



Understanding the dynamics of microplastics transport in urban stormwater runoff: Implications for pollution control and management[☆]

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ABSTRACT

The transport of microplastics (MPs) from urban environments to water resources via stormwater runoff poses significant concerns due to its adverse impacts on water safety and aquatic ecosystems. This study presents a modeling approach aimed at understanding the transport mechanisms of MPs in an urban residential setting, considering settling and buoyant MPs. To consider the effect of MP shapes, the settling velocity of various settling MPs in shapes of fibers, films, and fragments was calculated. Using an analogy of sediment transport, a Rouse number criterion was used to analyze the transport of MPs. For buoyant MPs, it was assumed that they transport as wash-load as soon as they float in the water and the travel time for them to reach the storm drain was determined. The calculation of settling velocity revealed the influence of shape on the settling velocity of MPs was particularly pronounced as the equivalent diameter of the MPs increased. The transport mechanism for the smallest settling MPs, irrespective of their shapes, density, and depth of flow, was wash-load. However, for larger MPs, the shape and size distribution of settling MPs, along with the depth of flow and slope significantly influenced their transport mechanisms compared to sediment particles. The influence of weathering on the MPs' transport mechanisms depended on their sizes and shapes. The site-specific characteristics, including slope and surface friction, significantly influenced the velocity of stormwater runoff and, consequently, the extent of MP transport during rain events. Moreover, an evaluation of the transport mechanism of settling MPs was conducted using the reported field data on MP abundance in road dust collected from residential and traffic sites. This study underscores the complexity of MP transport dynamics and provides a foundation for developing targeted strategies to mitigate MP pollution in urban environments.

1. Introduction

The increasing use of plastics has raised concerns regarding the magnitude of plastic pollutants released into the environment, posing potential threats to ecological safety and public health (Herath et al., 2023; Jazaei et al., 2022; Herath & Salehi, 2022; El Hadri et al., 2020; Andrady, 2011). It has been reported that 4.8 to 12.7 million metric tons of plastic pollutants enter the oceans annually (Brandon et al., 2019). Over 80% of the plastic loads introduced into the marine environment originated from inland sources (Lechner & Ramler, 2015). Despite the significant contribution of land-based sources to plastic pollution in the

marine environment, our understanding of the specific impact of individual land-based sources on plastic pollution remains limited. However, this information is critical for developing efficient and long-term strategies to combat plastic pollution. Among various sources, urban stormwater has been identified as a significant contributor to plastic pollution in both fresh and marine environments (Werbowski et al., 2021). Plastic litter, worn tire particles, road marking paints, construction, and demolition debris are examples of plastic debris released into urban stormwater runoff (Leite et al., 2014; Sadri & Thompson, 2014; Liu et al., 2019). Plastic debris can undergo environmental degradation when exposed to solar radiation and mechanical friction, forming small

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plastic particles ($d < 5 \text{ mm}$) known as secondary microplastic (MP). Additionally, various types of MPs manufactured at this size, called primary MPs could be released into the environment (Aghilinasrollahabadi et al., 2021; Hadiuzzaman et al., 2022; Battacharjee et al., 2023).

Urban runoff has been introduced as a concentrated source of MPs, with concentrations that vary depending on climate conditions (Symth et al., 2021). Various land-use categories, including residential, industrial, commercial, roads, and highways, are contributing to MP release into urban stormwater runoff (Tu et al., 2018; Siegfried et al., 2017). The literature indicated that approximately 42% of the total MP loading into rivers in Europe originates from tire and road wear particles (Horton et al., 2017). Proximity to urban regions, level of urbanization or industrialization, and rainfall rates have been identified as the key parameters impacting plastic debris outflow to the aquatic environment via stormwater runoff (Lebreton et al., 2017). Studies into the influence of land use on plastic debris input to the environment demonstrated a greater concentration of plastic debris released by industrial and commercial activities compared to residential areas (Magnusson et al., 2016). Microplastics (MPs) released to the road could be transported through various pathways to the surrounding environment. The wind could transport the light and small MPs (Magnusson et al., 2016). Depending on the characteristics of storm events, slope, and structure of the road, and the physical characteristics of the plastic fragment, the MPs could be washed off the road verge. Smaller MPs may be trapped in the pavement microstructure and/or adhere to vehicle tires. The MPs transported to the verge might become trapped within sediments or vegetation or could be conveyed to stormwater retention ponds or drains (Müller et al., 2020). The likelihood of transport for MPs that are trapped in vegetation or sediment is low, except for when an intense storm surge resuspends these trapped MPs into stormwater runoff (Vogelsang et al., 2018). The stormwater drainage was reported as a sink for MPs accumulation (664 particles per kg dry sediment) and a path for their transport to the marine and freshwater environment (Brooks et al., 2023). Moreover, the stormwater ponds treating the runoff from industrial, commercial, and residential sites are identified as the hot spots for MP accumulation (Liu et al., 2019). The MPs can eventually be transported to water resources, potentially resulting in the loss of aquatic habitats, harm to marine animals, and increased risk of human exposure (Dehghani et al., 2017; Holmes et al., 2012).

Recent studies on the export and transport of MPs in water bodies and terrestrial environments reported advection, aggregation, diffusion, degradation, adsorption, settling, and dispersion as the major processes that influence the MPs' distribution (Samavi et al., 2023). The MPs' density is expected to influence their diffusion and settling behavior. Limited investigations into the transport of MPs in the aquatic environment have primarily focused on coastal waters. These studies involved the development of hydrodynamic models to predict the advection and diffusion of MPs by coastal currents (Genc et al., 2020; Handyman et al., 2019). Moreover, a few studies focused on MPs' transport in river/bed sediment systems have assumed that MPs are following the sediment transport principles (Unice et al., 2019; Nizzetto et al., 2016; He et al., 2021). The recent study by Nizzetto et al. (2016) has upgraded the catchment hydrology, sediment budget, and soil erosion to describe the MPs' transport in a river stream and retention by riverbed sediment and soil/stream system. This study reported that MPs smaller than $200 \text{ }\mu\text{m}$ are generally not retained, irrespective of their density. On the other hand, larger MPs with densities slightly higher than water can be retained in the sediment (Nizzetto et al., 2016). Moreover, the study conducted by Bondelind et al. (2020) presented a hydrodynamic model to examine the role of size and density of tire wear particles on their fate within a river system. This study demonstrated that larger and denser particles were settled within the river, while smaller and lighter particles were transported to the marine environment (Bondelind et al., 2020).

