Pollution Study 2025, 6(2), 3294.
https://doi.org/10.54517/ps3294

Article

Spatial hotspots of microplastic accumulation in sediment associated with stream outflows into lakes and estuaries

Gabriella C. DeGennaro[1], **Tinsley Stewart**[2], **P. Zion Klos**[3,*]

[1] Undergraduate Research Program, Marist University, Poughkeepsie, NY 12601, USA
[2] Undergraduate Honors Thesis Program, Marist University, Poughkeepsie, NY 12601, USA
[3] Department of Environmental Science and Policy, Marist University, Poughkeepsie, NY 12601, USA
*** Corresponding author:** P. Zion Klos, zion.klos@marist.edu

CITATION

DeGennaro GC, Stewart T, Klos PZ. Spatial hotspots of microplastic accumulation in sediment associated with stream outflows into lakes and estuaries. Pollution Study. 2025; 6(2): 3294. https://doi.org/10.54517/ps3294

ARTICLE INFO

Received: 11 January 2025
Accepted: 12 February 2025
Available online: 2 April 2025

COPYRIGHT

Copyright © 2025 by author(s). *Pollution Study* is published by Asia Pacific Academy of Science Pte. Ltd. This work is licensed under the Creative Commons Attribution (CC BY) license. https://creativecommons.org/licenses/by/4.0/

Abstract: Microplastics are a major form of anthropogenic pollution, and over time, the sediment at the bottom of aquatic environments becomes the sink for the denser of these particles. By mapping and analyzing sediment from lake and estuary systems, this study aimed to find spatial relationships between water and sediment dynamics at stream-to-slack-water transitions and resulting microplastic sediment accumulation characteristics. Sediment was collected along transects extending from the stream mouth to open water depositional environments at four unique study sites. After a series of separations from collected sediment, microplastics were weighed to map longitudinal variations in plastic concentration. At all study sites, the highest concentrations of microplastics (up to 14% dry weight) in sediment were found to focus in spatial hotspots peaking 600–700 m down gradient from the transition to a low-energy environment in intertidal freshwater estuary systems, and 150 m downstream in a lake system, all being associated with environments of clay-dominated sediment deposition. The dominant types of plastics identified were cellophane and polydimethylsiloxane. We hypothesize these spatial hotspots of microplastic accumulation may result from the unique diversity of density ranges for microplastic sediment, ranging from just above 1 g/cm^3, but below the 2.7 g/cm^3 common for natural mineral sediment, thus creating plastic depositional locations that are spatially offset from those of common mineral grains.

Keywords: plastics; fluvial; lacustrine; reservoirs; impoundments; pollution; polymers; sediment mapping

1. Introduction

Synthesized polymers, known as plastic, have created one of the most pressing environmental issues of our time as they accumulate preferentially in certain geographic locations across our landscapes and waterways. Plastics are formed in the processes of polymerization and polycondensation, derived from organic sources such as crude oil, coal, and natural gas [1]. Although the first synthetic plastic was developed in the year 1907, its rapid production did not come to scale until the 1950s [2]. Since the 1950s plastic production has increased almost 200-fold and as of 2015, 6.3 billion tons of both primary and secondary plastic have been produced [3]. The size classifications of plastic are typically nano (< 100 nm), micro (0.0001–5 mm), meso (5–25 mm) and macro (> 25 mm) [4]. Examples of common microplastics are fragmented macroplastics, production pellets, microbeads within cosmetic and personal care products, fragmented fishing line and nets, paint, textiles, and electronic equipment debris [5]. Unlike macroplastics that can be observed polluting waterways, microplastics can go unnoticed until closer investigations and spatial mapping of sediment in these waterways are undertaken.

Due to the small size (< 5 mm) of these particles, environmental samples must be analyzed with more sophisticated methods to research microplastics [6]. A past study done on the Yangtze estuary in China has uncovered that microplastics account for more than 90% total plastic items in surface water [7]. According to the findings of Koutnik et al. [8], microplastic concentrations in soils, sediments, and surface water can range and vary up to eight orders of magnitude. With a high concentration of microplastics suspended in waterways, there are a variety of ways humans can be exposed to these pollutants, including in the seafood we consume [9]. This exposure has been studied through the lens of bioaccumulation in edible bivalve species. Within these edible bivalves, the accumulation of antibodies has been heavily aggravated by microplastics, therefore leading to tissue contamination [10]. Microplastics can also rest in sediment in terrestrial or aquatic ecosystems. Whether the microplastics are suspended in water or deposited in sediment can be attributed to their density. Microplastics with densities greater than the density of fresh water (~1 g/cm^3) will generally settle into the sediment, while fragments less dense than fresh water and seawater will float on the surface. Particles with a density around 1 g/cm^3 will remain suspended in the water column [11,12]. When exposed to direct UV radiation from sunlight and physical abrasion from water movement, plastic fragmentation and microplastic degradation will occur slowly in surface water [13]. However, this is not the case for sediment since it lacks direct exposure and abrasion [1]. This leads to a concentration difference in microplastics between surface water and sediment, with sediment typically having a higher concentration [14]. According to the results of Claessens et al. [15], all sediment samples taken in a marine coastal study contained plastics; this can be used as evidence that fragmented plastic is widespread in sediment in near-shore marine environments. In Vianello et al. [16], microplastics in sediment were distributed in a way that may suggest the existence of spatial patterns. Their results concluded that higher microplastic concentrations were observed in landward sites consisting of finer sediment. As this study was one of the first of its kind, the question of whether these results mirrored simply one network of near-shore marine systems, or a general systemic process, was hypothesized. The Venice lagoon, which is the overall site of this study, is a shallow intertidal saltwater body. Future work is needed to see if this spatial pattern found could also be applied to freshwater systems, because—compared to marine environments—plastic transport and microplastics within freshwater ecosystems are understudied [17]. Freshwater systems of flowing water in streams or rivers can slow in their transition to lakes and intertidal estuaries. When this slowing occurs, sediment suspended in the water column then begins to settle. The rates of sedimentation are controlled by Stokes Law, and different sizes and densities of particles result in faster and slower falling rates of suspended sediment, thus creating differentiated spatial locations of sediment of certain characteristics accumulating nearer or further from the transitional point to still water [18].

It is also necessary to verify if sediments of unique densities, outside the 2.7–3.3 g/cm^3 common of mineral sediment, are indeed plastics and not other natural compounds of similar density. For this, Fourier Transform Infrared Spectroscopy (FTIR) is commonly used for identifying the plastics found. FTIR works by inducing molecular vibrations in the material, resulting in a unique spectrum, which can be compared to a library database. However, library matches for FTIR are often limited due to weathering the plastics may experience [19]. Prolonged exposure to UV radiation can distort the polymers and make spectrum matching difficult [20]. Additionally, for these types of studies and the scale of particles being analyzed, μFTIR is preferred, so the size of the particle may decrease the confidence of results. Some of the most common microplastics found in other studies include polyethylene, polystyrene, polyurethane, polypropylene, polyvinyl chloride, and polyethylene terephthalate [21].

