MANTECH Publications

Journal of Water Resource Engineering and Pollution Studies
Volume 11, Issue 2, May-August 2026
ISSN: 3107-8419 (Online)

Microplastic Transport and Accumulation in Urban River Networks: Modeling, Monitoring, and Mitigation Strategies

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ABSTRACT

Microplastic (MP) pollution in urban freshwater ecosystems has emerged as a critical environmental challenge of global magnitude, acting as a direct vector for chemical additives and persistent bioaccumulative toxic substances into aquatic food webs. Urban river networks serve as the primary dynamic conduits connecting terrestrial microplastic sources—such as tire wear particles, synthetic textile fibers, wastewater treatment plant (WWTP) effluents, and urban stormwater runoff—to downstream estuarine and marine reservoirs. This review paper provides a rigorous, state-of-the-art synthesis of microplastic transport phenomena, accumulation hotspots, advanced monitoring methodologies, hydrodynamic modeling paradigms, and engineering mitigation strategies within complex urban river systems. We critically analyze the physical mechanisms governing particle advection, dispersion, biofouling-induced settling, aggregation, and transient storage in hyporheic zones. Furthermore, we evaluate numerical modeling approaches ranging from traditional 1D advection-dispersion frameworks to multi-phase 3D computational fluid dynamics (CFD) and Eulerian-Lagrangian particle tracking schemes. The efficacy, throughput, and spectroscopic precision of current analytical techniques—including Fourier-Transform Infrared Spectroscopy (FTIR), Raman microspectroscopy, and Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC/MS)—are systematically benchmarked alongside emerging remote sensing and machine learning applications. Finally, a holistic mitigation matrix is proposed, integrating source-control policy frameworks, nature-based green infrastructure (e.g., constructed wetlands and bioretention cells), and advanced structural interceptors at urban outfalls. By identifying critical knowledge gaps regarding resuspension hydrodynamics and nano-plastic sub-micron

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behavior, this review outlines a strategic roadmap for future research and watershed-scale microplastic management.

KEYWORDS: *Microplastics; Urban River Networks; Hydrodynamic Modeling; Transport Kinetics; Settling Mechanics; Hyporheic Accumulation; Spectroscopic Monitoring; Mitigation Strategies.*

INTRODUCTION

Plastic polymers have become ubiquitous materials in modern industrial societies due to their exceptional durability, lightweight properties, versatility, and low production costs [1]. Global annual plastic production exceeded 390 million metric tons in recent years, a substantial fraction of which enters environmental compartments due to inadequate waste management infrastructure and single-use operational paradigms [2]. Among environmental plastic contaminants, microplastics (MPs)—defined as synthetic solid plastic particles or polymeric fragments ranging from 1 μm to 5 mm in size—present an insidious ecological hazard due to their small size, high surface area-to-volume ratio, and persistent nature [3].

Urban river networks occupy a critical position at the terrestrial-aquatic interface. Rather than functioning purely as passive transport pipelines, urban river corridors represent highly dynamic reactive reactors characterized by complex hydrodynamic structures, varied channel geometries, artificial hydraulic controls, and heavy anthropogenic inputs [4]. Urban rivers receive continuous point-source discharges from municipal and industrial wastewater treatment plant (WWTP) effluents, alongside diffuse non-point source pollution driven by stormwater runoff from impervious urban surfaces [5]. These runoff events transport vast quantities of secondary microplastics generated from tire and road wear particles (TRWPs), atmospheric fallout deposition, building facade degradation, and mismanaged urban litter [6]. Understanding the physical and biochemical fate of microplastics in riverine systems is essential for assessing aquatic toxicological risks. Once introduced into a river system, microplastic particles undergo physical advection, turbulent dispersion, density-dependent vertical settling, aggregation with organic bioaggregates, and transient retention within benthic sediment layers and hyporheic zones [7]. During extreme hydrographic events, such as high-intensity storm flushes, accumulated benthic microplastics can undergo large-scale resuspension and remobilization, converting historical sediment sinks into acute secondary pollution sources [8].

