The hydrodynamic component resolved flow depth, velocity, and discharge along the river channel under time-varying upstream and lateral boundary conditions, using a computational domain discretized along the longitudinal gradient of the system. The model was forced with observed discharge at the upstream boundary and calibrated against measured discharge and velocity at monitoring stations using standard performance metrics, including the coefficient of determination and the Nash-Sutcliffe efficiency. Model performance was assessed separately for medium-to-high flow conditions and for the rapidly changing conditions associated with the onset and recession of the monsoon.

5.4 Coupled transport and flux estimation

The ecological component of the framework represented microplastic particles as passively transported constituents whose behavior depends on flow velocity, discharge, and particle characteristics. Particle transport was computed by combining modeled discharge with measured microplastic concentrations to generate reach-scale flux estimates, expressed as particles per day. Daily flux estimates were integrated over the annual hydrograph to produce a system-wide export estimate for the study year. The coupled model was used to evaluate the partitioning of particles between active downstream transport and temporary deposition under contrasting hydrological states, and to identify the hydrological conditions under which ecologically sensitive downstream areas experience peak exposure.

5.5 Source apportionment, uncertainty, and validation

Three source scenarios were evaluated: an upstream boundary loading scenario representing transboundary input alone, a local domestic-source scenario representing incremental sources introduced within the study area, and a combined scenario incorporating both. Each scenario was compared with observed downstream concentrations, and the combined model was evaluated using the mean absolute percentage error. The relative proportional contributions of upstream and local sources to the modeled annual downstream particle load were then estimated.

Uncertainty was quantified using Monte Carlo simulation, in which concentration, discharge, and particle transport parameters were sampled within plausible ranges to generate a prediction interval for annual downstream export. Model validation was performed using sampling observations withheld from the calibration process, and the agreement between observed and predicted concentrations was assessed. A sensitivity analysis was conducted to identify which parameters contributed most strongly to uncertainty in predicted downstream flux.

5.6 Conceptual framework

The overall analytical chain, from field observation through transport modeling to evidentiary output, is summarized in Fig. 1.

6. Results

6.1 Hydrodynamic characteristics of the study system

River discharge exhibited pronounced seasonal variability across the study period. Mean discharge during the monsoon season was approximately 3.2 to 4.7 times higher than during the dry season, with the largest increase observed in the lower Meghna reach. Mean surface-water velocity ranged from 0.31 to 1.18 m s⁻¹ across sampling locations, with higher velocities occurring during peak monsoon conditions.

The hydrodynamic model reproduced the observed seasonal discharge pattern reasonably well. Comparison between observed and modeled discharge produced an R² of 0.87, with a Nash-Sutcliffe efficiency of 0.81. Model performance was strongest during medium-to-high flow conditions, whereas greater deviations occurred during rapidly changing discharge conditions at the onset and recession of the monsoon. Summary hydrodynamic metrics are presented in Table 2.

Table 2
Hydrodynamic model characteristics and performance

Metric	Value
Monsoon-to-dry-season discharge ratio	3.2 to 4.7
Mean surface-water velocity (m s ⁻¹)	0.31 to 1.18
Coefficient of determination, observed versus modeled discharge	0.87
Nash-Sutcliffe efficiency	0.81

6.2 Spatial distribution of microplastic contamination

Microplastics were detected at all sampling locations during both sampling periods. Surface-water concentrations ranged from 7.8 to 41.6 particles L⁻¹, with a system-wide mean of 19.7 ± 8.9 particles L⁻¹. Upstream stations had comparatively lower concentrations, ranging from 7.8 to 14.3 particles L⁻¹, whereas concentrations increased progressively through the urbanized and industrialized middle reaches. The highest concentration, 41.6 particles L⁻¹, was recorded at a downstream station in the lower Meghna system during the monsoon.

Sediment samples contained between 74 and 386 particles kg⁻¹ dry weight, with higher concentrations generally occurring at low-velocity depositional sites. Unlike surface-water concentrations, sediment abundance did not show a consistent monotonic downstream increase. Concentration summary statistics are reported in Table 3.

