STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR-0003 (REV 04/2024)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA25-4052		

4. TITLE AND SUBTITLE	5. REPORT DATE
Study the impacts of Caltrans Thermoplastic Stripe, Markings and pavement Markers to microplastic pollution and develop potential solutions	September 2025
	6. PERFORMING ORGANIZATION CODE N/A
7. AUTHOR Pitiporn Asvapathanagul and Philip Gedalanga	8. PERFORMING ORGANIZATION REPORT NO. N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Civil Engineering and Construction Engineering Management California State University, Long Beach 1250 Bellflower Blvd. Long Beach, CA 90840	10. WORK UNIT NUMBER N/A
	11. CONTRACT OR GRANT NUMBER
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation (Caltrans) Division of Research, Innovation and System Information, MS-83 1727 30th Street Sacramento, CA 95816	13. TYPE OF REPORT AND PERIOD COVERED Final Report
	14. SPONSORING AGENCY CODE N/A

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Microplastic (MP) pollution has emerged as a critical environmental concern due to its pervasive presence and harmful impacts on human and environmental health. MPs, defined as plastic particles ranging from 1 nm to 5 mm, are problematic because of their ability to disperse widely across ecological habitats. Recent studies have illuminated roadways as a significant source of MPs, yet current best management practices for stormwater are not designed to address MP removal. This emphasizes the urgent need for solutions to mitigate MP pollution from transportation activities. Thermoplastic paint used in roadway markings and striping has been known as one source of MP pollution and the primary goal of this study was to quantify and characterize MP pollution from Caltrans facilities using samples of stormwater and roadway sweeping materials. The first street sweeping samples were taken on November 14, 2023, and stormwater samples were collected on February 19, 2024, and March 23, 2024, after the first local rain events. Each sample was deposited into a MPs treatment system's chamber, and then processed in a vortex separator. The results revealed that high number of MP counts were observed in the 45 to 1,000 μm size, and small particles (< 300 μm) were more mobile during storm events. Sweeping samples (11 classes) exhibited greater polymer diversity than stormwater samples (5-6 classes), and a strong correlation ($r = 0.79$, $p < 0.05$) between MPs in sweeping debris and March stormwater confirmed roadway-origin MPs were mobilized during rainfall. MP concentrations in stormwater varied from 83 to 157 MPs/L, which may be influenced by storm patterns, cleaning schedules, and sampling conditions. MPs of concern included polyolefins (polyalkenes), such as polyethylene (PE) and polypropylene (PP), as well as 'other plastics', which were present in large fractions in all environmental samples. The vortex separator achieved a 69.7% MP removal efficiency at 12 gpm, a system capacity, which was close to the MP target removal of 70%. However, the MPs removal efficiency dropped notably for particles in the 45 – 100 μm range, 14.0% ± 12.7%. A multivariable regression analysis for predicting MP removal by vortex separator identified a particle size parameter as the most significant factor influencing MP removal. Also, the settling compartment demonstrated high solids removal, not MP removal, percentage (> 99%) for particles > 100 μm. The solid removal performance of settling compartment declined at higher flow rates and for smaller particles.

17. KEY WORDS	18. DISTRIBUTION STATEMENT	
Stormwater, microplastics, microplastic pollution, thermoplastic paint		
19. SECURITY CLASSIFICATION *(of this report)* Unclassified	20. NUMBER OF PAGES 57	21. COST OF REPORT CHARGED

Reproduction of completed page authorized.

Treatment of Microplastic Particulate Pollutants from Road Wear and Thermoplastic Paint Marking

Caltrans Contract # 65A1025

Prepared for:

California Department of Transportation

May 31, 2025

Principal Investigators:

Pitiporn Asvapathanagul

Civil Engineering and Construction Engineering Management Department

California State University, Long Beach, Long Beach 90840

Phillip B Gedalanga

Department of Public Health

California State University, Fullerton, Fullerton 92834

CALTRANS DIVISION OF RESEARCH, INNOVATION AND SYSTEM INFORMATION

TRANSFORMING IDEAS INTO SOLUTIONS

DISCLAIMER

This report was prepared in cooperation with the California Department of Transportation (Caltrans). The content reflects the research and professional activities conducted by the principal investigators. The principal investigators are solely responsible for the scientific and engineering accuracy of the data and findings presented herein. The information and conclusions contained in this report are based on work supported by Caltrans and are intended to contribute to the advancement of knowledge in the relevant field.

Executive Summary

Microplastic (MP) pollution has emerged as a critical environmental concern due to its pervasive presence and harmful impacts on human and environmental health. MPs, defined as plastic particles ranging from 1 nm to 5 mm, are problematic because of their ability to disperse widely across ecological habitats. Recent studies have illuminated roadways as a significant source of MPs, yet current Best Management Practices (BMPs) for stormwater are not designed to address MP removal. This emphasizes the urgent need for solutions to mitigate MP pollution from transportation activities.

This project aimed to (i) survey MPs in environmental samples to inform the design of a MP removal system, and (ii) develop and evaluate a MP removal system tailored for freeway runoff, which integrated a vortex separator and a settling compartment along with a MP storage unit. The system was designed to meet a minimum 70% MP removal efficiency. Performance monitoring was conducted to validate the system's effectiveness under the design flow rates.

The surveys of stormwater and roadway sweeping materials revealed that high number of MP counts were observed in the 45 to 1,000 µm size, and small particles (< 300 µm) were more mobile during storm events. Sweeping samples (11 classes) exhibited greater polymer diversity than stormwater samples (5-6 classes), and a strong correlation ($r = 0.79$, $p < 0.05$) between MPs in sweeping debris and March stormwater confirmed roadway-origin MPs were mobilized during rainfall. MP concentrations in stormwater varied from 83 to 157 MPs/L, which may be influenced by storm patterns, cleaning schedules, and sampling conditions. MPs of concern included polyolefins (polyalkenes), such as polyethylene (PE) and polypropylene (PP), as well as 'other plastics', which were present in large fractions in all environmental samples.

The vortex separator achieved a 69.7% MP removal efficiency at 12 gpm, a system capacity, which was close to the MP target removal of 70%. However, the MPs removal efficiency dropped notably for particles in the 45 – 100 µm range, 14.0% ± 12.7%. A multivariable regression analysis for predicting MP removal by vortex separator identified a particle size parameter as the most significant factor influencing MP removal. Also, the settling compartment demonstrated high solids removal, not MP removal, percentage (> 99%) for particles > 100 µm. The solid removal performance of settling compartment declined at higher flow rates and for smaller particles.

Although some testing was incomplete by the project's conclusion, the available findings support the effectiveness of vortex separation and settling for MP control. The results also emphasize the importance of frequent roadway cleaning and accounting for the initial stormwater runoff generated by a storm, which is associated with greater proportions of pollutants, in system design. The developed system offers a promising foundation for evidence-based BMPs to mitigate MP pollution from roadways.

Table of Contents

ACRONYMS

Acronym	Definition
BMP	Best Management Practice
SWRCB	California State Water Resources Control Board
Caltrans	California Department of Transportation
ºC	Degree Celsius
cfs	Cufic Feet Per Second
CSULB	California State University, Long Beach
ft^2	Square Feet
ft/s	Feet Per Second
g/cm^3	Gram Per Cubic Centimeter
gpm	Gallons Per Minute
HRT	Hydraulic Retention Time
in	Inch
kg	Kilogram
mg/L	Milligram Per Liter
mins	Minutes
MPs	Microplastics
nm	Nanometer
OR	Overflow rate
PAM	Polyacrylamides
PE	Polyethylene
PP	Polypropylene
ppm	Parts Per Million
Project	Treatment of Microplastic Particulate Pollutants from Road Wear and Thermoplastic Paint Marking
PU	Polyurethane
PVC	Polyvinyl Chlorine
RWQCB	Regional Water Quality Control Board
µm	Micrometer

1 INTRODUCTION

1.1 Project Background and Need

Microplastics (MPs), due to their fine dimensions and low density, are easily dispersed and have now been documented across ecosystems. A significant portion of these pollutants originates from roadways, with tire wear, also classified as MP due to composited plastic-rubber composition, accounting for approximately 28% and thermoplastic road markings contributing around 7% of the MPs found in ocean waters (Boucher & Friot, 2017). While many MPs entering sewer systems are effectively removed through conventional water reclamation processes (Lares et al., 2018, Michielssen et al., 2016, Murphy et al., 2016, Talvitie et al., 2015), stormwater runoff, known as non-point source pollution, remains an unaddressed pathway. Existing Best Management Practices (BMPs) for stormwater treatment are not primarily designed for MP removal. As a result, MPs do not only bypass the treatment but can also interfere with current systems by clogging bioswales and overload retention ponds, which reduces their efficiency and potentially contributing to localized flooding on roadways and in parking areas. This underlines the urgent need to investigate the MP diversity and quantity coupled with their temporal and spatial dynamics, and to develop BMPs specifically tailored to capture MPs from roadway runoff, thereby mitigating their harmful impacts to the environment.