The transport models, focusing on stormwater runoff as the carrier for MPs, have investigated the downward export of MPs into the ground

or the MP movement on the land surface. Studying the downward mobility of MPs around the stormwater control measures (SCM) by Koutnik et al. (2022a,b) revealed that straining is the major mechanism for MPs' removal by the topsoil. However, no discussion was provided on the lateral transport of the MPs. Moreover, an exponential model was developed to link the subsurface retardation of MPs to land use and soil particle size (Koutnik et al., 2022a,b). Additionally, studying the transport of polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) MPs with diameters ranging from 0.1 to $1000 \text{ }\mu\text{m}$ by stormwater downward into the ground under natural freeze-thaw cycles using a force balance model revealed that smaller MPs ($<50 \text{ }\mu\text{m}$) can be pushed at a greater velocity by the ice-water interface, regardless of their density. However, the density of plastic becomes crucial when the size of MP exceeds $50 \text{ }\mu\text{m}$ (Koutnik et al., 2022a,b).

The study conducted by Unice et al. (2019) incorporated terrestrial and freshwater transport processes and employed a baseline watershed-scale MP mass balance model to investigate the emission of tire and road wear particles (TRWP) to the estuary. The mass balance accounted for TRWP generation and terrestrial transport to soil, air, and roadways, along with freshwater transport processes. The findings indicated that 2% of the generated TRWP (ranging from 0.5 to $200 \text{ }\mu\text{m}$) was transported to the estuary and 18% of those was transported to freshwater (Unice et al., 2018). By applying a sensitivity analysis of this model, it was found that TRWP diameter and density are significant factors influencing their export to the estuary (Unice et al., 2019). Moreover, the interaction of MPs with other components present in stormwater could influence their transport behavior. For instance, increased MPs' density caused by sediments, and aggregation of MPs in the presence of other natural particles could alter their settling velocity (Bonyadinejad & Salehi, 2024). Additionally, the slow-settling MPs may have been scavenged by fast-settling sediment particles, resulting in a greater rate of their removal from the water (Serra & Colomer, 2023). Few studies on the influence of MP density, shape, and size on their transport and settling velocities demonstrated significant deviation from typical sediment transport behavior. Thus, there is an immediate need to develop transport models specific to MPs.

Considering the extent of plastic pollution and the recent changes in the hydrologic responses to storm events caused by the increasing density of roadways, streets, and highways, it is critical to have a better understanding of how MPs are transported by urban storm runoff. Therefore, this study is conducted to identify the transport mechanism of MPs by stormwater runoff as a function of plastics' type, shape, size distribution, and site characteristics. Furthermore, the transport mechanism of settling MPs was assessed using the field data on MP abundance in road dust collected in a previous study. We hypothesize that (i) the transport mechanisms of settling MPs depend on their size, density, and shape, (ii) elevated flow depth and slope may facilitate the transport of larger particle sizes via wash-load and full suspension rather than bed-load and partial suspension, and (iii) site characteristics exert a notable influence on runoff velocity, thus impacting the extent of buoyant MPs' transportation to storm drains.

2. Methodology

2.1. Model description

(A) Terminal velocity of MPs: To calculate the terminal settling velocities of MPs, the drag law equation was solved through iterations by modifying the drag coefficient in an existing particle tracking model (Li et al., 2023; Li et al., 2022). The terminal velocity is given by equation (1), where V is the volume of the particle, C_D is the drag coefficient, g is gravitational acceleration, A_p is the projected area of the particle, ρ_f is the fluid density, and ρ_m is the particle density.

$$U_t = \sqrt{\frac{2V(\rho_m - \rho_f)}{A_p C_D \rho_f}} g \quad (1)$$

To consider the effect of shapes on the terminal velocities of MPs, we considered three different MP shapes: film, fiber, and fragment based on the data presented by Zhang and Choi (2022). In our modeling, each MP is characterized by three length scales: long-axial diameter (a), intermediate-axial diameter (b), and short-axial diameter (c). These three length scales are used to define two shape indices: flatness = c/b and elongation = b/a. When determining the terminal velocity of each MP, a fixed series of values of b are given while the values of a and c were calculated based on the combination of flatness and elongation values chosen in three types of MP shapes. Specifically, for fibers, we set elongation to 0.1, with flatness values of 0.3 within the typical range of 0.1–0.8. For films, a fixed flatness of 0.05 was applied, coupled with elongation values of 0.5 within the typical range of 0.2–1. For fragments, both elongation and flatness were set to 0.5. These selections were guided by the MP shape classification specified in Zhang and Choi (2022). Following Zhang and Choi (2022), the drag coefficient for MPs was calculated using equation (2), where Reynolds number (Re) and Aschenbrenner shape factor (ASF) are defined using equations (3) and (4). The area equivalent spherical diameter (d_{eqa}) is defined as equation (3). The volume equivalent spherical diameter (d_{eqv}) is defined in equation (5).

$$C_D = \frac{58.58ASF^{0.1936}}{Re^{0.8273}} \quad (2)$$

$$Re = U_t d_{eqa} / \nu \text{ with } d_{eqa} = \sqrt{4ab/\pi} \quad (3)$$

$$ASF = ac/b^2 \quad (4)$$

$$d_{eqv} = (abc)^{1/3} \quad (5)$$

(B) Settling velocity of sand: Settling velocity of sand is also calculated in this study as a comparison. Calculation of the settling velocity of sand follows the same procedure as solving the drag law equation through iterations. Sand particles are assumed spherical, and the drag coefficient is determined using equation (6) proposed by Cheng (1997), which was recently implemented and validated in determining sedimentation in streams (Wang et al., 2024). The density of sand is 2.65 g/cm³.