Table 3
Summary of microplastic concentrations across matrices and seasons

Descriptor	Value
Surface-water mean $\pm$ SD (particles L ⁻¹)	19.7 $\pm$ 8.9
Surface-water range (particles L ⁻¹)	7.8 to 41.6
Dry-season surface-water mean $\pm$ SD (particles L ⁻¹)	15.1 $\pm$ 6.2
Monsoon surface-water mean $\pm$ SD (particles L ⁻¹)	24.3 $\pm$ 9.8
Upstream station range (particles L ⁻¹)	7.8 to 14.3
Highest single surface-water measurement (particles L ⁻¹)	41.6
Sediment range (particles kg ⁻¹ dry weight)	74 to 386

6.3 Seasonal variability

Microplastic concentrations were consistently higher during the monsoon at 9 of the 12 sampling locations. Mean surface-water abundance increased from 15.1 $\pm$ 6.2 particles L⁻¹ during the dry season to 24.3 $\pm$ 9.8 particles L⁻¹ during the monsoon, corresponding to an approximately 61% increase. The seasonal contrast is illustrated in Fig. 2.

The seasonal difference was particularly pronounced at downstream stations, where increased discharge was accompanied by resuspension of previously deposited particles and enhanced downstream transport. A negative-binomial regression indicated a positive association between discharge and microplastic abundance after accounting for sampling location and season. The estimated incidence-rate ratio was 1.18 (95% CI: 1.09 to 1.28) for each standardized increase in discharge.

6.4 Particle characteristics and polymer composition

Fragments were the predominant particle morphology, accounting for 46.8% of identified particles, followed by fibers (38.5%), films (11.2%) and foam-like particles (3.5%). Morphological composition is shown in Fig. 3.

Particles smaller than 1 mm represented 58.7% of the recovered particles. The proportion declined to 27.4% for particles between 1 and 2 mm and 13.9% for particles between 2 and 5 mm.

Among particles subjected to polymer identification, polyethylene represented the largest proportion (31.4%), followed by polypropylene (PP; 27.1%), polyethylene terephthalate (PET; 18.6%), polystyrene (PS; 11.3%) and other polymers (11.6%). Polymer composition is shown in Fig. 4. The relative contribution of PE and PP was higher in surface-water samples, whereas PET-associated particles were relatively more frequent in sediment samples. Compositional data are summarized in Table 4.

Table 4
Morphological, size-class, and polymer composition of microplastic particles

Category	Class	Proportion (%)
Morphology	Fragments	46.8
Morphology	Fibers	38.5
Morphology	Films	11.2
Morphology	Foam-like	3.5
Size	Less than 1 mm	58.7
Size	1 to 2 mm	27.4
Size	2 to 5 mm	13.9
Polymer	Polyethylene	31.4
Polymer	Polypropylene	27.1
Polymer	Polyethylene terephthalate	18.6
Polymer	Polystyrene	11.3
Polymer	Other polymers	11.6

6.5 Particle transport

Coupling the microplastic concentration data with modeled river discharge substantially altered the interpretation of contamination patterns. Locations with moderate concentrations but high discharge generated considerably greater particle flux than high-concentration, low-discharge sites.

Estimated particle transport ranged from approximately 1.4×10^8 to 9.8×10^9 particles day⁻¹ across individual river reaches during the dry season. During the monsoon, modeled transport increased to approximately 5.6×10^8 to 4.2×10^{10} particles day⁻¹.

The highest modeled flux occurred in the lower Meghna reach during peak monsoon discharge. Integrating the modeled daily fluxes over the annual hydrograph produced an estimated system-wide export on the order of 10^{12} particles yr⁻¹ toward the coastal receiving environment. Transport estimates are summarized in Table 5.

Sensitivity analysis showed that discharge uncertainty contributed more strongly to annual flux uncertainty than moderate changes in the particle concentration parameter.