The goal of this work is to establish effective control of MPs originating from freeways by developing an MP removal system. This system integrates a vortex separator and a settling compartment, which are both physical settling-based treatment techniques, along with a storage component for MPs holding prior to disposal. The project also initially aims to establish evidence-based BMPs grounded in the performance of this proposed system, particularly for application on public roadways owned by Caltrans, that can achieve at least 70% MP removal efficiency. This target is validated through performance monitoring of the vortex separator, the settling/removal unit, and their combined operation in series, ensuring substantial reduction of MPs at the system's design flow rate.

1.2 Project Description

The project began with a survey of microplastics (MPs) originating from roadway and freeway sources. Stormwater runoff and roadway sweeping materials were sampled and analyzed to assess MP abundance and polymer diversity. MPs present in sweeping debris can be mobilized during storm events and transported into adjacent water bodies. The concentration and variation of MPs in runoff samples are influenced by both storm intensity and the existing accumulation of MPs on freeway surfaces. Lack of roadway cleaning before a precipitation event can lead to the buildup of larger MP amounts, which can be transported during subsequent storms. As part of this study, two stormwater runoff samples were collected in February and March 2024, along with one sweeping sample in November 2023. This data provides valuable insights into the types and quantities of MPs in roadway samples, which are critical for informing the design of an MP removal system.

The MP removal system was designed based on physical treatment strategies, known as "unit operations," grounded in fundamental fluid mechanics and dynamics principles to separate particulate pollutants from water. The MP removal unit integrated well-established design principles from environmental engineering, particularly those used in water and wastewater treatment. The system design incorporated flow rates commonly used in bioswale design: (i) flow under Water Quality Flow (WQF) conditions and (ii) flow during the design storm event (Caltrans, 2012).

Vortex Separator

Vortex separators utilize centrifugal force generated by tangential liquid flow to separate solids from the liquid matrix. A vortex is formed as water enters the chamber tangentially at the top, creating rotational motion. When centrifugal and gravitational forces act differently on particles and water, promoting momentum differences between solids and water, particles with a density significantly greater than 1.0 g/cm^3 settle to the bottom. Consequently, clarified water upward exits through the center where a low-pressure zone is created. This project includes the design, construction, and validation of 12-gallon-per-minute (gpm) and 24-gpm vortex separators. The flow rate of 12 gpm and 24 gpm are equivalent to runoff flows generated from 0.25-acre and 0.50-acre paved areas, respectively, at 25-year storm for bioswale design. A hydraulic retention time of 30 seconds for grit removal was applied in the design (Metcalf & Eddy, 2014).

MP Removal Compartment (Settling Unit)

The MP removal unit is a modified clarifier equipped with plate settlers to enhance particulate settling while minimizing the system footprint and head loss. This project represents the first known study to evaluate MP removal using a modified sedimentation unit with plate settlers. The 12-gpm and 24-gpm settling compartments were designed, constructed, and aligned with the capacities of the corresponding vortex separators.

MP Storage Unit

The MP storage unit is shared between the vortex separator and the MP removal compartment to collect settled MPs. It features both manual and electrically operated valves. Moisture in the MP matrix is allowed to evaporate through a grated cover, producing dried MPs that can be easily transported and disposed of. The storage unit includes:

(i) removal of MP residues using portable industrial vacuum equipment during maintenance, or

(ii) a removable container for storing dried MPs, which can be emptied during maintenance or disposal.

The storage capacity is designed for 1–2 years of MP accumulation, or a frequency consistent with current bioswale and retention pond maintenance schedules. However, it is recommended that MPs be transferred from the vortex separator and settling compartments at least twice per year. This transfer system can be operated manually or controlled electronically via a timer.

All treatment units are being tested using sweeping materials provided by Caltrans. The quality and quantity of MPs before and after treatment were documented, along with the influence of independent variables in the experimental setup. Since the theoretical design is based on solids removal, particles with similar physical properties to MPs such as grit, sand, and other debris also captured. Additionally, the system was constructed using plastic-free materials such as wood, stainless steel, and concrete to ensure that the MP removal unit does not become a source of microplastic pollution itself. The MP removal unit is illustrated in Figure 1.

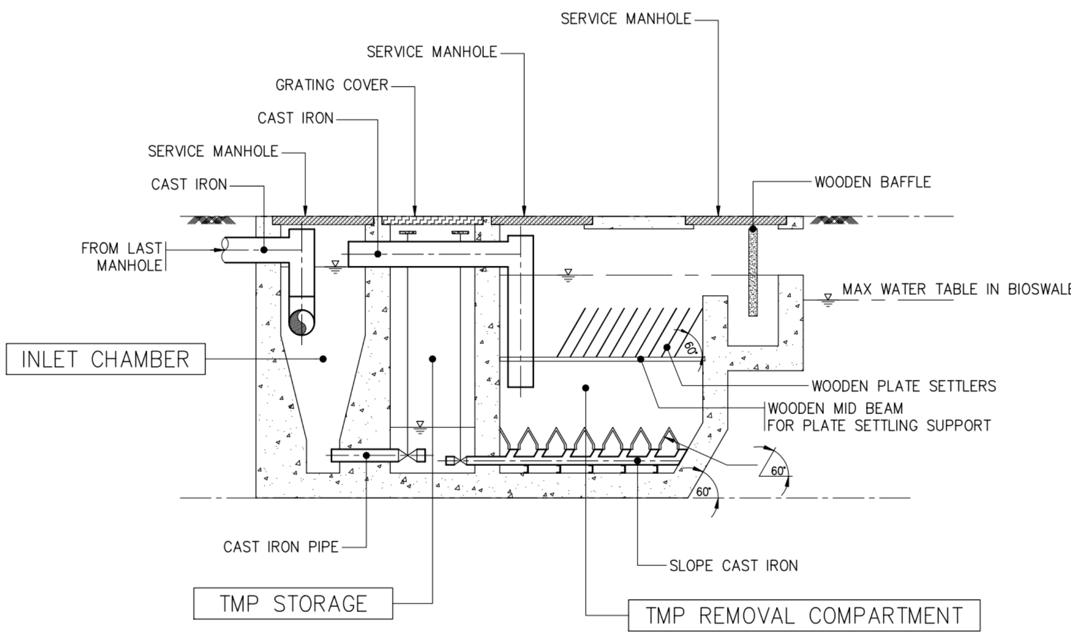


Figure 1. Conceptual approaches for MP particles removal from runoff and stormwater.

Disclaimer: This work is currently incomplete as outlined in the contract. The following summarizes the progress made to date:

- The survey of microplastics (MPs) in stormwater and roadway sweeping materials has been completed.
- The design, construction, and testing of the 12-gallon-per-minute (gpm) vortex separator have been completed.

- The 24-gpm vortex separator has been designed, but construction and testing have not yet been initiated.
- The 12-gpm settling compartment has been designed and constructed. The testing is ongoing but was halted due to the project ended.
- The 24-gpm settling compartment has been designed, but construction and testing have not been conducted.
- The following components have not yet been started: the storage unit, full system testing, and the development of Best Management Practices (BMPs).

