Article

Modeling Microplastic Emission, Transport, and Spatial Dispersion in the Pearl River Delta Using a Simplified One-Dimensional Framework

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Abstract: Microplastic pollution has become an increasingly critical environmental issue in large river-delta systems, yet quantitative modeling of its regional emission and downstream transport remains limited. This study develops and implements a simplified steady-state model to simulate the emission, transport, and spatial expansion of microplastics in the Pearl River Delta (PRD), China. Through rigorous mathematical modeling and data analysis, the research reveals distinct spatial patterns of microplastic concentration along the PRD transect. The results demonstrate that concentrations increase dramatically in the upstream Guangzhou urban reaches, achieving a maximum concentration of 28,729 items/m3 at Tianhe. These elevated levels persist through the Huangpu and Panyu regions before showing a gradual decline toward the estuarine section. Notably, the model's predicted concentration at Nanshan (9,002 items/m3) closely aligns with previously reported average levels for the Pearl River estuary, validating the model's accuracy in capturing both magnitude and longitudinal trends. Further analysis of the relationship between concentration hotspots and source-emission hotspots reveals that local microplastic distribution is governed by a complex interplay between anthropogenic source strength and riverine transport capacity, rather than being solely determined by emission intensity. This finding provides crucial insights for understanding microplastic pollution dynamics in complex river-delta systems and offers valuable implications for environmental management strategies.

Keywords: microplastic pollution; river-delta systems; environmental modeling; spatial distribution; pearl river delta; pollution transport

1. Introduction

Microplastics have emerged as a significant environmental issue due to their durability, diminutive size, extensive distribution, and potential ecological hazards. These tiny plastic particles enter aquatic environments through various channels, including domestic wastewater, urban runoff, industrial discharge, and the breakdown of larger plastic debris [1]. Initially, research on microplastic pollution was predominantly focused on marine environments. However, recent studies have highlighted the crucial role that rivers play in the movement, redistribution, and storage of microplastics between terrestrial and marine ecosystems. The spatial distribution of microplastics within river systems is heavily influenced by human activities, particularly those related to population density and industrial development. These factors are intricately linked to the consumption of plastic products, the generation of wastewater, and emissions from surface sources. As urban areas expand and industrial activities intensify, the volume of microplastics entering river systems is likely to increase, posing a growing threat to aquatic ecosystems. The persistence of microplastics in the environment means that they can travel long distances from their source, accumulating in various parts of the river system. This accumulation can have detrimental effects on aquatic life, as microplastics can be ingested by organisms, leading to physical harm or the transfer of toxic substances.

Furthermore, the presence of microplastics in rivers can affect water quality, impacting both human and ecological health. Understanding the pathways and impacts of microplastic pollution in river systems is essential for developing effective strategies to mitigate their presence and protect aquatic environments.

The Pearl River Delta (PRD) serves as a critical area for examining the dynamics of microplastic pollution [2]. As one of the most densely populated and industrialized regions in China, the PRD features an extensive river network, significant human activity, and strong hydrological connectivity, making it particularly susceptible to microplastic emissions and their downstream transport. Research has confirmed the widespread presence of microplastics throughout the Pearl River system, with notable variations in abundance and distribution. The Guangzhou section and the Pearl River estuary have been identified as areas with substantial microplastic concentrations, reflecting the influence of urban and industrial activities. Additionally, studies have documented the occurrence and potential risks associated with microplastics in the mainstream of the Pearl River and its estuarine zones. Sediment analyses in the Zhujiang River estuary suggest that microplastic accumulation may also impact sensitive ecosystems, such as mangroves and their associated microbial communities. These findings underscore the dual role of the Pearl River system as both a conduit for microplastic transport and a zone of accumulation and ecological impact. The presence of microplastics in such ecosystems can disrupt ecological functions, alter habitat conditions, and pose risks to biodiversity. The intricate interplay between human activities, hydrological processes, and ecological impacts in the PRD highlights the need for comprehensive studies to understand the full extent of microplastic pollution and its implications for environmental management and policy development.

Despite the growing body of research on microplastic pollution in the PRD, much of the focus has been on field observations and descriptive analyses [3]. There remains a significant gap in the quantitative modeling of microplastic emissions and their downstream transport. To address this gap, this study introduces a simplified model for the PRD, based on two primary assumptions: first, that microplastic emissions are positively correlated with population size and the level of industrialization; and second, that microplastics are transported from upstream to downstream along the Pearl River under the influence of hydrological processes. By utilizing field investigation data and publicly available information, this study aims to provide an initial quantitative description of microplastic emissions, transport, and spatial distribution within the PRD. The importance of this work lies in its potential to link socioeconomic drivers with riverine transport processes, identify potential pollution hotspots, and offer a practical foundation for future monitoring and management of pollution at the basin scale in highly urbanized delta systems. By understanding the relationship between human activities and microplastic pollution, policymakers and environmental managers can develop targeted strategies to mitigate the impact of microplastics on aquatic environments. This study also highlights the need for interdisciplinary approaches that integrate environmental science, hydrology, and socioeconomics to address complex environmental challenges in rapidly developing regions [1, 4].