Table 5
Estimated reach-scale and system-wide particle transport

Scale and period	Particle flux
Reach-scale, dry season (particles day ⁻¹)	1.4×10^8 to 9.8×10^9
Reach-scale, monsoon (particles day ⁻¹)	5.6×10^8 to 4.2×10^{10}
System-wide annual export (particles yr ⁻¹)	On the order of 10^{12}

6.6 Hydrodynamic-ecological coupling

The coupled model indicated that particle transport was strongly controlled by the interaction between flow velocity, discharge and particle characteristics. Smaller particles remained predominantly within the water column under high-flow conditions, whereas larger and denser particles showed greater probabilities of temporary deposition.

Approximately 63% of particles remained in active downstream transport during high-flow conditions, compared with approximately 38% during low-flow conditions. Conversely, modeled temporary deposition increased during low-flow periods, particularly in shallow depositional zones. This contrast is summarized in Table 6.

Ecologically sensitive downstream areas therefore experienced substantially different exposure depending on the hydrological state of the system. Model simulations indicated that peak exposure occurred during the transition from high-flow conditions to declining discharge, when previously mobilized particles were transported into slower-flowing coastal and estuarine environments.

Table 6
Partitioning of particles between active transport and deposition

Hydrological state	Particles in active downstream transport (%)
High flow	63
Low flow	38

6.7 Source-apportionment scenarios

Three source scenarios were evaluated to distinguish upstream loading from incremental domestic inputs.

Under the transboundary-input-only scenario, modeled downstream concentrations were substantially lower than measured concentrations at most urbanized downstream stations. The discrepancy increased progressively along the middle and lower river reaches.

Under the domestic-source-only scenario, upstream boundary concentrations could not be reproduced because measurable microplastic concentrations were already present at the upstream boundary stations.

The combined model, incorporating both upstream boundary loading and locally estimated sources, produced the closest correspondence with observed concentrations, with a mean absolute percentage error of 16.8%.

The simulations suggested that upstream inputs accounted for approximately 28% to 39% of the modeled annual downstream particle load, while locally introduced sources accounted for approximately 61% to 72%. These proportions varied substantially between seasons and river reaches. The apportionment is represented schematically in Fig. 5.

6.8 Uncertainty and model validation

Monte Carlo simulations incorporating uncertainty in concentration, discharge and particle transport parameters produced a 95% prediction interval of approximately 0.8×10^{12} to 2.7×10^{12} particles yr⁻¹ for annual downstream export.

Model validation using withheld sampling observations produced an R² of 0.74 between observed and predicted microplastic concentrations. The model performed better for downstream stations than for individual upstream stations, where localized variability in particle inputs produced greater prediction errors.

Sensitivity analysis identified discharge, upstream boundary concentration and local source strength as the three parameters contributing most strongly to uncertainty in predicted downstream flux. Apportionment and validation results are consolidated in Table 7.

Table 7
Source apportionment, model agreement, and uncertainty

Metric	Value
Upstream (transboundary) contribution to annual downstream load	28 to 39%
Local source contribution to annual downstream load	61 to 72%
Mean absolute percentage error, combined model	16.8%
Discharge-abundance incidence-rate ratio (95% CI)	1.18 (1.09 to 1.28)
Validation coefficient of determination, withheld observations	0.74
Annual export 95% prediction interval (particles yr ⁻¹)	0.8×10^{12} to 2.7×10^{12}

6.9 Relevance to transboundary dispute assessment

The coupled modeling framework produced three quantitatively distinguishable components of the contamination pathway: upstream boundary loading, incremental domestic loading, and downstream export. The results therefore allowed the physical transport pathway to be represented as a mass-balance relationship rather than relying solely on concentration measurements.

Importantly, the model did not establish legal responsibility for any particular state. Instead, it generated quantitative evidence that could potentially inform assessments of transboundary movement, contribution to downstream contamination, causal pathways and environmental exposure.