This study aims to investigate the spatial patterns of microplastic accumulation in sediment within both estuarine and lacustrine freshwater environments of deposition that exist immediately downgradient of rapidly flowing fluvial systems. Specifically, we seek to investigate if microplastic accumulation differs from the depositional patterns of natural mineral sediments in freshwater environments due to their known differences in particle density, as demonstrated by Stokes Law [18]. If so, this would support the existence of spatial hotspots of microplastic accumulation tied to easily observable changes in water velocity and dominant mineral sediment type.

2. Methods

2.1. Site

The Hudson River watershed, located in the eastern part of New York (NY) State, contains a large intertidal estuary, with several larger order tributaries feeding into it. Stemming from the Atlantic Ocean in NY harbor and ending at the Federal Dam in Troy, NY, the Hudson River consists of mostly brackish water south of Nyack (43 km from the mouth in NY City) and freshwater north of the mouth (the area of our study). The river experiences twice-daily tidal changes and intermittent reversing currents influencing the Hudson River estuary throughout its entire length (fully encompassing our study sites). Within the Hudson River watershed, three tributary estuaries and one upstream lake were examined for microplastic pollution in sediment accumulating in zones where fluvial energy transitioned from unidirectional in a stream to an area with low energy slack water during tidal transitions, or in a lake. The tributary estuaries for this study comprise the intertidal zones that occur roughly in the last kilometer of Esopus Creek, Rondout Creek, and Wappingers Creek, where these tributaries meet the intertidal forces of the greater Hudson River. The lake system, Chadwick Lake, was created by the damning of Quassaick Creek, which flows into the Hudson River at Newburgh, NY. This lake is solely composed of freshwater and is a drinking reservoir for the town of Newburgh. The locations of all four sites can be seen in **Figure 1**.

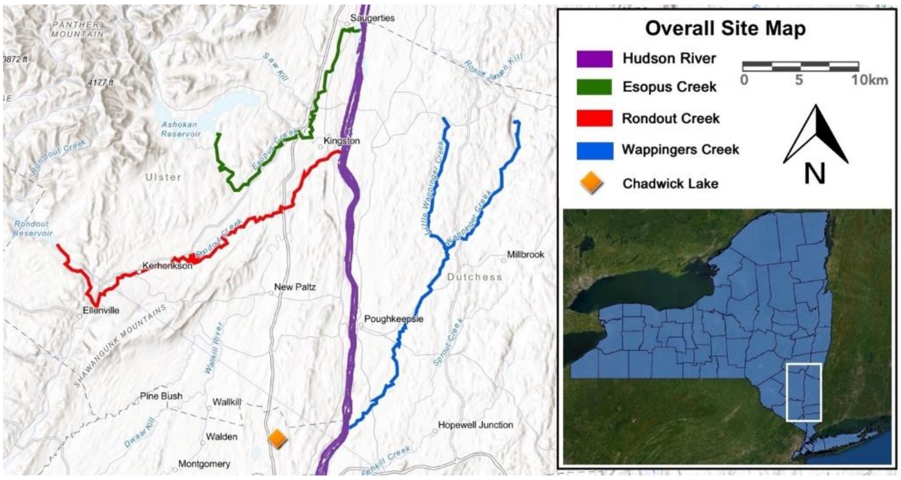


Figure 1. Map of study sites along the Hudson River estuary system, which spans between New York City (mouth) and Albany in New York State.

2.2. Field collection of sediment samples

To collect sediment samples for lab analysis of plastic concentration and type (**Figure 2**), sites that span stream-to-slack-water transitions were visited. For the three tributary estuaries—Esopus Creek (**Figure 3**), Rondout Creek (**Figure 4**), and Wappingers Creek (**Figure 5**)—three sediment samples were collected in each waterbody. Starting from the mouth of each tributary estuary, where it met the Hudson River, sediment samples were collected roughly every 300 m to span the intertidal slack water zone of the creek. The design aimed to collect one sample at the mouth itself, one sample collected at the upstream portion of the estuary section of the tributary (before the intertidal slack water zone ended due to a rise in slope that signified the transition to a normal unidirectional fluvial stream system with consistently high energy), and one sample collected at a mid-estuary location partway between the other two samples. For the Chadwick Lake site, a higher spatial resolution of sampling was sought, so sediment sample collection started at the mouth of the unidirectional Quassaick Creek as it emptied into the low-energy depositional environment of Chadwick Lake (**Figure 6**). This initial sample site is labeled as "A" in **Figure 6**. Using a paddle boat and a measuring tape, a new sampling location was chosen every 50 m, and a sediment sample was collected. This led to seven sample sites labeled A–G.

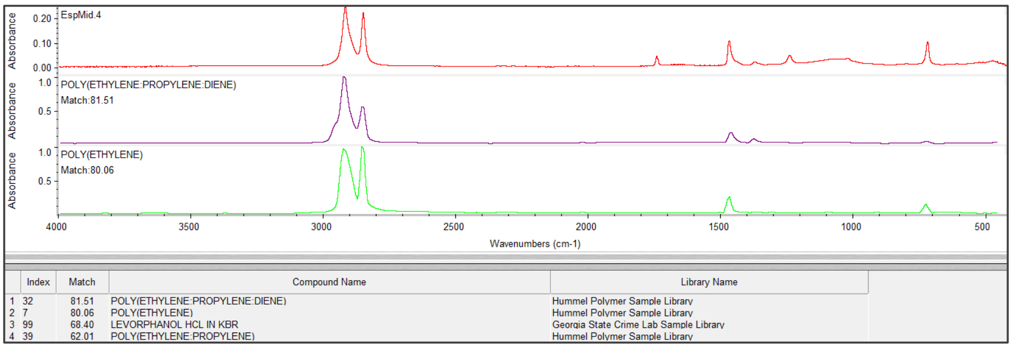
For all sample collection at all estuaries and tributary sites, free diving was used to sample sediment from the top 5 cm below the sediment-water interface. This was done using a standard 2 × 6 in soil sample tube that was inserted semi-horizontally into the sediment and capped in situ sub-aqueously. This near-surface sediment sampling approach was chosen because we wanted to explore contemporary processes, and in general microplastics tend to be more abundant within the top 10 cm of sediment in comparison to deeper sediment [22].

2.3. Lab analysis of sediment samples

After all sediment samples were collected in their respective 100 cc tubes, they were brought to the lab for analysis. Each sample was first sieved out to eliminate any particles bigger than 5 mm (macroparticles). Two different sieve sizes were used; a

4.75 mm size was used for the estuary sediment samples and a 2.35 mm size was used for the lake sediment samples. This provided two perspectives on size to identify if a similar pattern emerged at two different scales. In between samples, both sieves were cleaned thoroughly using filtered deionized water. After all samples went through the sieve, they were placed in a dehydrator to dry. After drying, each sample in their beaker was homogenized and weighed out to 10 g. Next a density separation was performed on each sample using a Sediment-Microplastic Isolation (SMI) unit [23]. This method involves a custom-built apparatus that separates microplastics from sediment using Zinc Chloride as a flotation media. The aqueous product resulting from this density separation was then subjected to a wet peroxide reaction. This test was modeled according to the description of a wet peroxide (WPO) reaction via NOAA's Marine Debris Program [24]. By doing this procedure, any organic matter left in a sample would be dissolved in the hydrogen peroxide leaving only synthetic particles. The final sample after this procedure would be dried and weighed to measure the mass of microplastic at each site, in proportion to the dry weight of the sediment sample. All samples may have experienced minor plastics contamination in the sampling and refining process, but the methods across all samples at each site were identical, so there is high confidence that the resulting relative differences within the sites are due to real spatial environmental variations. For this study a ThermoScientific Nicolet i5 FTIR was utilized to analyze a random aliquot of the suspected plastic particles. The plastic particles were removed from the sample beaker using a dissecting needle and gently placed in the center of the FTIR diamond sampling site for analysis.