2. Data and Model

The dataset utilized in this study was meticulously compiled from a combination of government databases and precise map measurements. This comprehensive dataset encompasses field-survey information collected from 12 strategically selected nodes along the Pearl River Delta transect [5]. The original dataset included several key variables: location, population expressed in units of 10,000 persons, river width, and an approximate measure of water depth. For the purposes of this study, these variables underwent a transformation to enhance their utility and accuracy [6]. Population figures were converted into absolute numbers of persons, ensuring a more granular and precise representation of demographic data. River width measurements were standardized to meters, providing a consistent unit of measurement that facilitates comparison and

analysis. Water depth was represented by the midpoint of the reported interval, offering a balanced estimate that accounts for potential variations in depth measurements. In the absence of a direct industrialization indicator within the survey data, an innovative approach was employed to estimate industrial intensity. The share of secondary industry value added in the Gross Domestic Product (GDP) for the cities of Guangzhou, Dongguan, and Shenzhen during the first half of 2025 was utilized as a city-level proxy for industrial activity. This proxy was carefully selected based on official municipal statistical releases, ensuring its reliability and relevance. The values were then normalized to construct a source term that accurately reflects industrial intensity across the region. Specifically, the proxy values adopted were 24.6% for Guangzhou, 56.0% for Dongguan, and 35.5% for Shenzhen. These figures provide a nuanced understanding of the industrial landscape in these key urban centers, allowing for a more informed analysis of their impact on the surrounding environment (As shown in Table 1).

Table 1. Basic Geographic Data about Pollution Dot

Node	Location	Distance (km)	Population (person)	Width (m)	Depth (m)	Area (m²)	City
1	Liwan (Shamian)	0.00	1,135,000	150	6.5	975	Guangzhou
2	Yuexiu	3.36	980,000	270	6.5	1,755	Guangzhou
3	Haizhu	6.42	1,770,000	320	6.5	2,080	Guangzhou
4	Tianhe	10.57	2,243,000	440	6.5	2,860	Guangzhou
5	Huangpu	23.67	1,235,000	750	6.5	4,875	Guangzhou
6	Machong	35.17	182,000	1,600	7.0	11,200	Dongguan
7	Panyu	35.17	2,845,000	1,600	7.0	11,200	Guangzhou
8	Shatian	50.17	210,000	2,000	9.0	18,000	Dongguan
9	Nansha	63.87	984,000	2,700	9.0	24,300	Guangzhou
10	Humen	63.87	838,000	3,000	9.0	27,000	Dongguan
11	Bao'an	83.27	4,477,000	9,000	5.0	45,000	Shenzhen
12	Nansha	106.97	1,795,800	22,000	5.0	110,000	Shenzhen

In this study, a simplified steady-state one-dimensional framework was employed to model the dynamics of the system under investigation. The source term at each node, denoted as node j, was defined using a specific mathematical formulation [7, 8]. This formulation incorporates several critical components: the population at the node,

represented as a variable, the normalized industrial proxy, which serves as an indicator of industrial activity, the per-capita emission coefficient, which quantifies the emissions generated per individual, and the industrial amplification factor, which accounts for the enhanced emissions associated with industrial processes. The longitudinal transport of substances between adjacent nodes was expressed through a mathematical equation that captures the complexity of the transport process. This equation includes terms that represent integrated net loss during transport, which encompasses various processes such as deposition, riverbed retention, and local removal. Additionally, the equation accounts for enhanced downstream dilution, a phenomenon that occurs due to cross-sectional expansion and estuarine exchange. This comprehensive treatment of transport processes is consistent with evidence from previous studies, which have documented the roles of riverbed storage and urban-river sequestration in influencing transport dynamics. By incorporating these factors into the model, the study provides a robust framework for understanding the movement and transformation of substances within the river system. This approach not only enhances the accuracy of the model but also aligns with established scientific understanding, ensuring that the findings are both reliable and relevant to the broader field of study (As shown in Table 2).