The results further demonstrated that detection of microplastics at an international boundary alone would provide insufficient evidence for attribution. Attribution was more robust when boundary concentrations were combined with discharge measurements, downstream concentration changes, modeled particle trajectories and uncertainty estimates. This distinction was particularly important because a substantial proportion of the modeled downstream load was generated within the study area after the particles had crossed the upstream boundary.

7. Conclusion

This study set out to determine whether a coupled hydrodynamic-ecological modeling framework could convert routine field observations of microplastic contamination into a quantitative, source-apportioned account of transboundary particle transport. The results indicate that it can, and that doing so changes the interpretation of contamination data in ways that are directly relevant to transboundary assessment.

The hydrodynamic analysis confirmed that the study system is strongly seasonal, with monsoon discharge approximately 3.2 to 4.7 times higher than dry-season discharge and mean surface-water velocities ranging from 0.31 to 1.18 m s⁻¹. The model reproduced observed discharge with an R² of 0.87 and a Nash-Sutcliffe efficiency of 0.81, with the strongest performance under medium-to-high flow conditions and larger deviations during the rapidly changing flows at the onset and recession of the monsoon. This performance profile is adequate for flux estimation but indicates that the transitional periods carry the greatest structural uncertainty.

Contamination was widespread and spatially structured. Surface-water concentrations ranged from 7.8 to 41.6 particles L⁻¹ with a mean of 19.7 ± 8.9 particles L⁻¹, sediment concentrations ranged from 74 to 386 particles kg⁻¹ dry weight, and abundance increased from 15.1 ± 6.2 to 24.3 ± 9.8 particles L⁻¹ between the dry and monsoon seasons, an increase of approximately 61% that occurred at 9 of the 12 locations. The negative-binomial regression supported a positive discharge-abundance association with an incidence-rate ratio of 1.18 (95% CI: 1.09 to 1.28). Particle characteristics were consistent with a mixed and partly degraded source pool, with fragments (46.8%) and fibers (38.5%) dominating morphology, particles smaller than 1 mm representing 58.7% of the assemblage, and PE (31.4%) and PP (27.1%) dominating polymer composition.

The most consequential finding concerns the divergence between concentration and flux. Coupling concentration data with discharge showed that moderate-concentration, high-discharge reaches generated far greater particle flux than high-concentration, low-discharge sites, with reach-scale transport ranging from 1.4 × 10⁸ to 9.8 × 10⁹ particles day⁻¹ in the dry season and 5.6 × 10⁸ to 4.2 × 10¹⁰ particles day⁻¹ during the monsoon. Integrated annual export was on the order of 10¹² particles yr⁻¹, and discharge uncertainty contributed more to the uncertainty of this figure than moderate changes in the

concentration parameter. Any assessment based on concentration alone would therefore misrepresent the relative importance of different reaches and the seasonality of exposure.

Source apportionment produced the clearest result for transboundary purposes. The transboundary-input-only scenario underestimated downstream concentrations, and the domestic-source-only scenario could not reproduce upstream boundary conditions, while the combined model achieved a mean absolute percentage error of 16.8%. Upstream inputs accounted for approximately 28% to 39% of the modeled annual downstream load, and locally introduced sources accounted for approximately 61% to 72%, with substantial variation between seasons and reaches. Monte Carlo simulation placed the annual export within a 95% prediction interval of 0.8×10^{12} to 2.7×10^{12} particles yr^{-1} , and validation against withheld observations produced an R^2 of 0.74, performing better at downstream than at upstream stations.

Two broader implications follow. First, the framework demonstrates that physical transport can be represented as a mass balance with separable components, which is the form of evidence most useful for assessments of movement, contribution, and causal pathway. Second, the results show that boundary detection alone is insufficient for attribution, because a substantial proportion of the downstream load is generated within the study area after particles have crossed the boundary. Robust attribution requires the combination of boundary concentrations, discharge measurements, downstream concentration changes, modeled trajectories, and uncertainty estimates.