After a spectrum was collected, OMNIC software was used to perform a library match against the Hummel Polymer Library and Nicolet Sampler Library. Comparing collected spectrums to the standard library provides a percentage match, which can be used to determine the confidence of identification. An example of the matching interface is included in **Figure 2**, where a plastic collected from the Mid-Estuary location of Esopus Creek was identified as polyethylene.



	Index	Match	Compound Name	Library Name
1	32	81.51	POLY(ETHYLENE:PROPYLENE:DIENE)	Hummel Polymer Sample Library
2	7	80.06	POLY(ETHYLENE)	Hummel Polymer Sample Library
3	99	68.40	LEVORPHANOL HCL IN KBR	Georgia State Crime Lab Sample Library
4	39	62.01	POLY(ETHYLENE:PROPYLENE)	Hummel Polymer Sample Library

Figure 2. Example of FTIR spectrum matching using the Hummel polymer library, distinctive peaks suggest the sample is polyethylene.

As the FTIR process is highly time intensive and the instrument was shared across multiple institutions, five particles were analyzed for each of the 16 sampled locations. To ensure that organic material was not misidentified as a polymer, several organic libraries were included in the spectrum-matching process, including the Georgia State Crime Lab and Sigma Biological Samples libraries.

3. Results

3.1. Microplastics in freshwater estuary systems

In the Esopus Creek tributary estuary system (**Figure 3**) the lowest proportion of dry weight of microplastics, 0.0053 mg/L, was taken at the mouth of the creek. At the mid-estuary site, it spikes to the heaviest proportion of microplastics with 0.0472 mg/L. The upper estuary measurement then decreases to a median proportion of 0.0181 mg/L. In the Rondout Creek tributary estuary system (**Figure 4**), the lowest proportion of microplastics, 0.0115 mg/L, was extracted from the mouth of the creek. The mid-estuary site peaks with the heaviest proportion of microplastics with 0.1357 mg/L. The upper estuary measurement falls to a proportion of 0.0123 mg/L. In the Wappingers Creek tributary estuary system (**Figure 5**), the lowest proportion of microplastics, 0.0044 mg/L was found at the mouth of the creek. At the mid-estuary site, the heaviest proportion of microplastics is collected with 0.0309 mg/L. The upper estuary measurement again decreases to a median proportion of 0.0144 mg/L.

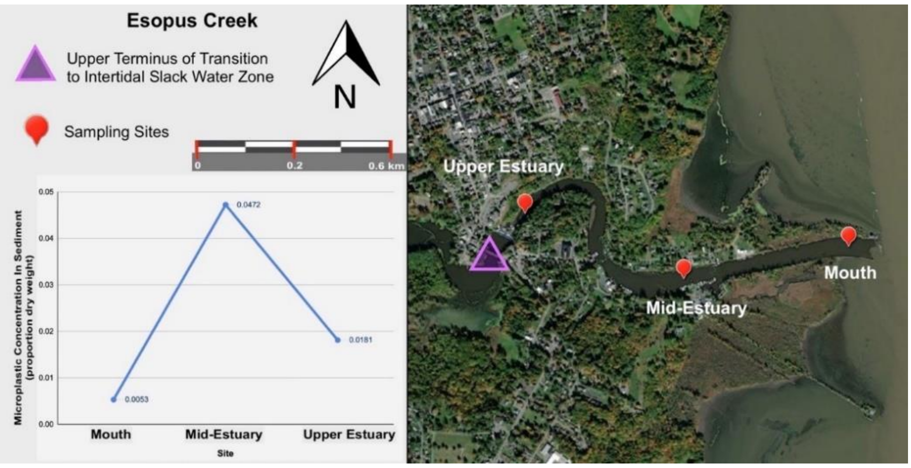


Figure 3. A map and results from the Esopus Creek tributary estuary system, showing respective sampling locations and microplastic concentration in collected sediment.

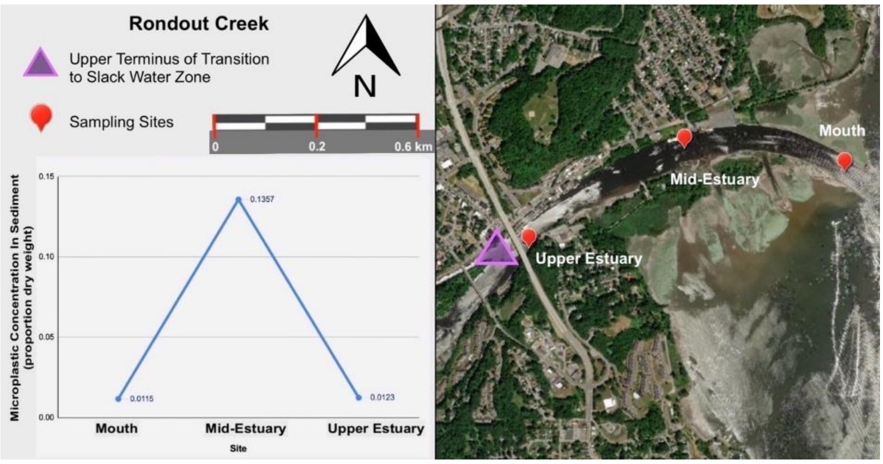


Figure 4. A map and results from the Rondout Creek tributary estuary system, showing respective sampling locations and microplastic concentration in collected sediment.

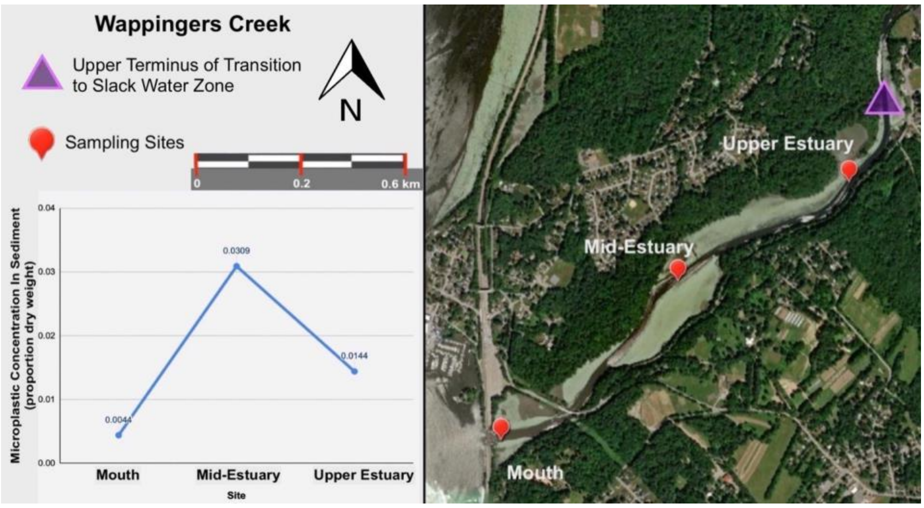


Figure 5. A map and results from the Wappingers Creek tributary estuary system, showing respective sampling locations and microplastic concentration in collected sediment.