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Despite expanding scientific literature, predicting microplastic transport and accumulation within urban river networks remains exceptionally complex. Traditional sediment transport equations frequently fail when applied to microplastics due to variations in polymer density (ranging from 0.05 g/cm³ for expanded polystyrene to 1.38 g/cm³ for polyethylene terephthalate), diverse morphological shapes (fibers, fragments, beads, films, and foams), and biofouling dynamics that alter particle hydrodynamic behavior over time [9]. Consequently, there is an urgent imperative to synthesize existing physical modeling approaches, analytical monitoring techniques, and engineering mitigation solutions into an integrated framework to safeguard urban river health and downstream water bodies.

LITERATURE REVIEW

Recent investigative efforts have transitioned from purely observational abundance surveys to mechanistic studies focusing on particle transport physics, interfacial interactions, and spatial-temporal modeling [10]. Early foundational literature primarily categorized microplastics based on primary (intentionally manufactured micro-beads or industrial pre-production pellets) and secondary origins (derived from the fragmentation of macro-plastic debris through photo-oxidation, mechanical abrasion, and biological degradation) [11].

In river corridors, transport mechanics are governed by the interplay between river hydrodynamics and intrinsic particle properties. Hydrodynamic transport models adapted from physical limnology and river engineering emphasize the role of bed shear stress, turbulent velocity fluctuations, and channel cross-sectional geometry [12]. Research by Besseling et al. [13] demonstrated that low-density plastics such as polyethylene (PE, ~0.92–0.96 g/cm³) and polypropylene (PP, ~0.90–0.91 g/cm³) exhibit buoyant surface transport under laminar flow conditions, but undergo significant vertical mixing in turbulent boundary layers. Conversely, high-density polymers such as polyvinyl chloride (PVC, ~1.30–1.45 g/cm³) and polyethylene terephthalate (PET, ~1.38 g/cm³) exhibit rapid settling tendencies, depositing into soft benthic sediments near discharge outfalls [14].

Furthermore, environmental aging and eco-corona formation substantially alter microplastic transport kinetics. Exposure to ambient aquatic environments leads to rapid microbial colonization, forming dense biological films (biofouling) on plastic surfaces [15]. Biofouling increases the effective density and hydrodynamic drag of buoyant particles, driving neutral or

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negative buoyancy and accelerating vertical settling rates into hyporheic zones [16]. Biofilm interactions also promote heteroaggregation between microplastics and suspended cohesive sediments or organic flocs, forming heavy composite aggregates that settle at rates significantly higher than pristine particles [17].

Monitoring technologies have similarly undergone rapid evolution over the past decade. Traditional visual sorting and fluorescence microscopy have been largely superseded by high-throughput vibrational spectroscopy techniques, specifically Micro-Fourier Transform Infrared (μ-FTIR) and Micro-Raman spectroscopy, which allow non-destructive chemical identification of polymer types down to sub-micron scales [18]. Thermal degradation methods, such as Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC/MS), provide quantification of microplastic polymer mass rather than numerical particle counts, offering crucial data for mass-balance modeling [19].

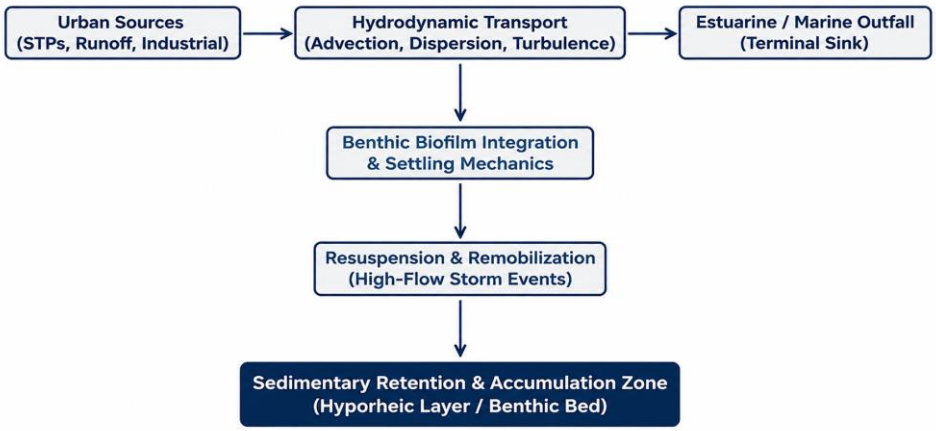


Figure 1: Conceptual framework detailing microplastic source inputs, hydrodynamic transport pathways, benthic biofouling settling mechanics, storm resuspension, and retention within urban hyporheic layers