2 MICROPLASTICS IN STORMWATER RUNOFF

Stormwater runoff has been implicated as a source of microplastics pollution in contaminated water resources (Österlund et al., 2023, Werbowski et al., 2021). As such, treatment systems are being developed to prevent the widespread contamination of microplastics into the broader environment. The two primary goals of the work included (i) a determination of microplastics pollution in stormwater runoff collected from a major freeway to estimate the microplastics load for the optimal design of our microplastics treatment unit and (ii) the characterization of microplastics pollution in stormwater runoff collected from a local freeway. These goals would be achieved by collecting stormwater runoff during storm events in Southern California. Since storm frequency is highly variable, we collected stormwater from any precipitation event that was possible given limitations in scheduling and safety considerations.

2.1 Materials and Methods: Microplastics in Stormwater

2.1.1 Field Sampling Location

The field sampling location was selected due to the proximity to a major freeway serving the Southern California population, proximity to a rain gauge to estimate precipitation at the field sampling location, ease of access to the site, and safety considerations for personnel during actual sample collection. The site was located just north of the Wardlow Road crossing bridge 53-1850 on the shoulder of the southbound side of the 605 Freeway in the City of Long Beach (605 LA RO 79; GPS 33.81802°N and 118.08176°W) and a rain gauge operated by the Los Angeles County Department of Public Works is located at the intersection of Spring Street & San Gabriel River in the City of Long Beach (Figure 2).

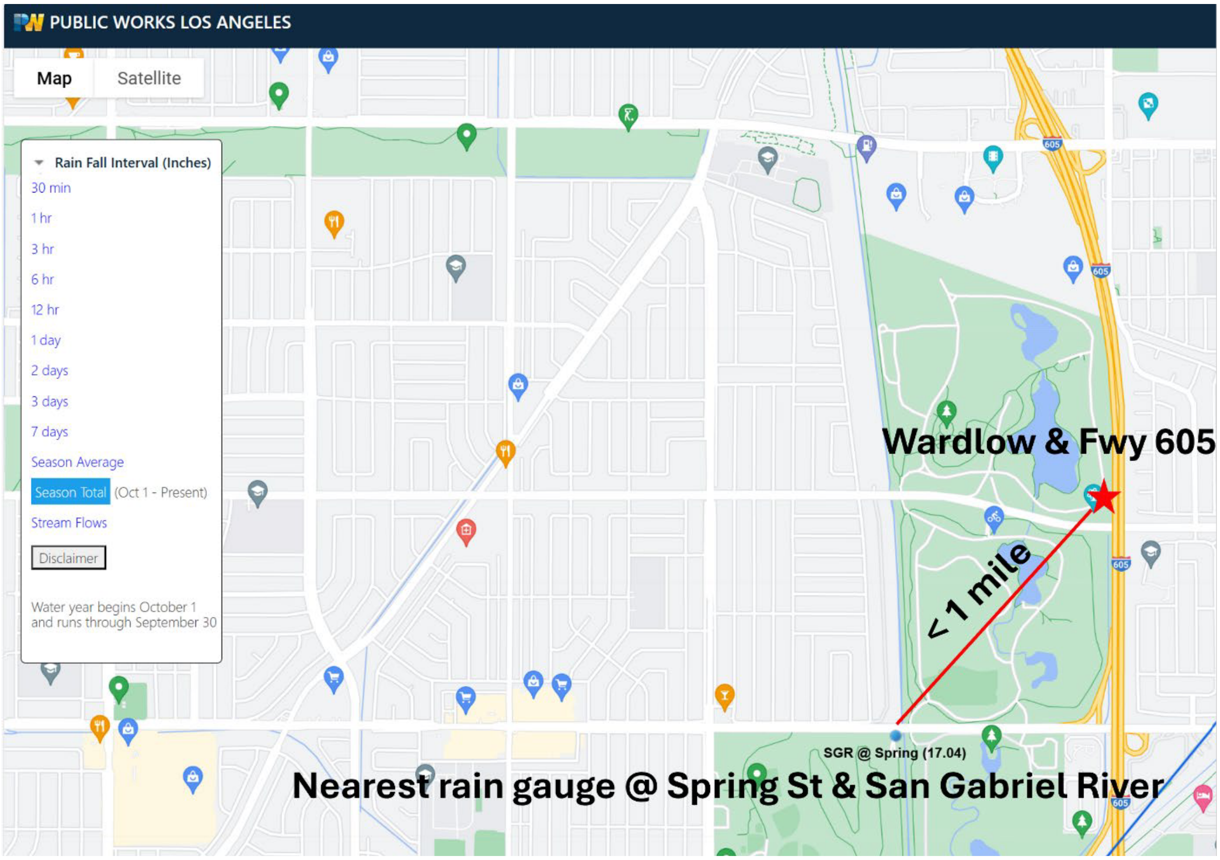


Figure 2. Stormwater runoff and rain gauge sampling locations. Stormwater runoff samples were collected on the southbound side of the 605 freeway just north of the Wardlow Road crossing bridge 53-1850.

2.1.2 Stormwater Sample and Microplastic Particle Collection

Stormwater runoff was collected at the sampling location during precipitation events on February 19, 2024, and March 23, 2024 (Figure 3). Microplastics were collected directly from stormwater through sieves to produce the following size fractions of particulate matter in stormwater runoff: 45µm – 99µm, 100µm – 299µm, 300µm – 999µm, and 1000µm – 4749µm. A total of 101.5 – 203.0 L of runoff was collected by partially filling up 10-gallon stainless steel containers with stormwater and transferring the solution to a 4L glass container marked at 3.5L to measure the volume of stormwater collected. The 3.5L volume was thoroughly mixed and the entire contents were transferred to the stacked sieves to size fractionate particles during the sample collection event. This process was repeated a total of 29 and 58 times to obtain 101.5L and 203.0L for the February and March sampling event, respectively. Size fractionated solids in brass sieves were transported to the laboratory and dried in a fume hood at 32°C for 48 hrs. Sieves were then processed in a sieve shaker for 5 minutes (RO-TAP RX-30, Mentor, OH) and stored at room temperature until ready for further characterization.

Figure 3. Sampling procedure during February 2024 and March 2024 runoff sampling events.

2.1.3 FTIR for Microplastic Characterization

Fourier transform infrared spectroscopy (FTIR) was used to determine the polymer composition of microplastics collected in stormwater runoff. A total mass of 1 mg for each sample is mounted on a stainless steel mesh filter and characterized for their quantities and polymer types using a Nicolet iN10 MX Infrared Imaging Microscope (Thermo Scientific, Waltham, MA) and processing FTIR data using Open Specy (Cowger et al., 2021).

2.2 Results

Stormwater runoff samples were collected during precipitation events on February 19, 2024 and March 23, 2024. Samples were collected in the morning towards the beginning of the precipitation event in an attempt to avoid complete washout of particles from the initial drainage of the roadway surfaces. Table 1 below describes the sampling conditions for each stormwater runoff collection event. The total dried solids concentration is reported at 30.2 mg/L and 14.1 mg/L for February and March sampling events, respectively. The variation of solids content can be caused by highway sweeping schedule or rainfall intensity before or during the sample collection.