3.2. Microplastics in a lacustrine system

The proportion of dry weight of microplastics in sites A-G from Chadwick Lake was plotted on a graph and corresponding map (**Figure 6**). The lowest microplastic concentration sample (0.00034) was from Site A, the mouth. Concentrations generally increased to their highest amounts at Site D (150 m) with a proportion of 0.00206 mg/L. After this peak of 0.00206 mg/L, Site E, F, and G decreased to average proportions ranging from 0.0005 mg/L and 0.001 mg/L. Extensive beds of invasive aquatic macrophytes were also observed and mapped, including European Water Chestnut and Eurasian Watermilfoil.

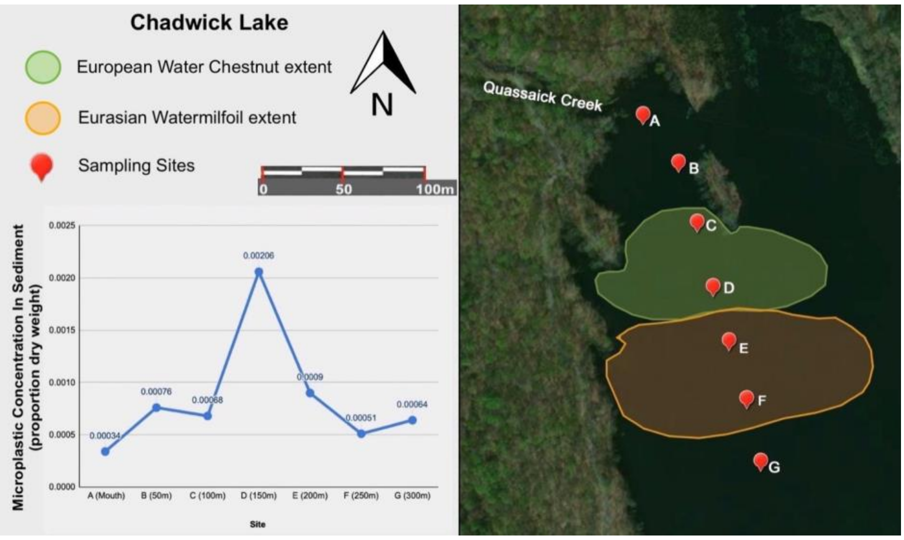


Figure 6. A map and results from Chadwick Lake, showing respective sampling locations and microplastic concentration in collected sediment, as well as the presence of invasive species European Water Chestnut and Eurasian Watermilfoil.

Photographs were taken of all nine microplastic samples collected at the mouth, midpoint, and upstream locations at each of the three creeks: Esopus, Rondout, and

Wappingers (**Figures 7–9**). The photographs represent each refined sample with moderate-density plastics underneath a microscope after being isolated from natural particles through the density separation and WPO reaction. Visually, the concentration of microplastics varies from the mouth, midpoint, and upstream locations, with a larger concentration favored at the midpoint sample.

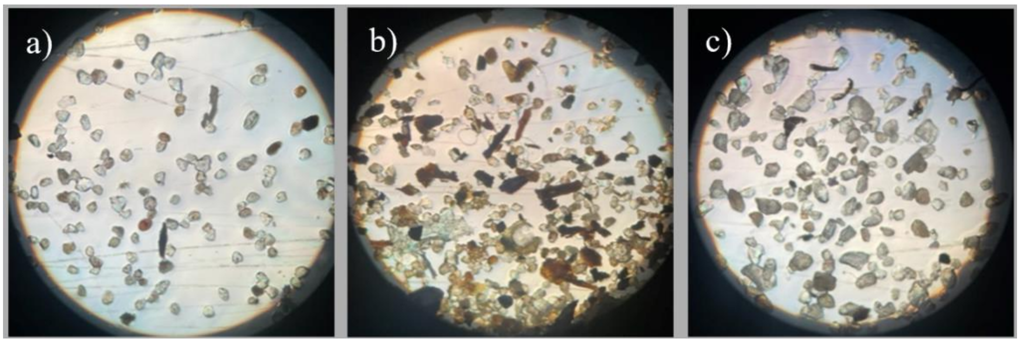


Figure 7. Microplastics from the upstream: **(a)** midpoint; **(b)** and mouth; **(c)** of Esopus Creek, as viewed under a microscope.

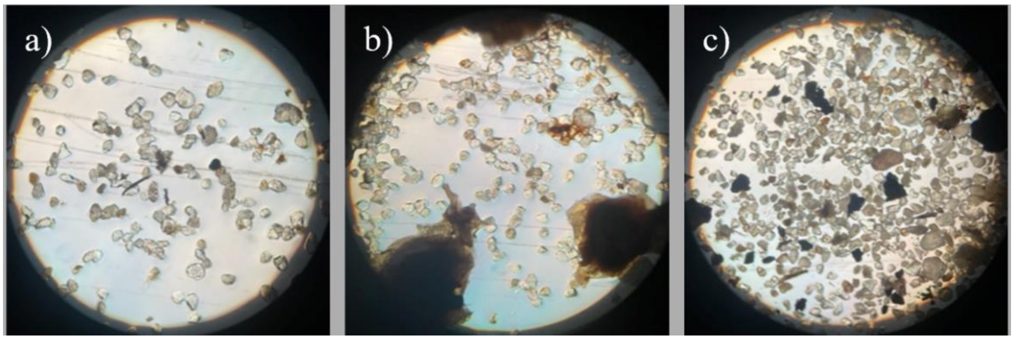


Figure 8. Microplastics from the upstream: **(a)** midpoint; **(b)** and mouth; **(c)** of Rondout Creek, as viewed under a microscope.

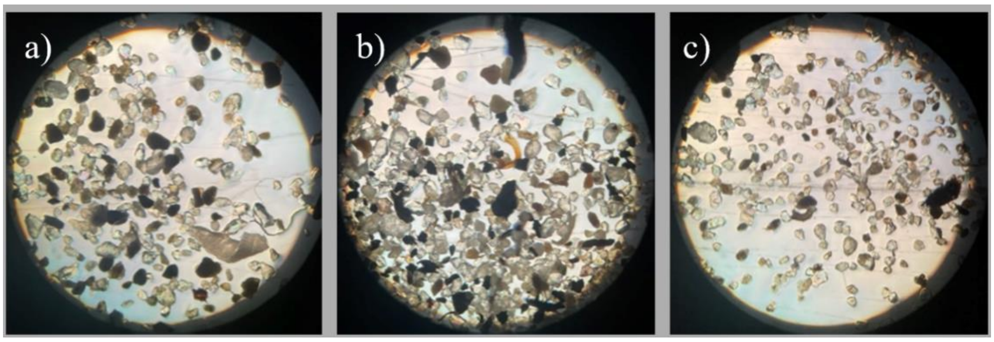


Figure 9. Microplastics from the upstream: **(a)** midpoint; **(b)** and mouth; **(c)** of Wappingers Creek, as viewed under a microscope.

3.3. Relative abundance of plastic types by location

For each of the 16 sample sites, 5 microplastic particles were identified using FTIR. These results, separated by location, are included in **Figures 10** and **11**.