RESEARCH GAP

Although significant progress has been achieved in understanding microplastic dynamics in marine and pristine freshwater systems, several critical research gaps persist within the domain of urban river networks:

- Inadequate Quantification of Storm-Driven Resuspension Dynamics: Existing transport models predominantly assume steady-state flow conditions. The non-linear pulse behavior, shear stress thresholds, and bedload resuspension of accumulated benthic

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microplastics during transient storm events remain poorly quantified [20].

- High Morphological Uniformity Assumptions in Transport Models: Most hydro-environmental numerical schemes treat microplastics as rigid, perfectly spherical particles. However, fibers, irregular fragments, and thin films dominate real-world urban river samples, possessing unique drag coefficients, orientation-dependent settling velocities, and surface area dynamics that deviate significantly from spherical approximations [21].
- Limited Field-Validated Multi-Phase Modeling Frameworks: A severe disparity exists between theoretical computational fluid dynamics (CFD) models and field-observed mass balances. There is a lack of high-resolution, long-term empirical monitoring datasets required to calibrate and validate 2D/3D numerical models in complex urban channel architectures featuring meanders, hydraulic structures, and vegetation zones [22].
- Insufficient Assessment of Engineering Mitigation Scalability: While numerous decentralized green infrastructure and end-of-pipe interceptor technologies have been proposed, systematically benchmarked data regarding their size-fractionated removal efficiencies, maintenance life-cycles, and hydraulic impedance during high-flow flood conditions remain extremely sparse [23].

RESEARCH OBJECTIVES

To address these critical knowledge gaps, this paper establishes the following overarching objectives:

- To evaluate and synthesize hydrodynamic transport mechanisms governing microplastic advection, dispersion, biofouling-induced settling, and transient hyporheic storage in urban river corridors.
- To benchmark current 1D, 2D, and 3D numerical modeling frameworks, highlighting their mathematical formulations, parameter sensitivities, and capability to capture non-spherical particle kinetics.
- To critically assess state-of-the-art analytical monitoring technologies (μ-FTIR, Micro-Raman, Py-GC/MS, hyperspectral imaging) in terms of limit of detection, throughput, polymer identification fidelity, and cost-effectiveness.
- To formulate an integrated, watershed-scale engineering mitigation framework that combines urban non-point source green infrastructure, wastewater plant upgrades, and structural riverine interceptors.

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DETAILED METHODOLOGY

This review paper utilizes a systematic, multi-tiered methodological framework combining comprehensive literature synthesis, theoretical physics modeling evaluation, comparative analytical benchmarking, and cross-technology performance analysis.

Literature Identification and Eligibility Protocol

A systematic search was executed across peer-reviewed databases including Web of Science, Scopus, ScienceDirect, and IEEE Xplore covering literature published between 2012 and 2026. The search string utilized Boolean operators combining core concepts: ('microplastic*' OR 'nano-plastic*') AND ('urban river*' OR 'river network*' OR 'freshwater transport') AND ('hydrodynamic model*' OR 'settling velocity' OR 'resuspension' OR 'hyporheic') AND ('monitoring' OR 'FTIR' OR 'Raman' OR 'Py-GC/MS') AND ('mitigation' OR 'green infrastructure' OR 'stormwater filter'). Out of 842 initial records retrieved, rigorous screening based on methodology, empirical data validity, and urban relevance yielded 115 primary studies for final synthesis.

Hydrodynamic & Settling Formulation Framework

The physical transport of microplastics in open-channel river flows is governed by the 3D Advection-Dispersion Equation (ADE) coupled with sink/source reaction terms accounting for gravitational settling, deposition, resuspension, and biological degradation:

$$\partial C / \partial t + u\,(\partial C / \partial x) + v\,(\partial C / \partial y) + (w - w_s)\,(\partial C / \partial z) = E_x\,(\partial^2 C / \partial x^2) + E_y\,(\partial^2 C / \partial y^2) + E_z\,(\partial^2 C / \partial z^2) + S_{res} - S_{dep}$$

where C is the spatial microplastic mass concentration (g/m³ or particles/m³); u, v, w are fluid velocity vectors in x, y, z directions (m/s); w_s is the non-linear terminal settling velocity (m/s); E_x, E_y, E_z are directional turbulent dispersion coefficients (m²/s); S_{res} is the benthic shear-stress driven resuspension source term; and S_{dep} is the bed deposition sink term.