$$C_D = \left(\left(\frac{32}{Re} \right)^{1.5} + 1 \right)^{1.5} \quad (6)$$

(C) Transport of settling MPs: The transport mechanism of settling MPs is determined analogous to sediment transport in streams and rivers. The modes of transport for MPs are classified as wash-load, suspended load, and bedload (Figs. SI–1), determined by the Rouse Number as the ratio of the MP settling velocity to the product of flow shear velocity and von Karman constant (Xu et al., 2024). von Karman constant is an essential universal factor in describing the velocity profile within the turbulent boundary layer of wall bounded flows. However, urban runoff might be too shallow for a boundary layer to develop. Therefore, we simply drop out the von Karman constant and use the ratio between the MP settling velocity and the shear velocity instead. The flow shear velocity (u^*) is calculated using Equation (7), where h is the flow depth, and m is the friction slope. In this study we assumed that the flow depth is equal to the runoff depth (Q), and calculated that using equation (8).

$$u_* = (ghm)^{0.5} \quad (7)$$

P is rainfall depth (in) and S is the amount of storage and is calculated using Equation (9), where CN is the curve number. The curve number is a function of land use and soil hydrological group.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (8)$$

$$S = \frac{1000}{CN} - 10 \quad (9)$$

The bedload occurs at a ratio of $U_t/u^* > 2.5$, partial suspension occurs at $1.2 < U_t/u^* < 2.5$, full suspension occurs at $0.8 < U_t/u^* < 1.2$, and the wash-load occurs at $U_t/u^* < 1.2$. The bedload involves the particles that move by rolling. However, they stay in contact with the bed surface, and this process is most common for larger and denser particles. However, the suspended load involves the particles that move through the water column and exchange with the particles in the bed. The water density and kinematic viscosity were considered as 0.9882 g/mL and 0.00001003 (m²/s) at 20 °C.

(B) Transport of buoyant MPs: When a buoyant MP is submerged in water, gravitational forces exert a downward pull, attempting to drag it beneath the surface, while buoyancy forces resist this pull, pushing the MP upwards. The magnitude of the buoyant force is equal to the weight of water that is displaced by the object. Alongside these, capillary forces, influenced by the interplay of surface tension and the wetting properties of the MP, also contribute to the equilibrium dynamics. Achieving a stable position at the water interface relies on a balance between these forces. The magnitude of these forces varies depending on several factors, including the size, shape, density, and hydrophilicity of the MP. Due to the complexity of these factors and their influence on the applied forces on MPs, we assumed that all buoyant MPs are transported through wash-load (Singh et al., 2010). Considering the site characteristics, we calculated the time it takes for them to reach the storm drain. The storm runoff was considered as a plug flow reactor (PFR) operating at steady-state conditions for conservative materials and a mass balance equation was applied to identify the MP concentration that reaches downstream. We may have some local mixing due to the turbulence caused by rain, but we assume no mixing occurs in the axial direction. The plug containing the MPs is considered a separate entity that flows down the road and enters the storm drain after the specific residence time. The residence time for a parcel of water is defined using Equation (10), where V is the volume, F is the flow rate, A is the area, x (m) is the distance between the inlet and stormwater drain, and U (m/s) is the horizontal velocity of the water. In this model, we assume a uniform distribution of MPs at the inlet, and no axial mixing occurs through the control volume. Thus, the travel time (TT) defines the duration of time that it takes for MPs to reach downstream after the beginning of floating, calculated using equation (10). The horizontal velocity of storm runoff on an impervious surface is determined using manning's equation (11) where R_h is the hydraulic radius, and n is Manning's roughness coefficient.

$$TT = \frac{V}{F} = \frac{Ax}{AU} = \frac{x}{U} \quad (10)$$

$$U = \frac{1}{n} (R_h)^{2/3} m^{1/2} \quad (11)$$

2.2. Modeling scenarios

In this study, we have targeted both buoyant MPs [e.g., polyethylene, polypropylene] and settling MPs [e.g., polyethylene terephthalate, polyamide]. The list of MPs considered for this study and their densities before and after weathering are shown in Table SI-1. The MP shape of fragments, fibers, and film are investigated. As reported in the literature, polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), PET, and PS plastics are the most prevalent types of plastics found within the urban environment (O'Brien et al., 2021; Yukioka et al., 2020). Moreover, we considered the characteristics of two residential sites in Memphis, TN, as representatives for the theoretical modeling process. The flow depths of minimum and average rainfall of both sites were

0.0001 and 0.008 m, respectively. The friction slopes were 0.73% and 1.04% for Site A and Site B, respectively. The drainage area was almost the same for sites A (5.8 m²) and B (5.7 m²). The hydraulic radius was 0.061 m and 0.076 m at sites A and B, respectively.

3. Results and discussion

3.1. Theoretical modeling

3.1.1. Terminal settling velocity of settling MPs

Using the plastic densities listed in Table SI-1, we calculated the settling velocities of PET, PS, and PA MPs. As shown in Fig. 1, the influence of shape on the settling velocity of MPs was particularly obvious as the equivalent diameter of the MPs increased. Additionally, this influence was more pronounced for MPs following the order of their density (PET > PA > PS). For the target MPs as the diameter increased, the settling velocity of fragments surpassed that of both fibers and films (Khatmullina & Isachenko, 2017). The experimental work conducted by Khatmullina and Isachenko (2017) confirms our findings (Khatmullina & Isachenko, 2017). Compared to sediment particles with a density of 2.65 g/cm³, all MPs settled at a lower velocity due to their significantly lower density. The settling velocities of PET MPs, with diameters ranging from 0.01 to 4 mm, varied from 0.006 mm/s to 251 mm/s; for PA MPs, they ranged from 0.002 mm/s to 105 mm/s; and for PS MPs, they ranged from 0.001 mm/s to 45 mm/s. These findings highlight the critical influence of size, shape, and density on the settling of MPs in stormwater. MPs with higher density and larger size, which are often fragmented from larger plastic residues, are likely to be swiftly removed from stormwater runoff and integrated into sediments, such as those found in road deposits. Conversely, fibers and films with a similar equivalent diameter may take longer to be removed from stormwater and could potentially end up in stormwater drains. Moreover, efforts to

mitigate MPs in stormwater runoff may benefit from targeting areas where settling is more likely to occur, such as infiltration systems, porous pavement, swales, and retention ponds (Vahvaselkä & Winquist, 2021). Additionally, customized floating devices for the removal of MPs from water streams could be particularly effective for targeting film and fiber MPs.