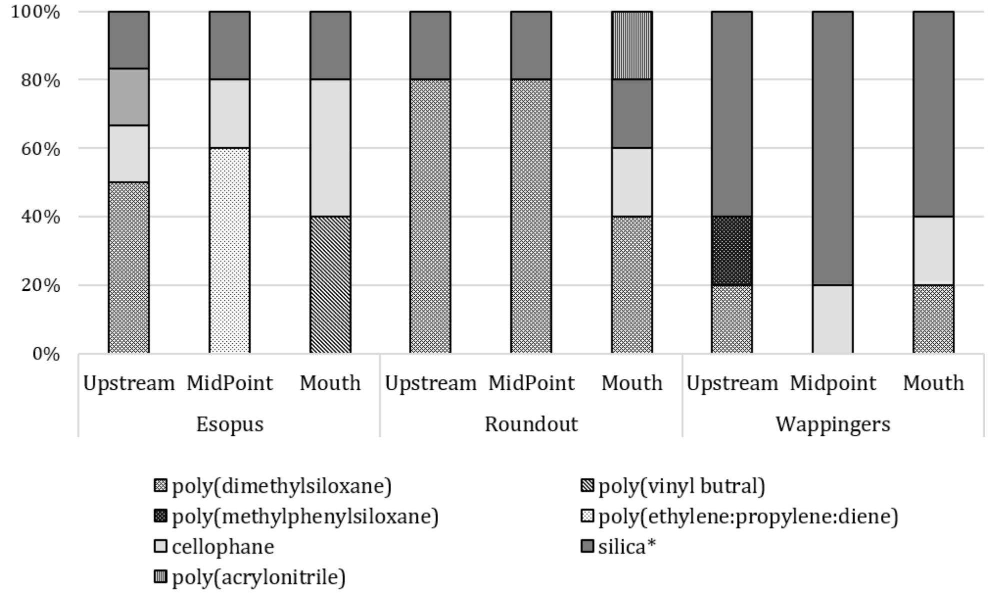


Figure 10. Relative amounts of plastics present in creek samples (*n* = 5 for each site).

Silica is present in many synthetic polymer blends which may account for their presence in the microplastic samples, see Discussion.

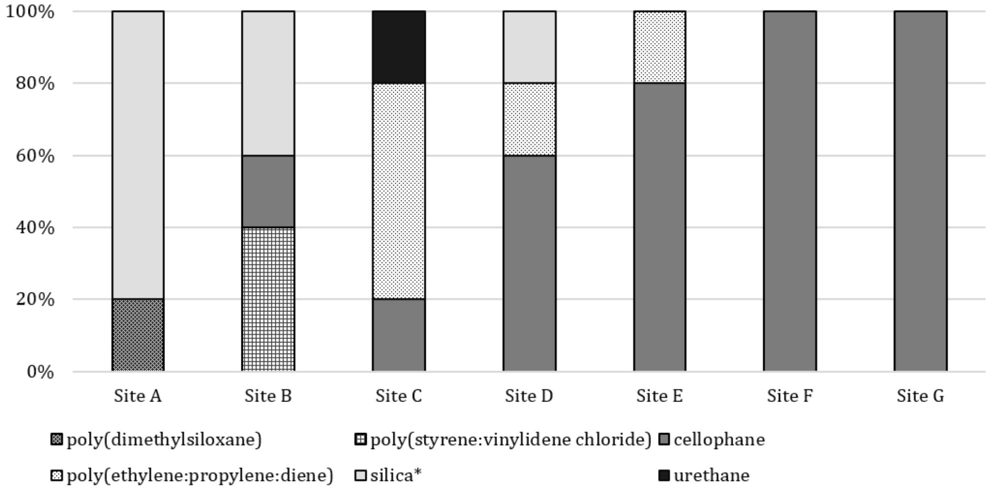


Figure 11. Relative amounts of plastics present in Chadwick Lake samples (*n* = 5 for each site). *See Discussion.

3.4. Total abundance of plastics identified

After identifying the plastics in each of the 16 locations, these results were combined to give an idea of the overall abundance of each of the types of plastics (**Figures 12** and **13**). In the nine samples from the freshwater estuary systems (Esopus, Rondout, and Wappingers Creeks), polydimethylsiloxane was the dominant plastic type identified outside of silica. As noted in the Discussion, silica and polydimethylsiloxane are associated with manufacturing processes. In the seven samples from the lacustrine system (Chadwick Lake), cellophane was the dominant plastic type identified. Cellophane is common amongst microplastics and is often used in consumer packaging.

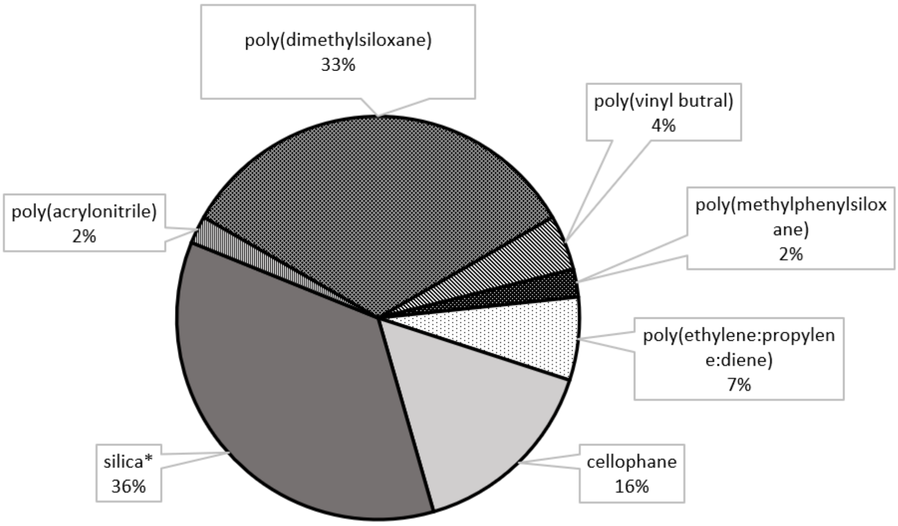


Figure 12. Relative amounts of plastics found from Esopus, Rondout, and Wappingers Creeks (*n* = 45). *See Discussion.

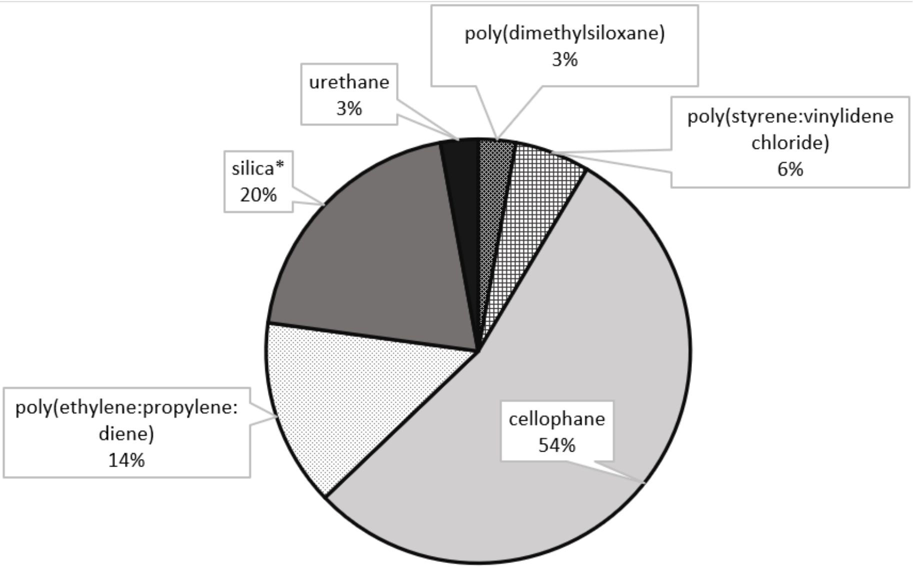


Figure 13. Relative amounts of plastics found in Chadwick Lake (*n* = 35). *See Discussion.