Table 1: Sample details, solids content and precipitation data of each sampling event

Event	February Sampling	March Sampling
Date	2/19/2024	3/23/2024
Time	10:30AM-11:15AM	9:45AM-10:50AM
Duration (mins)	45	65
Intensity (inch/hr)	0.036	0.055
Precipitation start time	8:47AM	8:30AM
Collected volume (L)	101.5L	203.0 L
Dried mass of collected debris (mg)	3,062.2	2,857.3
Solids concentration (mg/L)	30.2	14.1

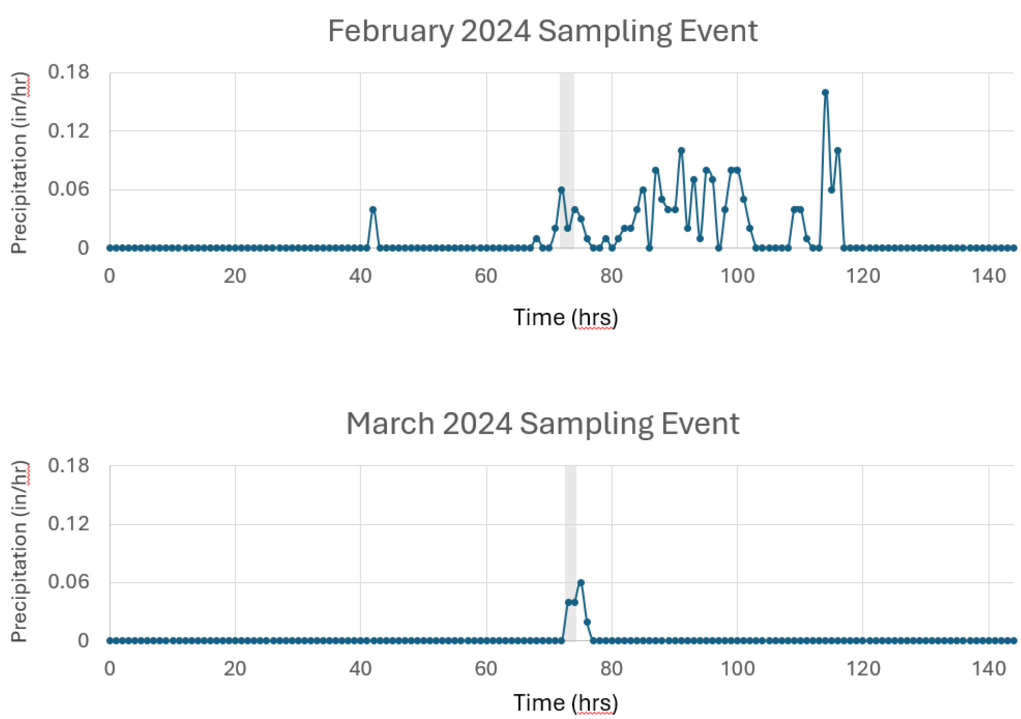


Figure 4. Precipitation data before and after stormwater collection.

Precipitation was monitored during each stormwater runoff sample collection event and is presented in Figure 4. The gray region represents the time during which samples were collected. The February 2024 sample was collected during a period of relatively moderate rain intensity (0.06 in/hr) with precipitation rates trending downward. The March 2024 sample was collected during relatively moderate rain intensity (0.05 in/hr) with precipitation rates trending upward towards 0.06 in/hr. These slight differences in precipitation characteristics during sample collection may result in variation in solids characterization from each stormwater runoff sample.

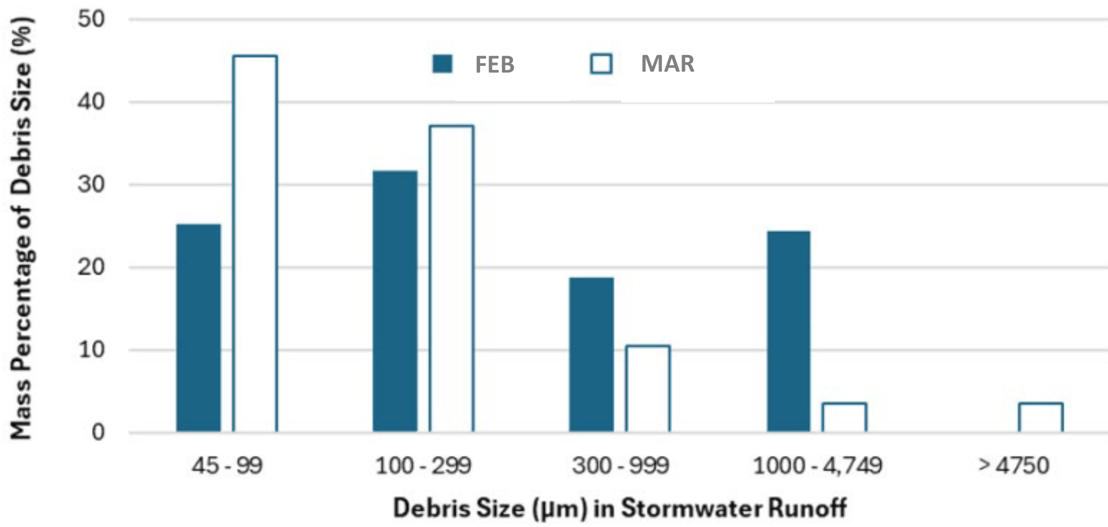


Figure 5. Size distribution of stormwater solids (debris) by mass (%).

The solid size distribution by mass in stormwater samples (%) demonstrated a larger fraction of smaller particles were present in stormwater runoff collected in February and March of 2024. This difference is likely attributed to the challenges of transporting larger particles in the flow rates experienced in these storms (Figure 5.) Overall trends between the 2 sampling events were similar with the exception of only the March samples with particles > 4750 μm. Since the February sampling occurred after the storm started and there was a small storm ~48 hours prior, large solids had sufficient time to reach the sampling location. However, the peak of the fine particle (44 – 99 μm) concentration was passed at the beginning of storm, so the 45 – 99 μm particle concentration was not observed at its maximum. On another hand, there was no storm before March sampling event, and the March sampling occurred right after the storm began. Therefore, fine particles, that were easily mobilized by storm compared to larger debris, were recorded at a larger amount compared to larger particles. For the purposes of this work, solids between 45 – 4749 μm will be the focus for further analysis.

FTIR analysis determined the abundance of microplastic particles obtained from stormwater runoff samples collected in February and March 2024 per 0.0010 gram (1 mg) of stormwater debris without pretreatment due to small mass collected. The distribution of microplastics in each size fraction is presented in Figure 6. Stormwater runoff from the February sampling event contained a larger fraction of microplastics in the 100 - 299 μm range whereas the 45-99 μm size fraction contained the largest fraction of microplastics in the March sampling event. The differences can be attributed to storm characteristics. During the March sampling event, the overall precipitation intensity was slightly higher resulting in a precipitation rate of 0.055 in/hr compared to 0.036 in/hr for the March and February storms, respectively. This higher precipitation intensity can flush surface materials more thoroughly and it is likely that our sampling time missed the bulk transport of solid particles resulting from dry deposition prior to the arrival of the storm. Indeed, the total amount of solids collected from February and March was 3,062.2 mg and 2,857.3 mg, respectively, indicating fewer solids per volume of stormwater collected in the March samples (Table 1).