The study has limitations that should qualify its interpretation. The analysis is based on two sampling campaigns, which constrains the resolution of seasonal dynamics, and the parameterization of local sources relies on estimated rather than directly inventoried inputs. Structural uncertainty in the hydrodynamic model is highest during transitional flow periods, precisely when mobilization and export are most dynamic. The framework does not resolve particle fragmentation or density change during transport, which the literature identifies as important processes affecting fate. Future work should extend the temporal coverage, incorporate direct source inventories, and integrate particle-aging processes into the transport description.

Despite these limitations, the study demonstrates a workable pathway from riverine measurement to evidentiary output. By expressing contamination as a quantified mass balance with explicit contribution shares and uncertainty bounds, the framework provides a defensible basis for technical input into transboundary discussions, while deliberately stopping short of assigning legal responsibility, which remains a matter for the appropriate institutions.

Declarations

Informed Consent Statement

Not Applicable.

Ethical Review

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Center for Higher Studies and Research (CHSR), Bangladesh University of Professionals (Protocol Code: CSR2024-04-4972).

Conflicts of Interest

Not applicable.

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Author Contributions:

NM had the idea and designed the research, performed the background study, literature search, data collection, and data analysis and provided support for drafting the manuscript. NM reviewed and revised the manuscript, and did the necessary linguistic corrections.

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Data Availability Statement:

The original contributions presented in this study are included in the article and supplementary material. Further inquiries can be directed to the corresponding author.