4. Discussion

The results of this limited field study indicate a similar geographic pattern exists within all four disparate study sites investigated, suggesting that these spatial hotspots of microplastic accumulation may be generalizable across many other polluted freshwater depositional systems. Within all of the studied estuaries (**Figures 3–5**), a distinct peak is clear in each mid-estuary site. Specifically, the sediment samples from the mouth sites of each tributary estuary system are consistently the lowest value in comparison to the mid-estuary and upper estuary samples. Similarly, the sediment samples from the upper estuary site are consistently a median value between the mouth and the mid-estuary samples (though much closer in value to the mouth site). The lacustrine depositional system, Chadwick Lake, also exhibits a similar pattern in results, but with a higher spatial resolution to the findings. Chadwick Lake (**Figure 6**) retains a similar spatial distribution with a definitive peak at the middle sample site (D, 150 m from the mouth). Overall, whether we look at higher or lower resolution spatial data, and whether it is a freshwater estuary or a lacustrine system, the proportion of microplastics in sediment by weight follows a similar single-peak spatial distribution pattern, suggesting in all currently investigated situations in these freshwater depositional environments, microplastics are uniquely concentrated in hotspots downstream of the transition from high to low energy. Microplastics are being deposited in a way that is conceptually similar, but spatially unique, to how the normal mineral sediments are being deposited in these same systems—thus creating hotspots with higher concentrations of microplastics in the sediment.

These unique spatial distribution patterns of microplastic accumulation in sediment are affected by a variety of physical and chemical factors. Based on the results of the study, all four peaks shown in **Figures 3–6** were located downstream of the transition between high gradient streamflow and low gradient lake or intertidal freshwater. These similar spatial patterns from across our unique sites suggest these microplastic accumulation hotspots may occur similarly elsewhere in relation to the transition locations from high to low energy, and the underlying control particle density exerts on sedimentation dynamics from Stokes Law. This suggests that reductions in flow velocity and energy affect microplastics (with their unique density ranges and shapes), in ways that are similar, but not identical, to the natural mineral sediments that dominate these depositional locations. The mathematical equation associated with Stokes Law can be found below in Equation (1).

$$V = \frac{2(\rho s - \rho l) \times r^2 \times g}{9\mu} \tag{1}$$

where,

V = rate of sedimentation.

ρs = density of the particle.

ρl = the density of the liquid.

r = the radius of the particle.

g = acceleration due to gravity.

μ = viscosity of the liquid.

The fundamental hydrophysical processes we believe are controlling the formation of these microplastic accumulation hotspots are outlined conceptually in **Figure 14.** Microplastic pollution within aquatic ecosystems can be either buoyant or non-buoyant depending on their polymer type. If the microplastics in question consist of polypropylene and polyethylene, they will be buoyant and have a lower density than both water and the higher density non-buoyant microplastics, with densities ranging above 1 g/cm^3 and comprised of acrylic, polyvinyl chloride, and a large variety of other chemically engineered synthetic compounds [25,26]. Unlike the density ranges of non-buoyant microplastics that start at just above 1 g/cm^3, common mineral sediment has an average density of around 2.7 g/cm^3 [27], but sometimes ranges up to 3.3 g/cm^3 for sediments dominated by mafic minerals. This difference in density ranges between the generally less-dense non-buoyant microplastic particles and the much narrower density range of generally more-dense natural mineral sediment particles can cause different transport properties and distribution patterns in accumulation (**Figure 14**). In a fluvial stream or river system, particles with lesser density, microplastics, will be carried downstream at a faster rate [25] than the denser particles comprising common mineral sediment. Since microplastics have a lower density, they will also remain suspended longer in the water, falling out of suspension farther downstream from the low-energy transition location that marks the start of any depositional aquatic environment (**Figure 14**). This difference in suspension time creates different peak locations for plastic versus mineral sediment accumulation, this then creates a system where microplastics are accumulating at a higher concentration in certain locations in these depositional environments, relative to the natural mineral sediments, forming microplastic hotspots in the sediment (**Figure 14**). Other studies have suggested and observed similar physical controls at play, a recent study from Australia [28] notes that spatial distributions in microplastic hotspots form in relation to distance-dominated flow velocities within tidal river systems. In general, others have discussed how the physical forces at play in depositional environments can affect the concentrations of microplastics, via deposition as sediment in relation to natural mineral sediment [29].

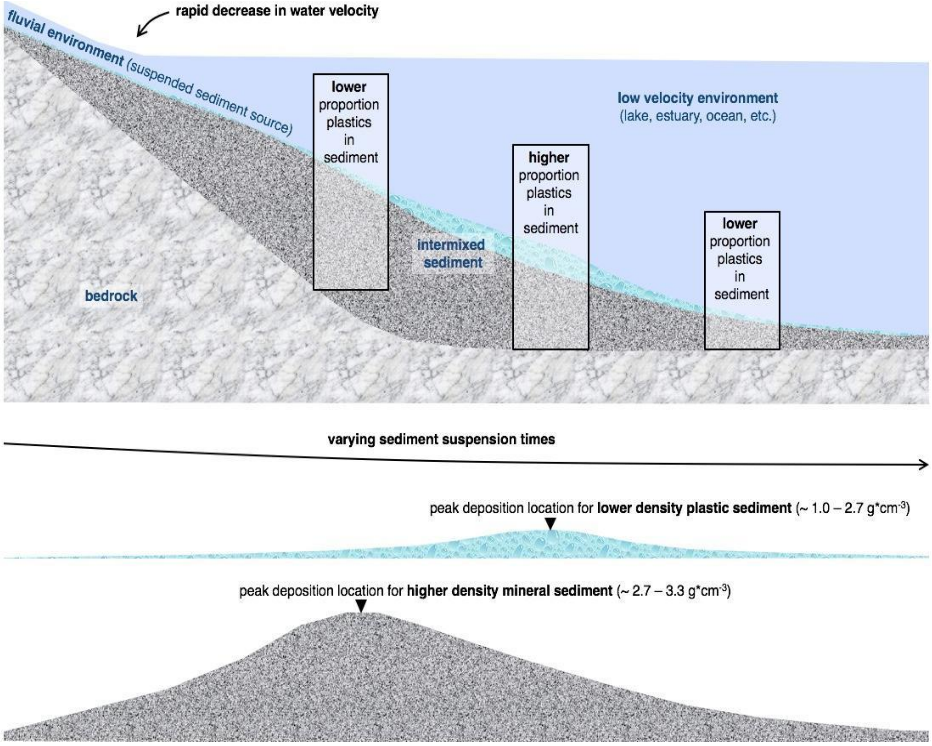


Figure 14. A physically based conceptual model using Stokes Law to compare the deposition behavior of common mineral sediment versus non-buoyant microplastics in locations where high-energy fluvial environments transition into low-energy depositional environments. The average range of densities for the two particle groups (plastic and mineral sediment) controls how long they are suspended in the water after the energy decreases due to varying fall velocities, and therefore where they are commonly deposited geographically. This difference in peak location results in spatial hotspots for the accumulation of microplastics in sediment, as observed at our four study sites.