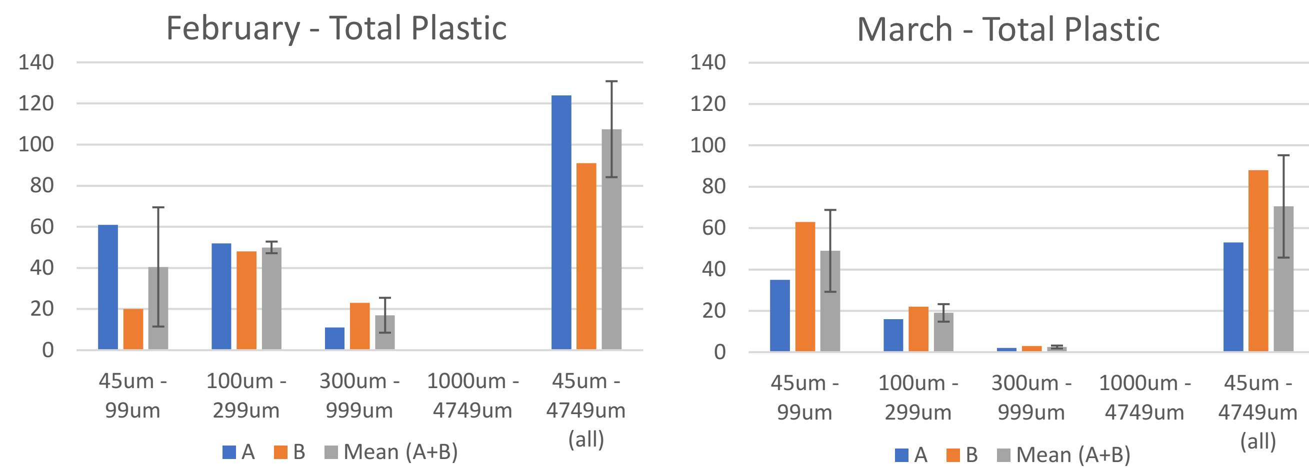


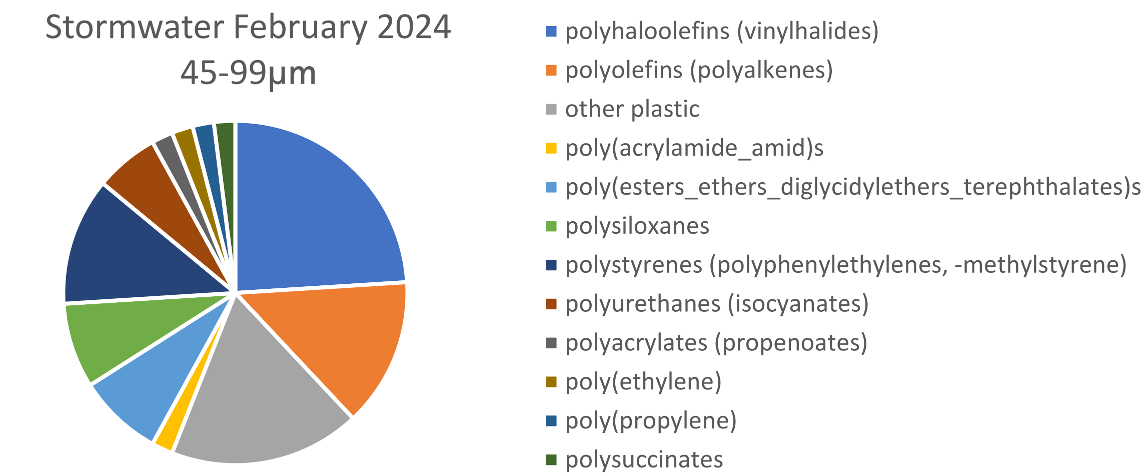
Figure 6. Total abundance of microplastic particles for each size fraction per 1 mg of solids (particles/mg) collected from February and March 2024 stormwater runoff. A and B representing replications and the error bars represent the standard deviation.

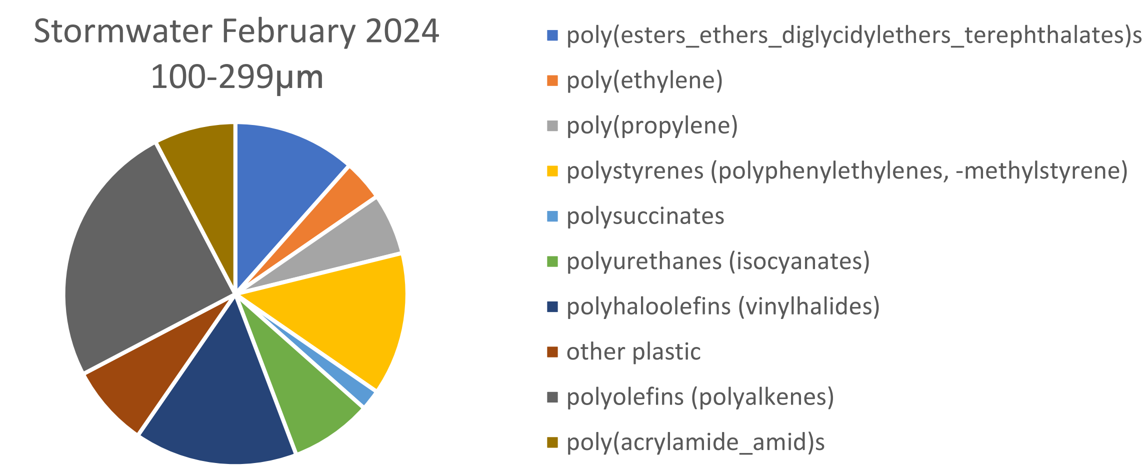
Polymers were widely distributed within each size fraction in the 1 mg February 2024 samples. Smaller size fractions of microplastics were observed to have the greatest polymer diversity. Polyhaloolefins and polyolefins were the most abundant types of plastic polymers quantified in microplastics within the 45 – 99 µm size fraction (Figure 7). Polytetrafluoroethylene (PTFE) is a type of polyhaloolefin and PTFE is commonly found in automotive applications in the forms of seals, gaskets, fuel system components, coatings, wire insulation, and various hoses (Drobny 2007). Polyesters and polyethylene were among the most abundant polymers found in the 100 – 299 µm size fraction.

Similar to the February 2024 stormwater runoff sample, microplastics in 1 mg March 2024 stormwater runoff also followed the trend of increased microplastic particle abundance with smaller size fractions (Figure 8). The 45 – 99 µm size fraction contained greater than double the concentration of microplastics compared to the 100 – 299 µm size fraction. This finding is attributed to the ease with which smaller size particles are transported by stormwater runoff. Polyolefins were also determined to be the most prevalent polymer found in all size fractions for the March 2024 stormwater runoff sample. This was consistent with the findings from the February 2024 sampling event. Interestingly, poly(ester/ether/diglycidylethers/terepthalates) were among the most abundant types of polymers quantified in the 100 – 299 µm size fraction from March 2024 stormwater runoff samples. This category of plastic polymers is considered to be more complex as it is comprised of multiple plastic polymers. The 300 – 999 size fraction contained the fewest number of microplastic particles and also had the least amount of polymer diversity. Polyhaloolefins, polyolefins, and other plastics were identified in the 300 – 999 size fraction collected from March 2024 stormwater runoff. Overall, stormwater from both February and March 2024 contained a significant concentration of microplastics with a wide range of polymer types.

The distribution of microplastic particles and polymer types was variable across both the February and March 2024 sampling events. After the size fraction by mass in Figure 5 was incorporated, total MP particles found in FWY stormwater runoff were 83 & 157 MPs/L for the February and March 2024 stormwater event, respectively. Our reported MPs in stormwater were higher than the MPs/L reported in other peer-reviewed literatures on stormwater runoff, 1.1 to 35 MPs/L, due to different particle size ranges included among studies (Kabir et al., Lui et al., 2019, Monira et al., 2022, 2023, Werbowski et al., 2021, Yano et al., 2021). Järlskog et al. (2020) reported only 5 particles/$L_{stormwater}$ of ≥ 100 µm tire and bitumen wear MPs (TBMPs), which was lowered compared to our study due to only two MP types (tire and bitumen) included and different techniques employed for polymer identification. The same study found up 5,900 particles/$L_{stormwater}$ of ≥ 20 µm TBMPs, which was higher than our 83 & 157 MPs/L reported when the smallest size in this project is 45 µm. This finding suggests that there are many MPs at a smaller sizer range that can contribute to adverse environmental impacts. > 5900 MPs/L is expected using FTIR to identify all plastic types.

A total of 6 categories of MPs were identified in both stormwater runoff samples combined (Figure 9). FTIR analysis revealed polyurethanes, polyesters, polyterepthalates, polystyrenes, polyolefins, and 'other plastic' polymers were identified in stormwater runoff samples (Figure 9). Unfortunately, this does not provide much information on the specific types of MPs found in stormwater since this category of plastics is assigned when µFTIR spectra are not aligned strongly with the signature plastic spectra in the database. Each of these categories of plastic polymers have been extensively used in the construction of interior and exterior components in an automobile including the engine bay in air ducts and battery casings (Vieyra et al., 2022). Studies of MPs in stormwater runoff from Denmark (Lui et al., 2019), San Francisco (Werbowski et al., 2021), and Japan (Kabir et al., 2023) shared the same findings as polyolefins (polyalkenes), commercially known as polyethylene (PE) and polypropylene (PP), was observed at the most abundance MPs in stormwater runoff samples. Additionally, polyolefins (polyalkenes) have occasionally been used in tire lining to help maintain air pressure and some estimates place polyolefins as being used in approximately 50% of the plastics found in automobiles (Sadiku et al., 2017). The total abundance of microplastics was nearly two times greater in stormwater runoff from March compared to February. This could be attributed to variation in street sweeping schedules and storm frequencies. Indeed, February 2024 had multiple storm events compared to March 2024 which may have removed debris and microplastic particles from road surfaces.