3.1.2. Transport mechanisms for settling MPs

In this study, the transport mechanism for settling PET, PA, and PS MPs in various forms (film, fiber, and fragments) was investigated and compared to that of sediment particles. The equivalent diameter (d_{eqv}) of the studied MPs ranged from 0.01 mm to around 4.0 mm. The results presented in Fig. 2a, for site A with a flow depth of 0.0001 m indicated that the transport mechanism for the smallest and largest sizes of the target MPs, regardless of their shape and density, was primarily through wash-load and bedload, respectively. The PET MPs with $d_{eqv} \geq 0.7$ mm were transported as bedload regardless of the shape. This is due to their greater density (1.38 g/cm³) than PA and PS MPs. However, a slightly lower density of PA MPs (1.13 g/cm³) altered the transport mechanism leading to the partial suspension of 0.7 mm fiber and film MPs, while the PA fragments with this diameter along with the larger PA MPs were transported as bedload. For PS MPs, only the largest sizes (4.0 and 2.0 mm) were transported as bedload, whereas the transport mechanism for smaller diameter PS MPs (1.0 mm and 0.7 mm) varied considerably depending on their shapes. For 0.7 mm PS MPs, the film and fiber MPs were transported as wash-load while fragments were fully suspended.

Moreover, our investigation into the transport mechanism of MPs has been extended to assess the impact of a greater flow depth of 0.008 m within the study site. The results as shown in Fig. 2b revealed that while the transport mechanism for the largest PET MPs (4.0 mm) remained unaffected by the increased flow depth, persisting as bedload transport, a shift was found for 2.0 mm PET film and fiber, transitioning to partial

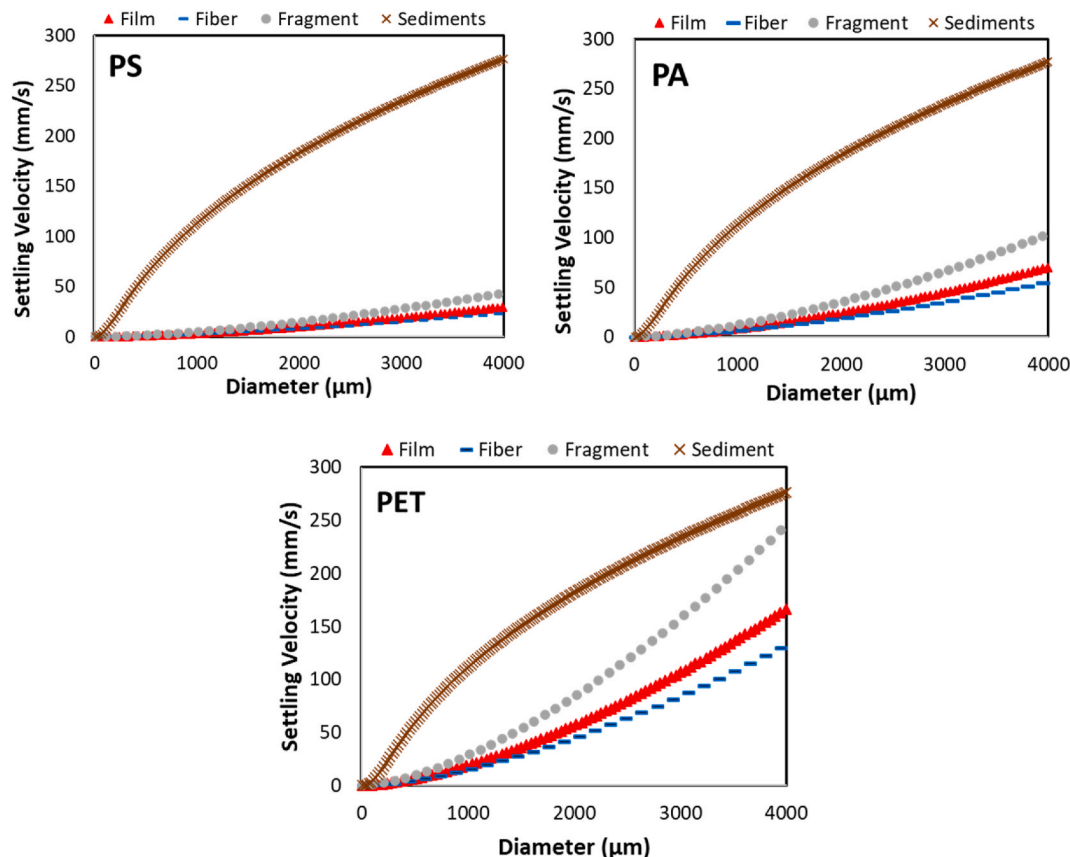


Fig. 1. The simulated settling velocity of PS, PA, and PET MPs shaping as film, fiber, and fragment in comparison to sediments.