Across all 16 sampling locations, 9 different types of plastics were observed with established confidence. The plastics found in highest abundance were cellophane, silica, and polydimethylsiloxane. Cellophane makes sense as a common microplastic, as it is often utilized in packaging and other consumer products [30]. However, silica and polydimethylsiloxane are puzzling results, as silica is a component of sand, and with a density of 2.65 g/cm^3 would not have made it through the density separation [31]. Polydimethylsiloxane is most often used as a lubricant or a putty-like material and would therefore not have the observed physical appearance of the microplastic samples collected [32]. It is possible that with continued spectral analysis samples that were matched as silica and polydimethylsiloxane will be some other kind of silicone polymer, which are commonly used in manufacturing due to their flexibility [33].

While there were not any strong patterns in the types of plastics found in each type of environment, it did appear that the same types of plastics were often found in the same location. This was especially true with the Chadwick Lake samples, where the plastics from the last two sites were all identified as cellophane. Based on the understanding of microplastics deposition, initially it was assumed that cellophane might be of a lighter density, but cellulose acetate (cellophane) has a density of 1.42 g/cm^3 which is well within the range of polymer densities, from 0.92 to 1.70 g/cm^3, with polyvinylchloride (PVC) being the heaviest and polystyrene the lightest [25]. Thus, it is unusual that cellophane would be so prevalent downstream, but perhaps all pieces of cellophane measured were fragments of a macro-plastic present in the nearby environment.

Unfortunately using spectrum matching for plastics identification does not often result in high percent matches. This may be due to chemical weathering of the plastics that occurs after prolonged exposure to UV radiation [20]. For this reason, percent matches of about 20% were accepted, with consideration given for characteristic peaks in the fingerprint region (1500–500 cm^{-1}). The fingerprint region refers to the area of the spectrum that is unique to a specific molecule, thus acting as an identifying “fingerprint”. Previous studies have noted that analyzing the spectrums “manually” by comparing these characteristic peaks may give higher confidence in plastics identification [19].

The size class of the natural sediment dominating any benthic location may also provide clues to the possible location for hotspots of microplastic accumulation. While taking sediment samples for this study, the sediment size class was roughly estimated at every sampling subsite and suggests that clay-dominated sediment size classes are more closely related to higher concentrations of microplastics. This is not surprising considering the flat shape of clay particles allows these grains to remain in suspension longer than silt and other larger size classes of spherical natural mineral sediment with similar densities [34]. However, according to a 2010 study investigating the spatial patterns of plastic debris on a shoreline, there was no correlation between clay proportion in the sampled sediment and a higher microplastic concentration overall [35]. However, their results did reveal a relationship between fine-grained sediment and microplastic chemical compositions comprised of relatively lower density plastics [35].

Although not investigated in this study, temporal changes in sediment dynamics and depositional processes can also affect the abundance of microplastics, and likely the locations of spatial hotspots. In another study comparing winter to late spring/early summer sediment accumulation at a site where there is also a notable seasonality, like ours, late spring/early summer is when a higher accumulation of microplastics occurred [36]. With late spring/early summer typically being a wet and warm season and winter being a cold and dry season in the northeastern United States, the two times of year vary in a range of hydrologic aspects. Some of these aspects include rainfall intensity, temperature, streamflow, and snow accumulation and melt [37]. According to a 2016 study done in south China, the abundances and weights of microplastics within sediment were significantly higher in the wet growing season compared to the dry winter season [38]. As the sediment samples in our study were collected in July during the wet growing season in the northeastern United States, we suggest additional sampling during drier seasons, or times with lower streamflow rates, should also be done here and elsewhere to compare the potential spatial variations this causes for the location of peak microplastic sediment accumulation.

5. Conclusion

This study has successfully identified a general trend in the spatial depositional patterns of microplastics in sediment that is consistent across four unique freshwater depositional environments. This trend can be defined as the presence of a spike, or hotspot, in the proportional dry weight of microplastics in the sediment, occurring slightly downstream from a waterbody’s transition from high to low energy. We argue that the physical differences between the density ranges of non-buoyant plastics versus natural mineral sediments cause the formation of these spatial hotspots. Both high spatial resolution (the lake in this study) and low spatial resolution (the freshwater estuaries in this study) sediment sampling has led us to the conclusion that this general spatial pattern occurs in polluted freshwater depositional environments globally. Most previous studies center on the patterns and behaviors of microplastics within the marine and coastal environments, with denser saltwater dominating the system. This finding is significant in contributing information not only to the behavior of microplastics in lower-density freshwater environments, but to the new and growing research around plastics in the geosphere. As the world grows in population and global plastic production and demand continue to increase, this form of pollution may continue to worsen. Both mitigation and remediation strategies must be implemented globally to curb this issue, and a better understanding of how and where this pollution occurs can help better focus and prioritize mitigation and remediation efforts.

Author contributions: Conceptualization, PZK; methodology, GCD, TS and PZK; software, GCD, TS and PZK; validation, GCD, TS and PZK; formal analysis, GCD and TS; investigation, GCD, TS and PZK; resources, PZK; data curation, GCD, TS and PZK; writing—original draft preparation, GCD and TS; writing—review and editing, GCD, TS and PZK; visualization, GCD and TS; supervision, PZK; project administration, PZK; funding acquisition, PZK. All authors have read and agreed to the published version of the manuscript.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