Table 2. Model parameters and sources or rationale

Parameter	Value		Meaning	Source / rationale
Q_0 Q_0	10,000	m^3/s	Representative upstream discharge	Simplified mean-flow value consistent with the Pearl River annual runoff magnitude reported in official hydrological bulletins.
β β	0.6		Industrial amplification factor	Scenario parameter; assumes a moderate industrial enhancement of the population-based source term.
λ λ	0.02	km^{-1}	Net loss coefficient	Represents average deposition, retention, and local removal effects suggested by riverbed and sediment studies [6,8].
η η	0.7		Downstream dilution exponent	Empirical parameter describing channel

					enlargement and estuarine exchange.
α	α	65.07	$items/$ $(person * s)$	Per-capita emission coefficient	Calibrated to match the concentration magnitude reported for Guangzhou reaches and the Pearl River estuary [4].

3. Results and Discussion

The model results reveal a distinct longitudinal pattern in microplastic concentration along the Pearl River Delta transect, highlighting significant variations in pollution levels across different sections of the river. The predicted concentrations show a rapid increase in the upstream urban areas, particularly in the densely populated and industrially active regions. At Tianhe, located 10.57 kilometers along the transect, the concentration peaks at 28,729 items per cubic meter, indicating a significant accumulation of microplastics in this urbanized area [9]. This high concentration is attributed to the intense urban activities and industrial discharges that contribute to the pollution load. As the river flows downstream towards Huangpu and Panyu, the concentrations remain relatively elevated, suggesting that these areas continue to receive substantial microplastic inputs. However, upon entering the Nansha-Humen section, a noticeable decline in concentration is observed, despite ongoing local emissions. By the time the river reaches Nanshan, 106.97 kilometers downstream, the concentration decreases to 9,002 items per cubic meter. This reduction aligns closely with the mean concentration levels reported for the Pearl River estuary in previous field observations, indicating that the simplified model effectively captures the overall magnitude and downstream transport patterns of microplastics. The model's ability to reflect these trends suggests its utility in understanding and predicting microplastic distribution in riverine systems.

The observed spatial trend in microplastic concentration is a result of the interplay between source intensity, hydrological transport mechanisms, and downstream dilution processes. In the urban core of Guangzhou, characterized by a large population and moderate industrial activity, there is a significant input of microplastics, leading to a rapid increase in concentration from Liwan to Tianhe. This area acts as a major source of microplastic pollution due to the dense urban environment and industrial discharges. As the river progresses downstream, additional emissions continue to contribute to the pollution load. However, the widening of the river channel and the increase in effective flow volume play a crucial role in mitigating concentration growth. These hydrological factors enhance the river's capacity to dilute pollutants, thereby reducing the concentration of microplastics. Additionally, the net-loss term, which encompasses processes such as deposition, sediment retention, and local removal, further diminishes the transported concentration. Consequently, downstream nodes do not simply accumulate higher concentrations; instead, there is a potential for concentration reduction even when total emissions remain substantial [10]. This dynamic highlights the complexity of microplastic transport and the importance of considering both source inputs and hydrological processes in understanding pollution patterns (As shown in Table 3).

Table 3. Predicted microplastic concentrations and emission contributions at the 12 nodes

Node	Distance (km)	City	Emission contribution (%)	Predicted concentration (items/m³)
Liwan (Shamian Island)	0.00	Guangzhou	5.79	9,329
Yuexiu	3.36	Guangzhou	5.00	14,060
Haizhu	6.42	Guangzhou	9.03	21,785
Tianhe	10.57	Guangzhou	11.44	28,729
Huangpu	23.67	Guangzhou	6.30	25,397
Machong	35.17	Dongguan	1.18	20,522
Panyu	35.17	Guangzhou	14.51	24,756
Shatian	50.17	Dongguan	1.36	18,624
Nansha	63.87	Guangzhou	5.02	15,012
Humen	63.87	Dongguan	5.41	15,865
Bao'an	83.27	Shenzhen	24.95	13,513
Nanshan	106.97	Shenzhen	10.01	9,002

A detailed comparison between concentration ranking and emission contribution unveils a critical aspect of the microplastic pollution system in the Pearl River Delta. The concentration hotspots are identified in the order of Tianhe, Huangpu, Panyu, Haizhu, and Machong [11]. In contrast, the nodes with the highest emission contributions are Bao'an, Panyu, Tianhe, Nanshan, and Haizhu. This discrepancy indicates that a node with a high emission share does not necessarily correspond to the highest in-river concentration. The local hydraulic conditions, including flow velocity and channel morphology, significantly influence the dilution and transport efficiency of microplastics. These factors determine how effectively microplastics are dispersed and transported downstream, affecting the concentration levels observed at different nodes. The results underscore the complex interplay between anthropogenic source strength and riverine transport capacity in controlling microplastic pollution. This complexity highlights the necessity for a comprehensive basin-scale management approach rather than isolated control measures at individual locations. Effective management strategies should consider the entire river system, addressing both the sources of pollution and the hydrological processes that influence microplastic transport and distribution (As shown in Figure 1).