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Figures

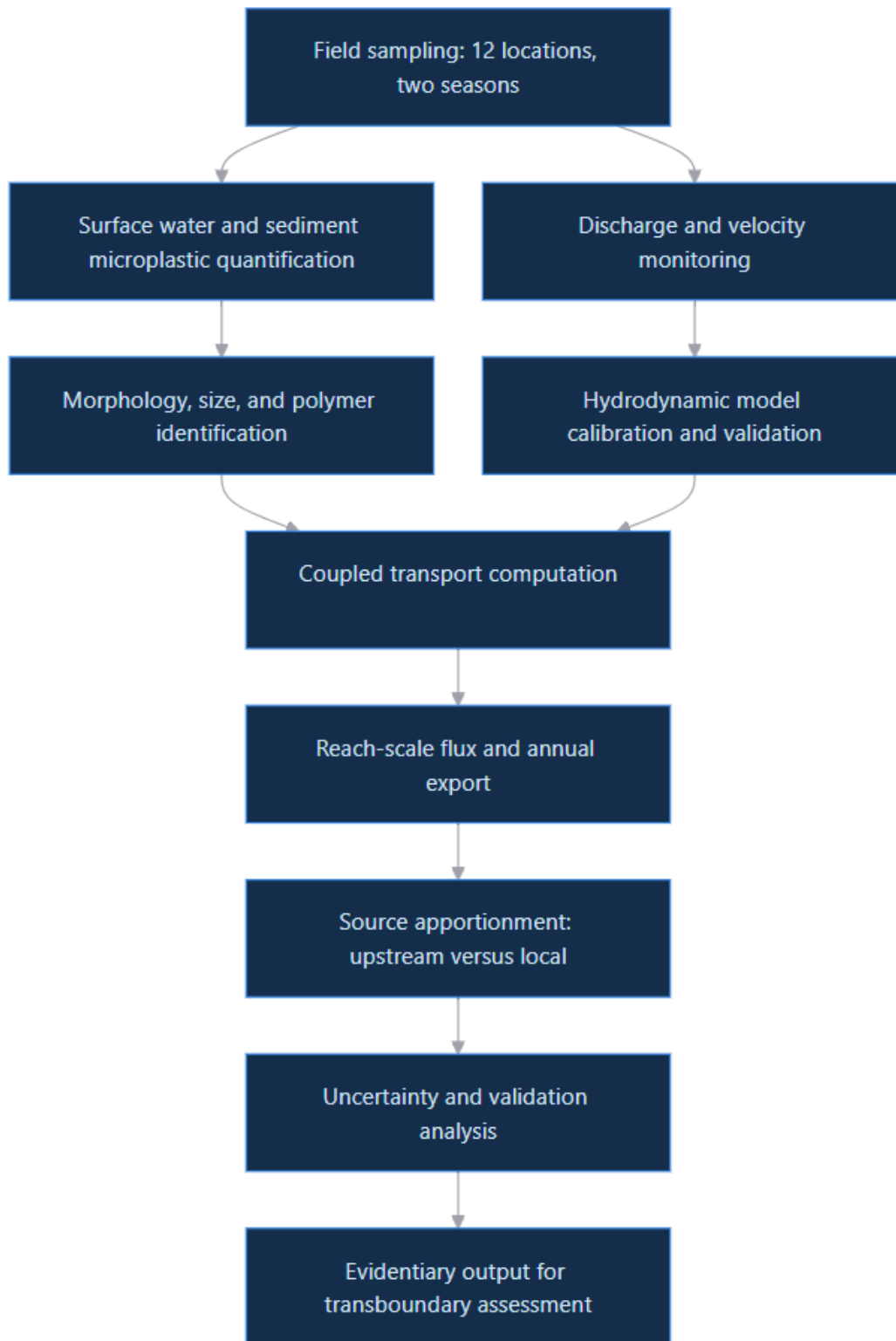


Figure 1

Conceptual workflow of the coupled hydrodynamic-ecological modeling framework.