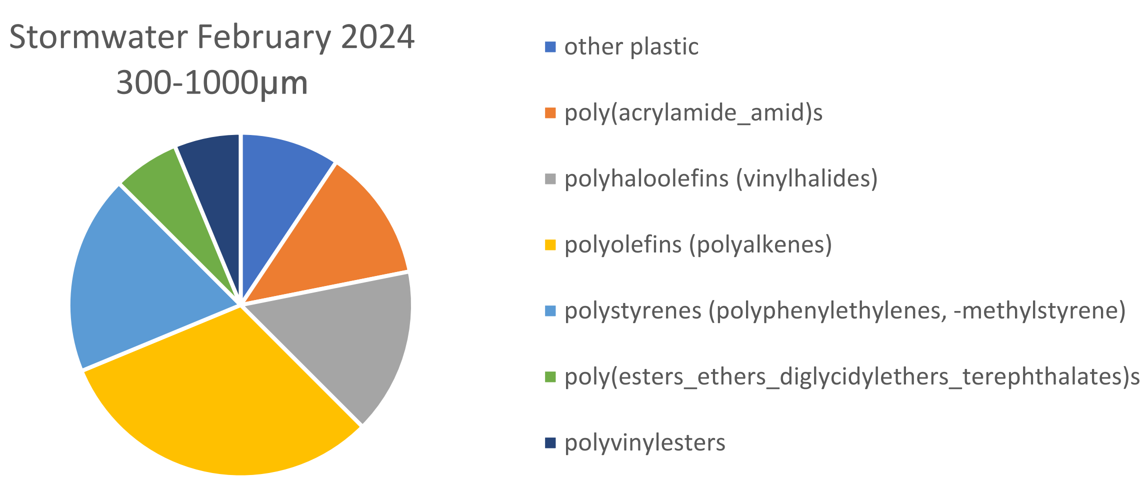


Figure 7. Distribution of microplastic polymers in each size fraction in 1 mg stormwater runoff collected in February 2024

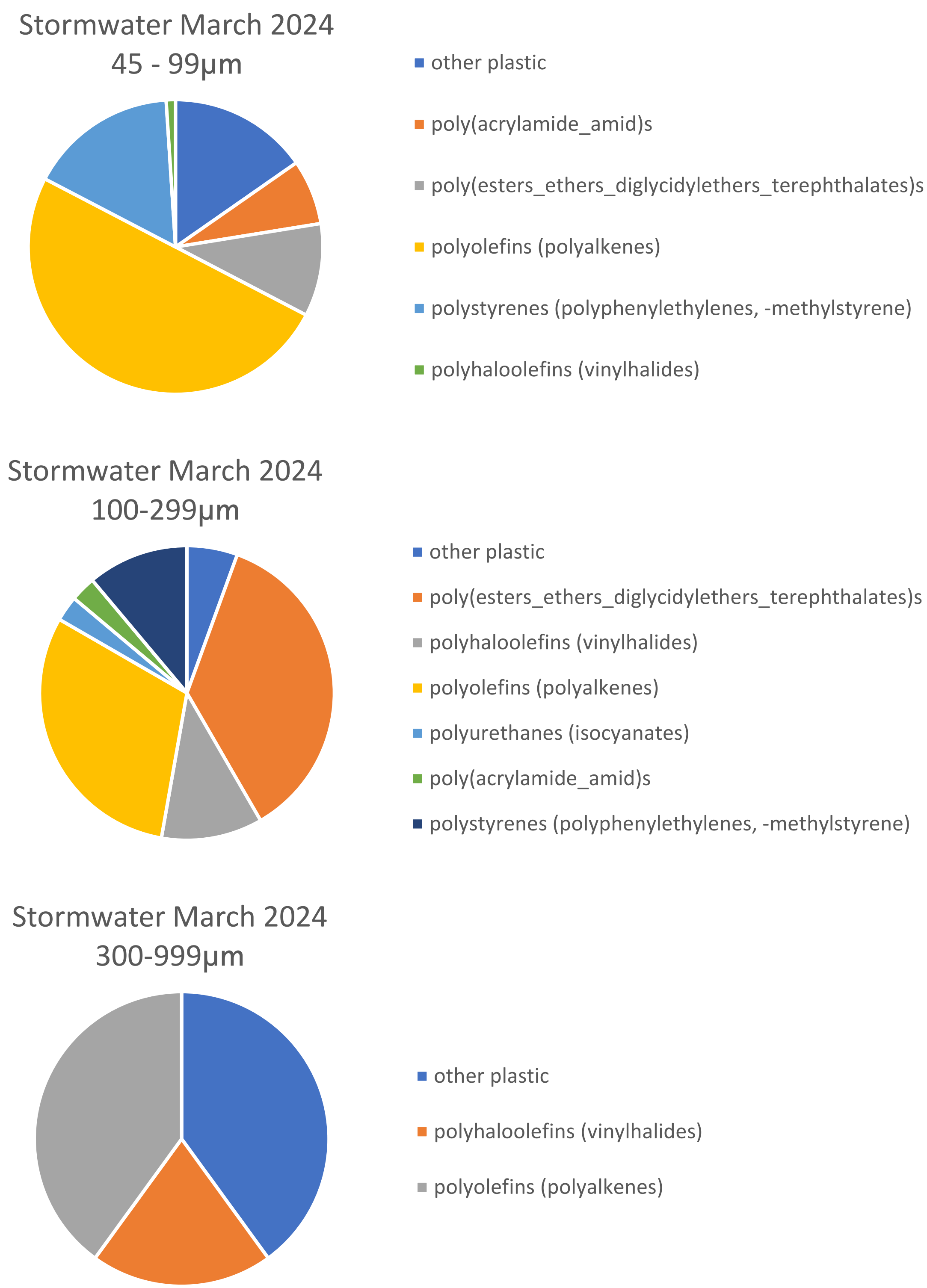


Figure 8. Distribution of microplastic polymers in each size fraction in 1 mg stormwater runoff collected in March 2024

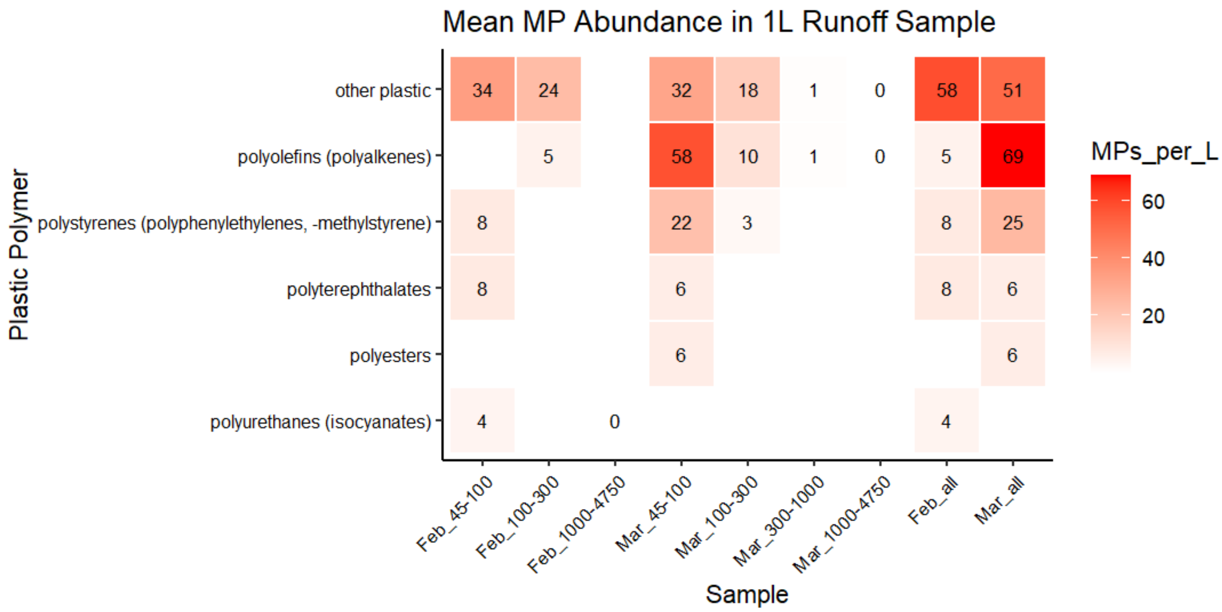


Figure 9. Microplastic polymer types and abundances in stormwater runoff from February and March 2024 when size distribution by mass incorporated.