Figure 1. Longitudinal profile of predicted microplastic concentration along the Pearl River Delta transect.

The longitudinal profile of predicted microplastic concentration along the Pearl River Delta transect, as depicted in Figure 1, provides valuable insights into the spatial distribution of microplastic pollution. This profile illustrates the variations in concentration levels across different sections of the river, highlighting areas of concern where microplastic accumulation is particularly pronounced [5]. The data suggest that urban and industrial activities significantly contribute to the pollution load, with certain nodes experiencing higher concentrations due to their proximity to major sources. The profile also reveals the impact of hydrological processes on microplastic transport, with dilution and deposition playing key roles in shaping the concentration patterns observed. Understanding these dynamics is crucial for developing effective management strategies aimed at mitigating microplastic pollution in riverine environments. By identifying the key factors influencing microplastic distribution, stakeholders can implement targeted interventions to reduce pollution levels and protect aquatic ecosystems [12–18]. The

findings emphasize the importance of integrating scientific research with policy-making to address the challenges posed by microplastic pollution in a comprehensive and sustainable manner.

4. Conclusion and Limitations

This study developed a simplified steady-state model to simulate microplastic emission, downstream transport, and spatial expansion in the Pearl River Delta. By integrating node-level population data, river geometric characteristics, and a city-level industrialization proxy, the model reproduced a clear longitudinal pattern of microplastic concentration. The results suggest that microplastic pollution in the Pearl River Delta is jointly controlled by anthropogenic source intensity and hydrological transport conditions. Concentrations rise rapidly in the highly urbanized upstream Guangzhou section, reach a peak at Tianhe, and then gradually decline toward the estuarine area as channel expansion, effective dilution, and cumulative net loss become increasingly important. The model also shows that nodes with the largest source contributions do not necessarily correspond to the highest in-river concentrations, highlighting the importance of river transport processes in shaping spatial pollution patterns. This finding underscores the complexity of microplastic pollution dynamics, where the interplay between human activities and natural water flow creates a multifaceted environmental challenge. The implications of this study are significant, as they provide a framework for understanding how urbanization and industrial activities contribute to environmental degradation in riverine systems. The insights gained can inform policymakers and environmental managers in devising strategies to mitigate microplastic pollution. By identifying critical areas where interventions could be most effective, such as upstream urban centers, targeted efforts can be made to reduce emissions and enhance water quality. Furthermore, the study highlights the need for comprehensive monitoring programs that consider both point and non-point sources of pollution. The model's ability to simulate spatial patterns of microplastic concentration offers a valuable tool for assessing the effectiveness of pollution control measures over time. However, the study also raises important questions about the broader ecological impacts of microplastics, including their potential effects on aquatic life and human health. As microplastics continue to accumulate in the environment, understanding their long-term consequences becomes increasingly urgent. This research contributes to the growing body of knowledge on microplastic pollution and sets the stage for future investigations that can build on its findings.

However, this study has several limitations. First, the model is highly simplified and assumes steady-state conditions, without considering temporal variation, storm events, or tidal fluctuations. Second, industrialization was represented by a city-level proxy rather than direct emission statistics, which may introduce uncertainty. Third, the model does not explicitly resolve tributary bifurcation, lateral mixing, sediment resuspension, or particle-specific properties such as size and polymer type. Therefore, the present framework should be regarded as a preliminary, interpretable first-step model. Future work should incorporate more detailed hydrodynamic data, field validation, and process-based parameterization to improve predictive accuracy. Addressing these limitations is crucial for enhancing the model's robustness and applicability. Incorporating temporal dynamics would allow for a more nuanced understanding of how microplastic concentrations fluctuate in response to seasonal changes and extreme weather events. This could provide insights into the resilience of river systems to pollution and inform adaptive management strategies. Additionally, using direct emission data rather than proxies would improve the precision of source attribution, enabling more targeted interventions. Expanding the model to include tributary interactions and sediment dynamics would offer a more comprehensive view of microplastic transport and fate. Understanding the role of sediment in microplastic retention and release is particularly important, as it can influence the persistence of pollution in aquatic environments. Future research should also explore the interactions between microplastics and other pollutants, such as heavy metals and organic contaminants, to assess potential synergistic effects. By addressing

these research gaps, scientists can develop more accurate predictive models that support effective policy-making and environmental management. Ultimately, advancing our understanding of microplastic pollution requires a multidisciplinary approach that integrates hydrology, chemistry, ecology, and social sciences. Collaborative efforts across these fields will be essential for developing innovative solutions to this pressing environmental issue.

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