References

1. Karbalaei S, Hanachi P, Walker TR, et al. Occurrence, sources, human health impacts and mitigation of microplastic pollution. Environmental Science and Pollution Research. 2018; 25(36): 36046-36063. doi: 10.1007/s11356-018-3508-7
2. Ritchie H, Roser M. Plastic pollution. Our World in Data; 2018.
3. Rhodes CJ. Plastic Pollution and Potential Solutions. Science Progress. 2018; 101(3): 207-260. doi: 10.3184/003685018x15294876706211
4. Windsor FM, Durance I, Horton AA, et al. A catchment-scale perspective of plastic pollution. Global Change Biology. 2019; 25(4): 1207-1221. doi: 10.1111/gcb.14572
5. Barboza LGA, Dick Vethaak A, Lavorante BRBO, et al. Marine microplastic debris: An emerging issue for food security, food safety and human health. Marine Pollution Bulletin. 2018; 133: 336-348. doi: 10.1016/j.marpolbul.2018.05.047
6. Klein S, Dimzon IK, Eubeler J, Knepper TP. Analysis, occurrence, and degradation of microplastics in the aqueous environment. Freshwater Microplastics. 2018; 58: 51-67. doi: 10.1007/978-3-319-61615-5_3
7. Zhao S, Zhu L, Wang T, et al. Suspended microplastics in the surface water of the Yangtze Estuary System, China: First observations on occurrence, distribution. Marine Pollution Bulletin. 2014; 86(1-2): 562-568. doi: 10.1016/j.marpolbul.2014.06.032
8. Koutnik VS, Leonard J, Alkidim S, et al. Distribution of microplastics in soil and freshwater environments: Global analysis and framework for transport modeling. Environmental Pollution. 2021; 274: 116552. doi: 10.1016/j.envpol.2021.116552
9. Smith M, Love DC, Rochman CM, et al. Microplastics in Seafood and the Implications for Human Health. Current Environmental Health Reports. 2018; 5(3): 375-386. doi: 10.1007/s40572-018-0206-z
10. Zhou W, Han Y, Tang Y, et al. Microplastics Aggravate the Bioaccumulation of Two Waterborne Veterinary Antibiotics in an Edible Bivalve Species: Potential Mechanisms and Implications for Human Health. Environmental Science & Technology. 2020; 54(13): 8115-8122. doi: 10.1021/acs.est.0c01575
11. Pico Y, Alfarhan A, Barcelo D. Nano- and microplastic analysis: Focus on their occurrence in freshwater ecosystems and remediation technologies. TrAC Trends in Analytical Chemistry. 2019; 113: 409-425. doi: 10.1016/j.trac.2018.08.022
12. Brignac KC, Jung MR, King C, et al. Marine Debris Polymers on Main Hawaiian Island Beaches, Sea Surface, and Seafloor. Environmental Science & Technology. 2019; 53(21): 12218-12226. doi: 10.1021/acs.est.9b03561
13. Andrady AL. Microplastics in the marine environment. Marine Pollution Bulletin. 2011; 62(8): 1596-1605. doi: 10.1016/j.marpolbul.2011.05.030
14. Lorenz C, Roscher L, Meyer MS, et al. Spatial distribution of microplastics in sediments and surface waters of the southern North Sea. Environmental Pollution. 2019; 252: 1719-1729. doi: 10.1016/j.envpol.2019.06.093
15. Claessens M, Meester SD, Landuyt LV, et al. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Marine Pollution Bulletin. 2011; 62(10): 2199-2204. doi: 10.1016/j.marpolbul.2011.06.030
16. Vianello A, Boldrin A, Guerriero P, et al. Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification. Estuarine, Coastal and Shelf Science. 2013; 130: 54-61. doi: 10.1016/j.ecss.2013.03.022
17. van Emmerik T, Schwarz A. Plastic debris in rivers. WIREs Water. 2019; 7(1). doi: 10.1002/wat2.1398
18. Stokes GG. On the effect of internal friction of fluids on the motion of pendulums. Transactions of the Cambridge Philosophical Society; 1850.
19. Renner G, Sauerbier P, Schmidt TC, et al. Robust Automatic Identification of Microplastics in Environmental Samples Using FTIR Microscopy. Analytical Chemistry. 2019; 91(15): 9656-9664. doi: 10.1021/acs.analchem.9b01095
20. Chabuka BK, Kalivas JH. Application of a Hybrid Fusion Classification Process for Identification of Microplastics Based on Fourier Transform Infrared Spectroscopy. Applied Spectroscopy. 2020; 74(9): 1167-1183. doi: 10.1177/0003702820923993
21. Osman AI, Hosny M, Eltaweil AS, et al. Microplastic sources, formation, toxicity and remediation: a review. Environmental Chemistry Letters. 2023; 21(4): 2129-2169. doi: 10.1007/s10311-023-01593-3
22. Díaz-Jaramillo M, Islas MS, Gonzalez M. Spatial distribution patterns and identification of microplastics on intertidal sediments from urban and semi-natural SW Atlantic estuaries. Environmental Pollution. 2021; 273: 116398. doi: 10.1016/j.envpol.2020.116398

23. Coppock RL, Cole M, Lindeque PK, et al. A small-scale, portable method for extracting microplastics from marine sediments. Environmental Pollution. 2017; 230: 829-837. doi: 10.1016/j.envpol.2017.07.017
24. Masura J, Baker J, Foster G, and Arthur C. Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for quantifying synthetic particles in waters and sediments. NOAA; 2015.
25. Hoellein TJ, Shogren AJ, Tank JL, et al. Microplastic deposition velocity in streams follows patterns for naturally occurring allochthonous particles. Scientific Reports. 2019; 9(1). doi: 10.1038/s41598-019-40126-3
26. Kooi M, Koelmans AA. Simplifying Microplastic via Continuous Probability Distributions for Size, Shape, and Density. Environmental Science & Technology Letters. 2019; 6(9): 551-557. doi: 10.1021/acs.estlett.9b00379
27. Blake GR, Hartge KH. Particle Density. Methods of Soil Analysis. 2018; 377-382. doi: 10.2136/sssabookser5.1.2ed.c14
28. He B, Goonetilleke A, Ayoko GA, et al. Abundance, distribution patterns, and identification of microplastics in Brisbane River sediments, Australia. Science of The Total Environment. 2020; 700: 134467. doi: 10.1016/j.scitotenv.2019.134467
29. Campanale C, Stock F, Massarelli C, et al. Microplastics and their possible sources: The example of Ofanto river in southeast Italy. Environmental Pollution. 2020; 258: 113284. doi: 10.1016/j.envpol.2019.113284
30. Jessieleena A, Rathinavelu S, Velmaiel KE, et al. Residential houses—a major point source of microplastic pollution: insights on the various sources, their transport, transformation, and toxicity behaviour. Environmental Science and Pollution Research. 2023; 30(26): 67919-67940. doi: 10.1007/s11356-023-26918-1
31. Wypych G. Fillers – Origin, Chemical Composition, Properties, and Morphology. Handbook of Fillers; 2021. doi: 10.1016/b978-1-927885-79-6.50005-7
32. Polydimethylsiloxane. American Chemical Society. Available online: https://www.acs.org/molecule-of-the-week/archive/p/polydimethylsiloxane.html (accessed on 15 January 2025).
33. Tilli M, Paulasto-Kröckel M, Motooka T, et al. Handbook of Silicon Based MEMS Materials and Technologies. Elsevier Science & Technology Books: San Diego, UNITED STATES; 2010.
34. Blair RM, Waldron S, Phoenix VR, et al. Microscopy and elemental analysis characterisation of microplastics in sediment of a freshwater urban river in Scotland, UK. Environmental Science and Pollution Research. 2019; 26(12): 12491-12504. doi: 10.1007/s11356-019-04678-1
35. Browne MA, Galloway TS, Thompson RC. Spatial Patterns of Plastic Debris along Estuarine Shorelines. Environmental Science & Technology. 2010; 44(9): 3404-3409. doi: 10.1021/es903784e
36. Saarni S, Hartikainen S, Meronen S, et al. Sediment trapping – An attempt to monitor temporal variation of microplastic flux rates in aquatic systems. Environmental Pollution. 2021; 274: 116568. doi: 10.1016/j.envpol.2021.116568
37. Hayhoe K, Wake CP, Huntington TG, et al. Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics. 2006; 28(4): 381-407. doi: 10.1007/s00382-006-0187-8
38. Cheung PK, Cheung LTO, Fok L. Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. Science of The Total Environment. 2016; 562: 658-665. doi: 10.1016/j.scitotenv.2016.04.048