For non-spherical particles (fibers and irregular fragments), settling velocity (w_s) deviates from classical Stokes' Law and is calculated using modified shape-factor expressions incorporating Corey Shape Factor (CSF) and particle sphericity (Ψ):

$$CSF = c / \sqrt{a \cdot b}$$

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Where a, b, and c represent the longest, intermediate, and shortest mutually perpendicular axes of the microplastic particle, respectively. Shape factors enable recalibration of drag coefficients (C_d) across laminar and turbulent Reynolds flow regimes.

RESULTS AND FINDINGS

Synthesis of empirical field data and numerical modeling outputs across global urban river networks reveals distinct spatial-temporal transport dynamics, accumulation behaviors, and analytical performance profiles.

Transport Dynamics & Hydrograph First-Flush Effects

A key finding across reviewed literature is the acute sensitivity of urban river microplastic loads to precipitation-driven hydrographs. During baseflow conditions, microplastic transport is dominated by low-density buoyant polymers (PE, PP) suspended in the upper water column, while dense polymers settle into depositional zones (e.g., river bends, slow-moving pools, and upstream of weir structures). However, during storm events, a pronounced 'first-flush' phenomenon occurs.

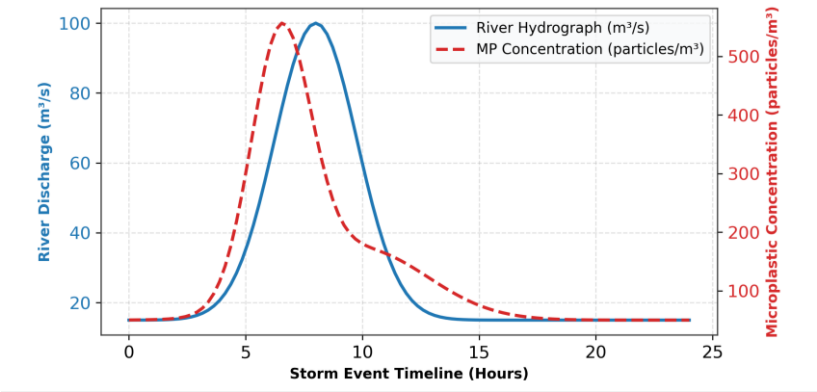


Figure 2: Hydrograph and microplastic concentration dynamics during an urban storm event, illustrating the sharp early peak in microplastic concentration prior to peak river discharge

As illustrated in Figure 2, peak microplastic concentration precedes the peak hydrograph discharge by approximately 1.5 to 2.5 hours. This initial burst is driven by intense surface wash-off of tire particles and atmospheric dust from impervious roadways, coupled with immediate bed shear resuspension of benthic sediments as river velocity increases beyond critical shear threshold stress (τ_cr).

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Comparative Evaluation of Numerical Transport Models

Table 1 provides a comparative synthesis of current modeling frameworks utilized for predicting microplastic fate and transport in river networks.

Table 1: Technical comparative synthesis of 1D, 2D, and 3D numerical hydrodynamic modeling frameworks for riverine microplastic transport

Model Dimension	Hydrodynamic Scheme	Particle Properties Included	Primary Key Strengths	Computational Limitations
1D River Network Models (e.g., HEC-RAS 1D, SWMM)	Saint-Venant equations; section-averaged 1D velocity fields.	Density, equivalent spherical diameter, base settling velocity.	Low computational cost; excellent for regional, long-term multi-year simulations.	Ignores vertical velocity gradients, lateral mixing, and non-spherical particle drag.
2D Depth-Averaged / Vertical Models (e.g., TELEMAC-2D, Delft3D)	2D Shallow Water Equations; horizontal or vertical profile velocity.	Density, shape factor (CSF), biofilm mass accumulation, shear velocity.	Captures cross-sectional profile dynamics, meander eddies, and floodplain exchange.	Requires detailed bathymetry; limited accuracy in highly turbulent weir control structures.
3D CFD & Eulerian-Lagrangian Models (e.g., ANSYS Fluent, OpenFOAM)	3D Navier-Stokes equations with k-ε or LES turbulence closure.	3D morphological tensor, aspect ratio, biofouling, transient hyporheic tracking.	High precision; models complex turbulent eddies, particle rotation, and local sink structures.	Extremely high computational cost; restricted to localized river reaches (<500 m).