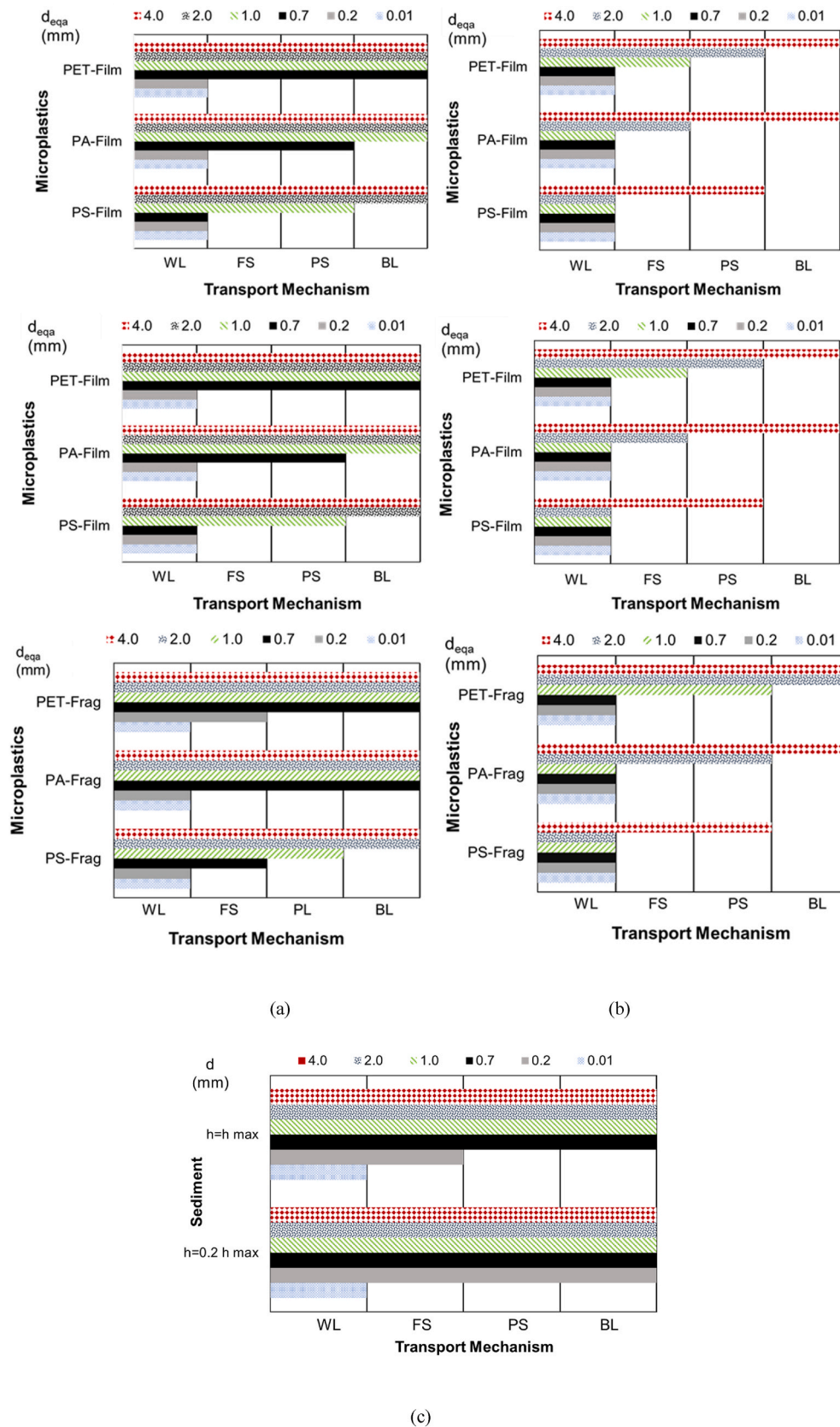


Fig. 2. The mechanisms of MPs transport via stormwater runoff as a function of their shape and d_{eqv} for the different flow depths (h) of (a) 0.0001 m and (b) 0.008 m, and (c) mechanism of the sediment transport in site A. WL: wash-load, FS: full suspension, PS: partial suspension, BL: bedload.

suspension. However, PET fragments of this size retained their bedload transport behavior. By increasing the depth of flow from 0.0001 m to 0.008 m, an interplay between MP shape and transport mechanism became increasingly apparent. Notably, PET MPs with a 1.0 mm diameter exhibited distinct transport behaviors based on their form: fully suspended as film, wash-load as fiber, and partially suspended as fragments. However, for PA and PS MPs, characterized by lower densities compared to PET, the increasing depth of flow resulted in a uniform transport pattern: MPs with diameters ≤ 1.0 mm were uniformly transported as wash-load, irrespective of their shapes. The flow depths of 0.0001 m and 0.008 m were applied for modeling calculations, considering the minimum and average annual rainfall of the chosen urban area in 2022. We selected only two depths to illustrate the patterns of variation in the transport mechanism with increasing depth. It is evident that increasing the depth of the flow results in larger MPs being transported through the wash-load mechanism, whereas reducing the flow depth promotes the transport of larger MPs through bedload or partial suspension.

A comparison of the transport mechanisms of MPs (Fig. 2a and b) and sediments (Fig. 2c) of similar diameters reveals notable distinctions. While only the smallest sediment sizes (0.01 mm) are transported via wash-load, similar to MPs of comparable size, the majority of sediment sizes are transported through bedload, resembling PET MPs with a diameter of 4.0 mm. However, the transport mechanisms for other types and shapes of MPs vary, with some transported via wash-load or suspension depending on their characteristics.

The predicted transport mechanisms for MPs of various shapes and diameters at site B, at $h = 0.0001$ m, are illustrated in Figs. SI-2. These results indicate no significant changes in MPs' transport mechanisms between sites B and A. The transport mechanisms of PET film and fibers, PS fibers, and PA film MP were similar at both sites, with only minor changes observed for certain sizes and shapes of MPs. For instance, the transport mechanism of 0.2 mm PE fragments shifted from wash-load to partial suspension, and 0.7 mm PA fragments were transported as partial suspension rather than full suspension. The distinct variations in transport mechanisms between sites A and B are attributed to the different friction slopes at these sites.

To assess the impact of slope on the transport mechanism of settling MPs, we have considered a hypothetical condition of 4.0% slope in site A with a flow depth of 0.008 m. We subsequently analyzed the transport mechanism for settling MPs under these conditions (Figs. SI-3) and compared the results with those presented in Fig. 2b for a similar flow depth at this site with a 0.7% slope. This comparison revealed that by increasing the site slope, the majority of the target settling MPs are transported as wash-load. In particular, the transport mechanisms of PET fragments with diameters of 2.0 mm and 1.0 mm transitioned to wash-load with increased slope. All PS film, fragments, and fiber MPs were consistently transported as wash-load. Similarly, all PA film, fragments, and fibers were transported as wash-load except for those with a diameter of 4.0 mm, which were transported through suspension. The modeling results for settling MPs showed an interplay between MPs' characteristics (size, shape, density), flow depth, site slope, and transport mechanism. Moreover, our findings emphasize the importance of considering local geomorphological factors, such as friction slopes, when assessing the transport dynamics of MPs and sediment particles via stormwater runoff.