Mean surface-water microplastic abundance by season

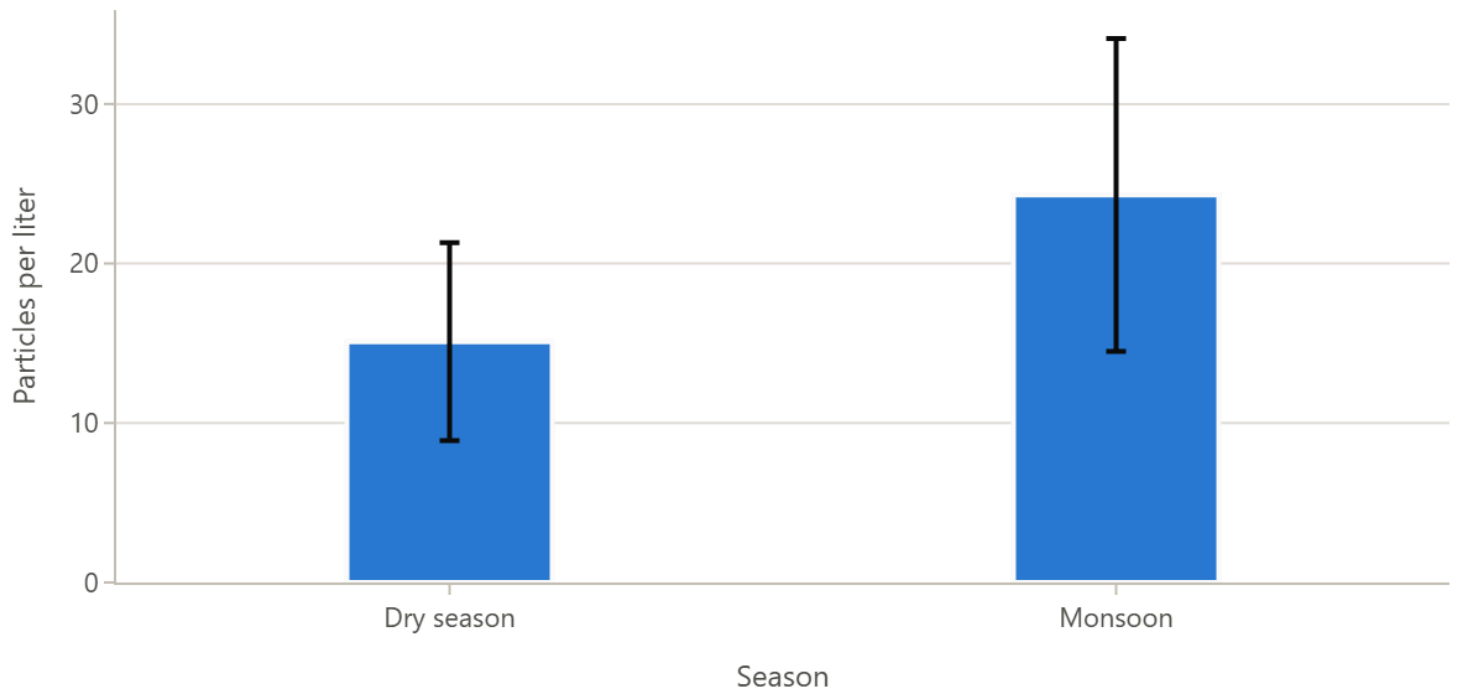


Figure 2

Mean surface-water microplastic abundance during the dry and monsoon seasons, with standard deviation error bars.