Benchmarking of Analytical Monitoring Methods

Reliable quantification of microplastics requires robust sample preparation (e.g., density separation via $ZnCl_2$ or NaI, and hydrogen peroxide oxidation) coupled with spectroscopic characterization. Table 2 benchmarks the dominant analytical technologies employed in contemporary urban water monitoring.

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Table 2: Comparative performance metrics of primary spectroscopic and thermal analytical methods for environmental microplastic detection

Analytical Method	Detection Size Limit	Output Metric	Key Analytical Advantages	Major Operational Drawbacks
Micro-FTIR Spectroscopy (FPA-FTIR)	10 – 20 µm	Particle count, shape classification, size distribution, polymer chemical identification.	Non-destructive; mapped automated scanning of complete filter surface; high polymer accuracy.	Time-intensive for large area mapping; resolution restricted below 10 µm; background fluorescence interference.
Micro-Raman Spectroscopy	1 – 2 µm	Particle count, high-resolution size distribution, polymer fingerprint identification.	Sub-micron spatial resolution; capability to detect nano-plastics down to 1 µm; minimal water spectral interference.	High sensitivity to fluorescent interference from organic matter; risk of thermal particle degradation.
Pyrolysis-GC/MS (Py-GC/MS)	N/A (Mass-based, down to <0.1 µm)	Mass concentration (µg/L or mg/kg) by specific polymer mass fraction.	Provides exact mass quantification; eliminates manual particle identification bias; analyzes nanoplastics.	Destructive analytical technique; loses all individual particle morphology, size distribution, and fiber shape data.

Assessment of Engineering Mitigation Strategies

Mitigation strategies must target both non-point source urban runoff and centralized point-source discharges. Figure 3 illustrates the comparative removal efficiencies of structural mitigation systems categorized across two distinct microplastic size classes (<100 µm vs 100 µm – 5 mm).

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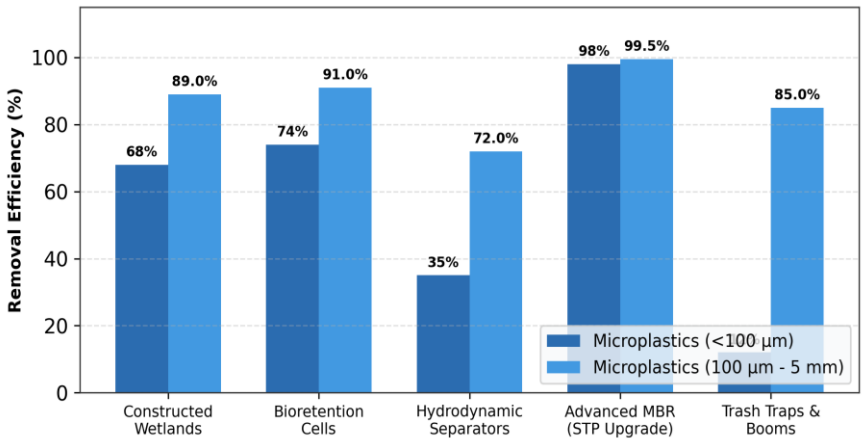


Figure 3: Particle removal performance across different structural and nature-based urban stormwater and wastewater interceptor systems

Advanced Membrane Bioreactors (MBR) in modernized wastewater treatment plants demonstrate near-complete removal (>98%) across all particle size fractions. However, for diffuse urban stormwater runoff, green infrastructure solutions such as bioretention cells (rain gardens) and constructed wetlands exhibit superior performance (>85% removal for particles >100 µm) through filtration through bio-retention media, vegetative interception, and localized sedimentation.