3.1.3. Transport of buoyant MPs

The buoyant MPs are transported with a similar velocity as stormwater runoff via a wash-load mechanism as soon as they float in water. The stormwater runoff velocities for both sites considering two values for slope and two different pavement types of concrete and asphalt were calculated using equation (10), and the corresponding values are shown in Table SI-2. The difference in runoff velocities in sites A and B can be attributed to slope and surface roughness. In particular, the greater surface roughness of asphalt, in comparison to concrete, led to a lower

runoff velocity. On the other hand, the steeper ground slope contributed to an increased runoff velocity. The travel time of MPs varies from 66 s to 452 s, when the distance between the inlet and storm drainage is 121.9 m. Other studies revealed that low-density MPs such as polyethylene ($0.90\text{--}0.99\text{ g/cm}^3$) in turbulent flow conditions can travel for long distances while high-density MPs can either be suspended or settled down at a specific distance of translocation or the bottom of a river (Kumar et al., 2021). Our findings underscore the significance of rainfall depth and site characteristics in influencing the flotation and then transport of buoyant MPs. Thus, to mitigate the transport of these MPs, strategies aimed at enhancing pavement surface permeability could be promising. Implementation of permeable pavement materials, such as porous concrete or permeable asphalt, in urban settings can promote water infiltration, minimizing the rainfall depth and reducing the likelihood of MPs floating and being swiftly transported. Additionally, integrating green infrastructure features like permeable swales or retention ponds can serve as effective barriers, capturing buoyant MPs before they reach storm drains and preventing their further transport.

3.1.4. Impacts of microplastics weathering on their transport

Recent studies have highlighted the role of biofilm accumulation on MPs in promoting their aggregation with sediment and organic matter, leading to increased density and altered settling velocities (Lee et al., 2022). For instance, Lagarde et al. (2016) reported a density increase in PP from 0.9 g/cm^3 to 1.2 g/cm^3 due to the aggregation of freshwater microalgae. This colonization of microorganisms on buoyant MPs can eventually result in their sinking. Additionally, our prior study has shown that mechanical weathering of MPs occurs through the abrasion of MPs with sediment particles, resulting in the attachment of the sediment particles onto the surface of MPs. Sharp-edge sediment particles may abrade the plastic surface, creating potential sites for it to settle (Aghilinasrollahabadi et al., 2021). Given the notably higher density of sediments compared to pristine MPs, this process could ultimately lead to an increase in the overall density of MPs. However, the extent to which the density of MPs changes due to environmental weathering may vary depending on factors such as the type of plastic, environmental conditions, and the duration that MPs remain in the environment. In this study, we assumed a 10% increase in the density of pristine MPs due to environmental weathering, recalculated settling velocities for various sizes, and examined transport mechanisms (Fig. 3). Consequently, the density of HDPE MPs was increased to 1.03 g/cm^3 transitioning from buoyant to settling MPs. A comparison between Figs. 2 and 3 data reveals significant alterations in MP transport mechanisms due to environmental weathering.

The effect of weathering on transport mechanism alteration depended on the MP shape. For example, new PET fiber MPs with diameters between 1.0 mm and 2.0 mm shifted from partial suspension and wash-load to bedload and full suspension, while other sizes remained unchanged. However, transport mechanism for PET fragments with a diameter of 0.7 mm shifted from wash-load to full suspension, and PET film MPs transitioned from partial suspension to bedload, while others remained unaffected. Notably, transport mechanisms for smaller MPs (0.01 mm, 0.2 mm) remained unchanged due to weathering, continuing to be transported through wash-load. The impact of weathering on transport mechanism alteration was more pronounced for MPs with diameters ranging from 1.0 mm to 2.0 mm. Increased HDPE MP density due to weathering predominantly altered the main transport mechanism for larger sizes, transitioning from wash-load. However, this alteration was highly shape-dependent; weathered HDPE fiber and film MPs were transported as fully suspended, while weathered HDPE fragments were transported as partially suspended. As we mentioned earlier the extent of density variation due to the biofouling and aggregation of MPs with sediment particles could vary significantly. Investigating the influence of increasing MP density from 5% to 30% on the transport mechanism of PS fragments with diameters ranging from 0.01 to 4 mm is demonstrated in Figs. SI-4. The results revealed that the impacts of density

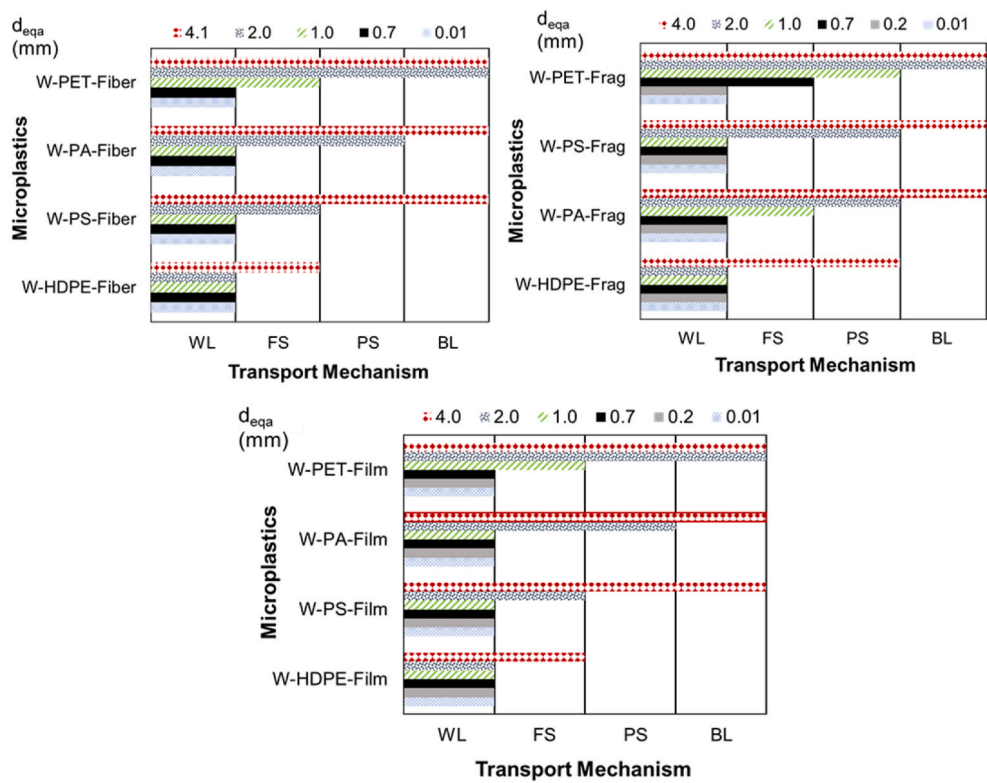


Fig. 3. The mechanisms of transport of weathered MPs via stormwater runoff as a function of their shape and diameter for the flow depth (h) of 0.008 m and slope of 0.73% in site A. WL: wash-load, FS: full suspension, PS: partial suspension, BL: bedload.