2.3 Conclusion and Recommendations

1. Six common types of microplastics were observed in stormwater runoff samples, including 'other plastic', polyolefins (polyalkenes) or known as polyethylene and polypropylene, polystyrenes, polyterephthalates, polyesters, and polyurethanes. This diversity reflects the wide range of plastic materials used in transportation infrastructure, vehicle components, and roadside litter.

2. Despite the February storm event exhibiting a higher total solids concentration (30.2 mg/L) than the March event (14.1 mg/L), the microplastic abundance was paradoxically lower in February. This discrepancy is attributed to particle size distribution. The February sample contained a higher proportion of large particles, which contribute more to mass but less to particle count. Furthermore, the March sample had finer particles, which, although lighter, resulted in a higher number of microplastic particles per unit mass, including MPs. This suggests that early-stage stormwater runoff generated at the beginning or within the first 2 hours of the first storm event, which is often referred to as the "first flush." This is likely to carry a higher number of MP particles due to their small size and ease of mobilization, which is more difficult to

mitigate compared to larger particles. This finding suggests prioritizing treatment during the initial stages of storm events, when microplastic concentrations are likely to peak.

3. The substantial microplastic load in freeway runoff is claimed to pose a significant burden on existing stormwater treatment systems, which are typically not designed to effectively capture particles in the micro-size range. This can lead to untreated MPs entering aquatic ecosystems, and failure of existing stormwater runoff facilities, contributing to long-term environmental contamination. Upgrade or retrofit existing stormwater treatment facilities with filtration systems capable of capturing microplastics, particularly those in the fine particle range can mitigate the MP pollution. The MP abundance reported in this project at 83 and 157 MPs/L can be varied seasonally and spatially. After heavy storm events and no freeway cleaning prior, a greater number of MPs can be observed in stormwater runoff, especially in the region with more precipitation than Southern California.
4. A notable portion of the microplastics appears to originate from existing roadway sweeping materials, indicating that road wear (e.g., tire and brake dust), degraded road markings, and roadside litter are key contributors. Hence, proper management of roadway debris can minimize the impacts of MPs from the transportation sector to the environment such as (i) increase the frequency and effectiveness of street sweeping, especially before forecasted storm events, and (ii) promote the use of low-wear materials in road construction and vehicle components.

The results prove the need for MP contaminants control from roadways with suggestions to conduct longitudinal studies to assess seasonal and spatial trends in microplastic runoff, develop regulatory guidelines for microplastic discharge limits in urban runoff, and encourage collaboration between transportation agencies, environmental scientists, and policymakers to address this emerging pollutant.

3 MICROPLASTIC ABUNDANCE & CHARACTERISTICS OF SWEEPING MATERIALS

Roadway sweeping debris represents a potential microplastic (MP) non-point source pollution, particularly through mobilization by stormwater runoff into the surface water and oceans. The goal of this work is to survey microplastics in order to discover their existence and identity in sweeping debris. This section presents the abundance and polymer composition of microplastics identified in a grab sample of sweeping materials. The methodology and sample preparation procedures are also detailed.

Sweeping debris samples were collected from the interstate freeway 405 section in the City of Long Beach and were provided by the Long Beach Maintenance Facility, California Department of Transportation (Caltrans) located at 22101 South Santa Fe Avenue, Long Beach, CA 90810 on November 14, 2023. Sweeping materials were transferred using metal shovels, stored in four 10-gallon (37-liter) microplastic-free galvanized metal containers with metal lids (Behrens, MN), and transported to the laboratory located within the California State University, Long Beach (CSULB). The total amount of sweeping debris gathered was 138.2 kg in four metal containers.

3.1 Sweeping Debris Size Distribution

Sweeping materials were subjected to sieve analysis (RC-TAP: H-4320, HUMBOLDT) for 5 mins to obtain MP size distribution in accordance with ASTM C136-06 (ASTM, 2006; Figure 10) in the geotechnical engineering laboratory, CSULB. Sweeping debris were segregated into 6 size ranges, including (i) < 45 µm (pan), (ii) 45 µm – 100 µm, (iii) 100 µm – 300 µm, (iv) 300 µm – 1,000 µm, (v) 1,000 µm – 4,750 µm, and (vi) larger than 4,750 µm. The target particle size range for this work was 45 – 4,750 µm. Microplastics (MPs) are typically defined as particulate pollutants with a size smaller than 5 mm, but larger than 1 nm. In drinking water, the state of California has adopted a resolution to define microplastics as three dimensional, solid polymeric materials, that are between 1 nm and 5 mm in size (SWRCB, 2020). On the other hand, Gigault et al. (2018) defined a definition of nanoplastics with a size ranging from 1 nm to 1 µm. Therefore, the target MPs included in this work covers a board size range of MPs. Our originally accepted proposal included the use of laboratory-generated MPs and known Caltrans plastic materials to evaluate our systems. As a result, all test materials consisted solely of MPs, without the presence of non-target particles. These MPs could be quantified using fluorescence or bright-field microscopy through manual counting. A minimum particle size of 45 µm was selected for this project due to the limitations of manual counting techniques in our laboratory.

Figure 10. Sieve analysis of sweeping materials

The mass distribution percentage of sweeping materials for all six size ranges is represented in this report (Figure 11a). The mass percentage of combined sweeping materials from four containers with a size of < 45 µm, 45 – 100 µm, 100 – 300 µm, 300 –1,000 µm, 1,000 – 4,750 µm and larger than 4,750 µm were 0.49%, 9.26%, 31.32%, 30.03%, 21.77% and 7.12%, respectively. The data was normalized using total debris collected. A large amount, 92.39% by mass, of total sweeping debris was in the target microplastic (MP) size range (smaller than 5mm and larger or equal to 45 µm).