Morphological composition of recovered microplastic particles

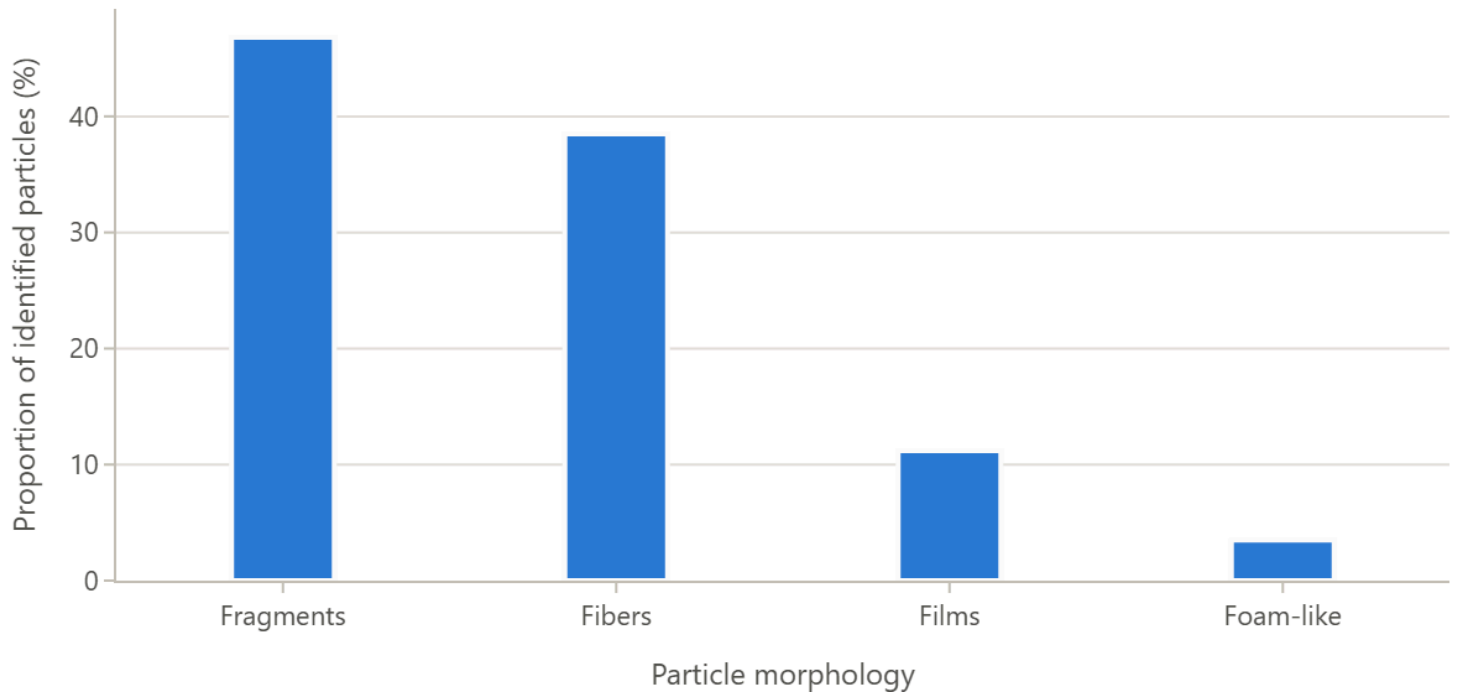


Figure 3

Morphological composition of recovered microplastic particles

Polymer composition of identified microplastic particles

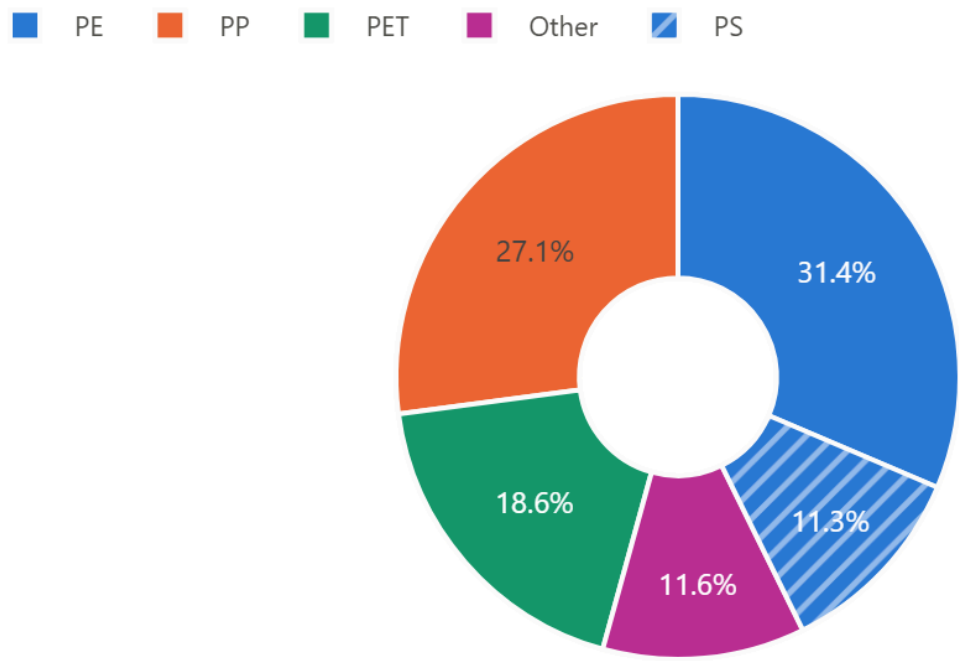


Figure 4

Polymer composition of identified microplastic particles.

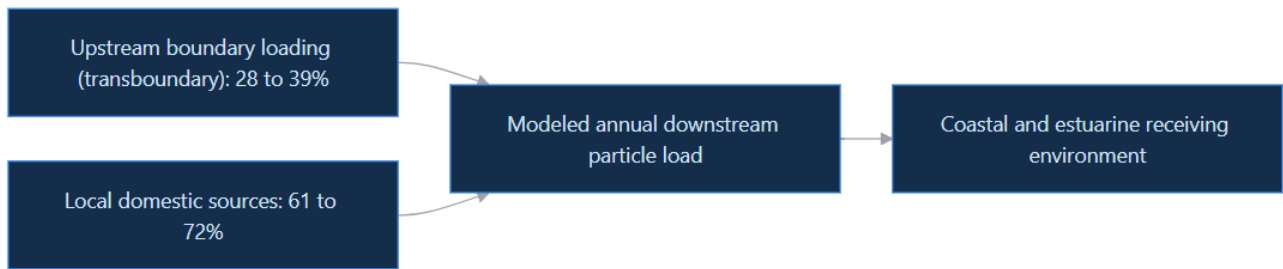


Figure 5

Schematic mass balance of the modeled annual downstream particle load.