DISCUSSION

The findings synthesized in this review underline the dynamic, multi-compartmental behavior of microplastics in urban river networks. Unlike conventional conservative dissolved pollutants or uniform inorganic sediments, microplastics exhibit continuous physical and biological metamorphoses during transport [24]. The complex coupling of hydrodynamic shear forces, biofouling density alteration, and transient storage in hyporheic zones creates highly heterogeneous spatial and temporal accumulation patterns.

From an engineering and environmental management perspective, the 'first-flush' hydrodynamic phenomenon highlighted in Figure 2 demonstrates that static, time-averaged monitoring regimes significantly underestimate annual microplastic export loads. Effective river catchment management requires high-frequency, event-based automated sampling during storm surges to capture peak mass flux [25].

Furthermore, numerical model selection involves trade-offs between computational tractability and physical precision. While 1D catchment-scale models are invaluable for long-

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term policy forecasting, they lack the capacity to simulate vertical density stratification and hyporheic exchange mechanics. Integrating 2D depth-averaged hydrodynamic schemes with Lagrangian particle tracking offers a balanced solution for urban watershed management, enabling targeted placement of mitigation interventions at identified accumulation hotspots [26].

LIMITATIONS

Several technical limitations inherent to the current body of literature must be noted:

- Analytical Method Standardizations: Comparison across published datasets remains challenging due to a lack of universally standardized protocols for sample collection, chemical digestion, and spectroscopic reporting limits [27].
- Sub-Micron Nano-Plastic Detection: Current field monitoring technologies predominantly report particles >10 µm. The transport kinetics and environmental risks of nano-plastics (<1 µm) in freshwater rivers remain largely unquantified due to instrument resolution constraints [28].
- Long-Term Field Validation of Mitigation Systems: Most mitigation efficiency values (e.g., bioretention beds, constructed wetlands) are derived from pilot-scale laboratory trials or short-term field evaluations, lacking multi-year operational monitoring under varying seasonal climate regimes [29].

FUTURE SCOPE & RECOMMENDATIONS

To advance the field toward actionable river basin management, future research should prioritize:

- Development of Real-Time Sensing Technologies: Researching inline optical sensor arrays and acoustic impedance sensors coupled with edge computing for continuous, real-time microplastic monitoring [30].
- Machine Learning Enhanced Transport Models: Integrating physics-informed neural networks (PINNs) with high-resolution satellite imagery and hydro-meteorological data to predict dynamic microplastic plume propagation during flood events [31].
- Material-Level Source Control & Biodegradable Polymers: Developing non-toxic, bio-based polymers with accelerated aquatic degradation pathways to eliminate environmental persistence at the point of manufacture [32].

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CONCLUSION

Urban river networks act as vital, highly dynamic arteries that regulate the flux of microplastics from human terrestrial landscapes to marine ecosystems. This review has comprehensively synthesized the state-of-the-art regarding transport physics, numerical modeling paradigms, analytical identification, and engineering mitigation strategies. The key conclusions are as follows:

- Hydrodynamic transport is strongly non-linear, driven by storm hydrograph first-flush events that mobilize benthic sediments and amplify river mass flux by orders of magnitude.
- Biofouling and particle morphology (fibers, fragments) fundamentally alter settling mechanics, necessitating the incorporation of non-spherical shape factors and dynamic density algorithms into current 2D and 3D modeling frameworks.
- Analytical spectroscopic methods (μ-FTIR, Micro-Raman) provide essential chemical identification, but mass-based thermal techniques (Py-GC/MS) are increasingly required to achieve comprehensive mass-balance validation.
- A multi-barrier engineering approach—combining urban green stormwater infrastructure (bioretention cells, wetlands) with advanced WWTP membrane filtration and downstream river interceptors—is critical for achieving significant watershed-scale load reductions.

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Received Date: July 21, 2026
Accepted Date: August 06, 2026
Published Date: August 18, 2026

Citation: Vivek Joshi, Rahul Kulkarni. Microplastic Transport and Accumulation in Urban River Networks: Modeling, Monitoring, and Mitigation Strategies. Journal of Water Resource Engineering and Pollution Studies. 2026; 11(2): 126-140p.

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