enhancement on transport mechanisms depend on the size of MPs. Increasing the density from 5% to 30% did not change the transport mechanism of the smallest ($d = 0.01$ mm) and largest ($d = 4.0$ mm) target MPs, which remained as wash-load and bedload, respectively. However, increasing the density from 5% to 10% and then to 20% altered the transport mechanism of 2 mm PS fragments from fully suspended to bedload.

4. MPs transport mechanism using the field-collected data

We've utilized the quantification data reported by O'Brien et al. (2021) regarding the abundance of PS, PVC, PMMA, and PET MP in road dust within two residential sites and one traffic site. This data enabled us to gain a better understanding of how these MPs are transported through different mechanisms. Although specific details about the sampling sites were lacking, we assumed flow depths of 0.0001 m and 0.008 m,

resembling those at site A in this study. Furthermore, as the shapes of the MPs were not provided, we considered those as fragments. Although the mass loading of MPs in road dust was presented for the size range of $<250 \mu\text{m}$, $250\text{--}500 \mu\text{m}$, $500\text{--}1000 \mu\text{m}$, $1000\text{--}2000 \mu\text{m}$, and $2000\text{--}5000 \mu\text{m}$, we considered $250 \mu\text{m}$, and median diameter in each size range as d_{eqa} of fragment MPs to study their transport mechanism using this experimental data. Further details on the sampling and quantification can be found in O'Brien et al. (2021). The summarized results in Table 1 indicate that at the lower flow depth (h_1) considered in our evaluation, PET and PVC MPs are primarily transported via full suspension within traffic sites due to their smaller diameter. However, as the diameter of these MPs increases, their transportation shifts predominantly to partial suspension and wash-load within residential sites. Meanwhile, the larger size of PMMA MPs in both traffic and residential sites results in the majority being transported as bedload. The lower density of PS, coupled with their smaller size distribution, leads to their transportation

Table 1
The evaluation of the transport mechanisms for settling MPs that were quantified by O'Brien et al. (2021) at $h_1 = 0.0001$ m and $h_2 = 0.008$ m, C: concentration of MPs in road dust, PMMA: Polymethyl methacrylate.

MP type		Traffic				City (1)				City (2)			
		WL%	FS%	PS%	BD%	WL%	FS%	PS%	BD%	WL%	FS%	PS%	BD%
PET	C	0.78 (mg/g)				0.58 (mg/g)				0.80 (mg/g)			
	h_1	0.0	56.1	12.2	31.7	0.0	0.0	27.2	72.8	0.0	22.9	18.6	58.5
	h_2	75.3	0.0	11.9	12.8	68.8	0.0	31.2	0.0	59.9	0.0	20.7	19.4
PVC	C	1.87 (mg/g)				2.98 (mg/g)				4.81 (mg/g)			
	h_1	0.0	49.1	13.1	37.8	0.0	21.3	20.3	58.4	0.0	31.4	16.0	52.6
	h_2	74.8	0.0	11.8	13.4	73.2	0.0	26.8	0.0	67.8	0.0	24.2	8.0
PMMA	C	0.04 (mg/g)				1.04 (mg/g)				0.94 (mg/g)			
	h_1	0.0	0.0	0.0	100.0	0.0	12.2	0.0	87.8	25.7	14.9	0.0	59.4
	h_2	0.0	0.0	0.0	100.0	44.0	0.0	56.0	0.0	71.3	0.0	28.7	0.0
PS	C	0.15 (mg/g)				0.00 (mg/g)				0.09 (mg/g)			
	h_1	46.1	19.7	0.0	34.2	0.0	0.0	0.0	0.0	62.0	38.0	0.0	0.0
	h_2	78.3	0.0	21.7	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

primarily as wash-load.

Increasing the depth of flow significantly alters the transport mechanism for these MPs, resulting in a substantial increase in wash-load for the majority of MPs in the target sites. This underscores the importance of considering flow dynamics in understanding the transport pathways of MPs in road environments. The transport mechanisms for MPs critically influence their mobility, eventual fate, and impacts on the environment. MPs transported through wash-load can be efficiently transported over long distances, as they remain suspended in the water. Conversely, those transported as bedload move more slowly and may accumulate in certain areas, where they can have localized impacts on ecosystems and habitats. Understanding these transport mechanisms is crucial for assessing the potential spread and distribution of MPs in aquatic environments. Wash-loaded MPs have the potential to travel far distances, posing risks to diverse ecosystems along their path. In contrast, bedload transport can lead to the deposition of MPs in specific locations, where they may persist and accumulate over time, potentially exacerbating environmental contamination and ecological impacts in those areas.

5. Limitations, broader implications, and future research needs

This study, while informative, is associated with several limitations. While we have accounted for three different shapes of the MPs in our study using representative factors of flatness and elongation, it's essential to acknowledge that in real environmental conditions, MPs are present in a multitude of shapes. This variation in shape could significantly influence their settling behavior and, consequently, their transport mechanisms. Thus, the limited scope of shapes considered in our study may not fully capture the complexity of MP behavior in natural environments. Although in this study we have assumed a certain increase in MP density due to weathering, future laboratory investigations should be conducted to determine the density variations of MPs as a function of their characteristics and environmental conditions over time. Furthermore, while we have considered the increase in density of MPs due to weathering within the environment, it is imperative to also consider the variations in surface hydrophobicity and subsequent capillary forces acting on MPs as they weather. These factors could have a significant influence on the transport mechanisms of MPs, and their omission represents a limitation in our study.

While considering the effect of shapes on the parameterization of drag coefficient, the definition of Reynolds number, and plastic length scale, we note that various forms of equations using different formats of shape factors (e.g., ASF, Corey shape factor, Dellino shape factor) have been proposed in the literature (Zhang and Choi, 2022; Francalanci et al., 2021; Dioguardi et al., 2018; Waldschlager et al., 2019), these different parameterization methods have been validated separately, a systematic study may be needed in the future to examine their suitability for particular plastic types and/or shapes. Additionally, we assumed that the transport of buoyant MPs follows steady-state conditions using Manning's equation which is applicable for uniform open channel flows. However, in real environmental settings, depending on the site's and MP's characteristics, substantial nonuniformity and unsteady flow conditions may occur, and some MPs might become trapped at the surface of the pavement. In addition, the concepts and transport criteria for suspended load, wash-load, and bedload used in this study are an analogy to the sediment transport in rivers and streams. However, the exact suspension and transport mechanisms are subject to future studies.

Despite its limitations, this study provides the foundation for future studies on MP transport by stormwater runoff. Understanding the transport dynamics of MPs in stormwater runoff underscores the importance of tailored pollution control strategies. This knowledge can inform the development of more effective stormwater management practices to reduce MP contamination in urban areas considering the type and size distribution of MPs that are commonly found within a specific type of land-use. Moreover, this study highlights the role of site-

specific factors such as slope and surface friction in MP transport. Thus, urban planners can utilize this information to design more resilient and sustainable urban landscapes that mitigate MP pollution. This study's insights into MP transport mechanisms in urban stormwater significantly contribute to our understanding of urban pollution dynamics and have implications for urban environmental management and policy-making. Key among these is the integration of green infrastructure (GI) as a strategic component in urban planning to mitigate the transport of MPs. For example, our findings highlight the role of pavement permeability in reducing MP transport. The utilization of porous concrete or permeable asphalt can significantly lower surface runoff, thereby reducing the flotation and rapid transport of lower density MPs. This aligns with our observation that buoyant MPs with lower densities than water are rapidly transported by stormwater runoff as soon as they float. Therefore, increasing surface permeability through GI such as permeable pavements can be a proactive measure in reducing MP pollution. Also, the study highlights the potential of vegetated systems, like rain gardens and vegetated buffer strips, in trapping and filtering MPs. The implementation of such systems in urban landscapes not only enhances aesthetic benefits but also serves as a natural barrier against MP transport into water bodies. This is particularly crucial given the varied transport mechanisms of MPs based on their size and density, as identified in our study.

The research revealed that site-specific characteristics such as slope and surface friction significantly influence stormwater runoff velocity, impacting the transport dynamics of MPs. This finding suggests that GI components need to be designed for local geomorphological factors. Swales and retention ponds can be strategically located and designed to maximize their efficiency in areas where MP deposition is likely. The integration of GI into urban planning presents a pathway towards creating more resilient urban environments. By mitigating MP pollution, GI contributes to preserving aquatic ecosystems and improving the overall quality of urban environments. This is particularly pertinent given the study's emphasis on the importance of site-specific characteristics in influencing MP transport. The study also points to the need for future research focusing on the effectiveness of various GI elements in mitigating MP pollution, considering a wide range of MP shapes, sizes, and densities. Systematic field investigations into the effectiveness of GI in real-world conditions would provide valuable data to refine and optimize urban stormwater management strategies. Additionally, different land covers, such as urban, agricultural, or forested areas, significantly affect the runoff characteristics and, consequently, the transport of MPs. Urban areas with impervious surfaces tend to have higher runoff speeds and volumes, potentially carrying MPs further and faster compared to more permeable surfaces like those in forested or agricultural areas. The topography of a CA, including its slope and the presence of features such as hills and valleys, can alter the flow paths and accumulation zones of stormwater runoff. Steeper slopes may increase runoff velocity, thereby enhancing the transport capacity for MPs, especially those that are buoyant. By understanding the interaction between MPs and these environmental variables, practitioners can more accurately predict hotspots for MP accumulation and design effective mitigation strategies. For example, implementing GI in areas prone to high runoff speeds or adjusting stormwater management practices to account for specific land cover types can greatly reduce MP transport. We also recommend further research into the specific impacts of land cover and topography on MP transport dynamics to refine predictive models and improve practical applications for environmental management.

6. Conclusion

This study addresses the escalating issue of MP pollution in urban environments, with a particular focus on the role of stormwater runoff in transporting these particles to the surrounding aquatic ecosystems. Stormwater runoff, driven by increased impervious surfaces and altered

hydrological pathways in urban areas, has emerged as a primary vector for the transport of MPs into water bodies. In this study, a modeling framework was provided to study the transport of settling and buoyant MPs and distinguish that from the sediment particles, while considering the site-specific characteristics. The findings highlight the significant influence of MPs' shape, density, and size distribution on their transport mechanisms. Specifically, we found that settling velocity deviates more prominently among different shapes of MPs as their size and density increase. Additionally, a greater depth of flow and increased slope shifted the transport mechanisms of MPs from partial suspension and bedload to wash-load and full suspension. Moreover, the study suggests that site-specific characteristics, such as slope and surface friction, significantly impact the velocity of stormwater runoff and subsequently the time it takes for MPs with a lower density than water to be transported to the storm drain, highlighting the potential effectiveness of stormwater management practices in reducing MP pollution. This insight underscores the potential effectiveness of tailored stormwater management practices as a means of mitigating MP pollution in urban environments, aligning with the broader goals of safeguarding aquatic ecosystems and improving urban environmental quality.

CRedit authorship contribution statement

Arghavan Beheshtimaal: Writing – original draft, Methodology, Investigation. **Nasrin Alamdari:** Writing – review & editing, Methodology, Conceptualization. **Binbin Wang:** Writing – review & editing, Investigation. **Meysam Kamali:** Investigation. **Maryam Salehi:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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