After, the particles with a size smaller than 45 µm and larger than 4,750 µm were excluded, the mass distribution for 45 – 4,750 µm particles is illustrated in Figure 11b. The data was renormalized by the total mass of particles with a size equal or larger than 45 µm but smaller than 4,750 µm. The mass distribution was measured at 10.02%, 33.90%, 32.51% and 23.57% for 45 – 100 µm, 100 – 300 µm, 300 – 1,000 µm and 1,000 – 4,750 µm ranges, respectively. **From both analyses, large amounts by mass of particles having MP size ranges were observed in 100 – 300 µm, 300 – 1,000 µm and 1,000 – 4,750 µm.**

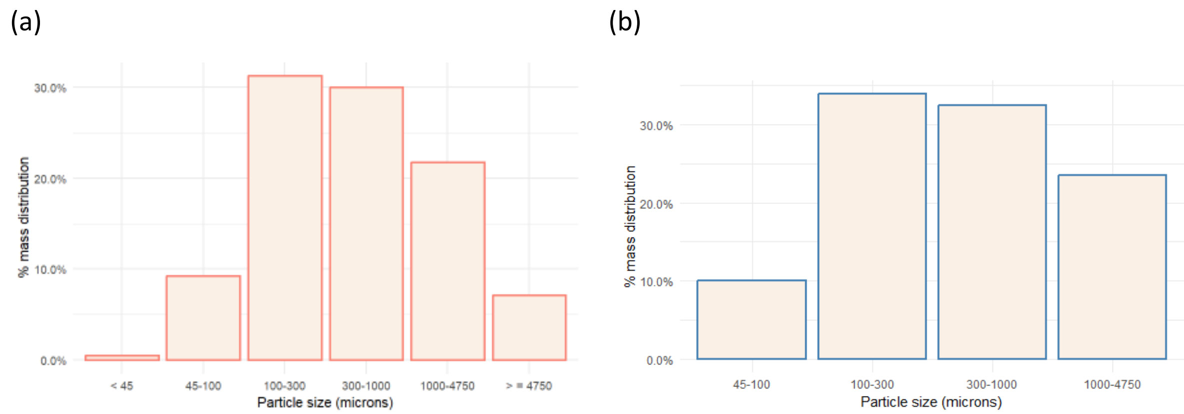


Figure 11. Sweeping debris size distribution percentage by mass (a) for all sizes and (b) for 45 µm to 4,750 µm

3.2 Sweeping Debris Sample Processing/Preparation

Sweeping materials were further subjected to sample preparation using (i) density separation for all target sizes, and (ii) chemical digestion for particles with a size smaller than 500 µm, which were 45 – 100 µm and 100 – 300 µm, to yield the highest digestion efficiency (SCCWRP 2020). Density separation helps separate non-microplastic particles having specific gravity (S.G) greater than 1.4 such as minerals, rock and metals using microplastic-free calcium chloride ($CaCl_2$) solution with S.G. of 1.4. Chemical digestion oxidizes organic particles, non-microplastics, using iron solution and hydrogen peroxide (H_2O_2). The density separation and chemical digestion procedure followed SCCWRP (2020).

The maximum mass recovery, %, after density separation using a calcium chloride ($CaCl_2$) solution with a specific gravity (S.G) of 1.4 was observed in the 45 – 100 µm sample with a mean ± standard deviation (s.d.) of 43.1% ± 10.8%, while other size samples exhibited comparable recovery percentages of 20.0% ± 5.5%, 23.3% ± 21.8%, and 17.3% ± 7.5% for 100 – 300 µm, 300 – 1,000 µm and 1,000 – 4,750 µm, respectively (Figure 12). **This data indicates that density separation is recommended as a sample treatment step to remove more than 50% of non-MP particles from the samples in general (Figure 12). Specifically, particles with a size of 100 µm or larger contained large number of inorganic constituents, but the smaller particles with a size of 45 – 100 µm had approximately 50% of particles with S.G. >**

1.4. However, a large variation of particle removal via density separation was observed, which suggests inconsistent debris distribution in each sub-sample.

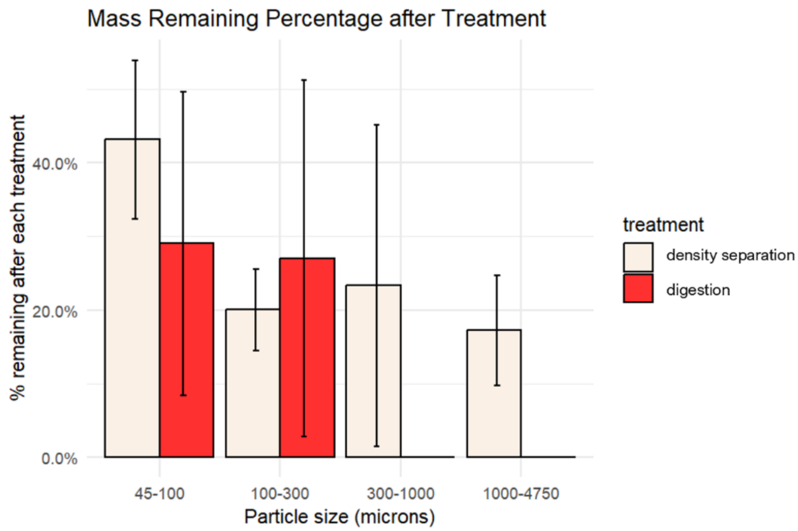


Figure 12 Solids recovery after density separation and chemical digestion

Note: chemical digestion performed only 45 – 100 µm and 100 – 300 µm. Standard deviation derived from each container subsample.

The rinsed and dried particles collected after density separation with a specific gravity (S.G.) less than or equal to 1.4, were treated with a high concentration of hydrogen peroxide in the presence of an iron solution at a temperature between 35°C and 40°C. This chemical digestion process was repeated five times (SCCWRP 2020). The recovery percentages for the 45 – 100 µm and 100 – 300 µm samples were 29.0% ± 20.6% and 27.0% ± 24.2%, respectively (Figure 12). **These results suggest that a significant portion of the sweeping materials consisted of organic particles, specifically 70% organic contents, which were digested during the chemical treatment, leaving behind potential microplastic (MP) candidates for polymer confirmation in subsequent analyses.** Similar to the findings after density separation, the large variation in remaining debris after digestion was observed, which indicates inconsistency in the organic contents among samples. The 300 – 1,000 µm and 1,000 – 4,750 µm fractions were not subjected to chemical digestion due to their larger sizes, which reduce digestion efficiency (SCCWRP 2020).

The analyzed data on the percentage of debris remaining after pre-treatment for all replicates revealed that, for the 45 – 100 µm and 100 – 300 µm samples, over 80% of non-microplastic materials were removed following both treatment steps, with some variation observed (Figure 13). Similarly, for the 300 – 1,000 µm and 1,000 – 4,750 µm samples, the average percentage of total debris remaining after density separation alone was below 20% compared to the raw samples, except for the 300 – 1,000 µm sample from Set 2 (Container 2), which showed over 50% recovered debris, and the 1,000 – 4,750 µm sample from Set 4 (Container 4), which had just under 30% remaining materials. **These findings support the use of density separation and chemical digestion as essential pre-treatment steps for MP quantification and polymer identification in sweeping debris to eliminate non-target microplastics for downstream**

processing. The data also highlights the importance of careful homogenization due to the inconsistent distribution of inorganic matter, organic debris, and microplastics in complex sweeping material samples.

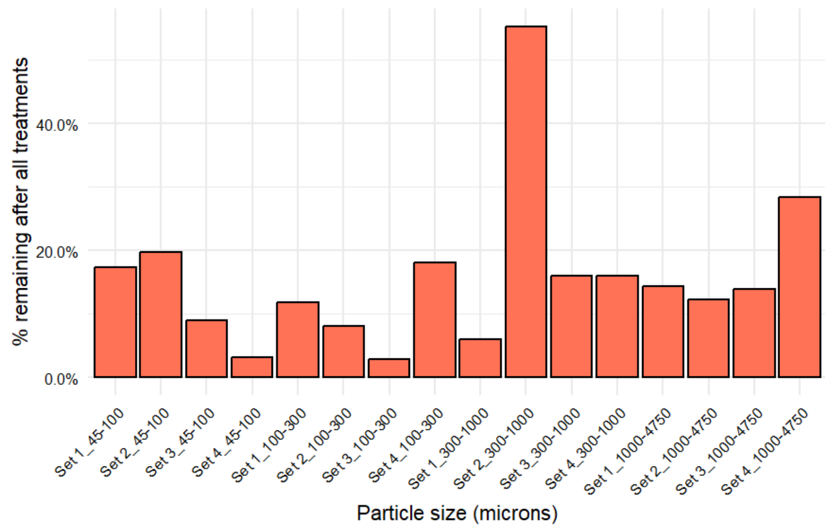


Figure 13. Solids remaining after density separation and chemical digestion for 45 – 100 µm and 100 – 300 µm samples, and solely density separation for 300 – 1,000 µm and 1,000 – 4,750 µm samples.

Note: Set representing subsampling from each sampling container 1 – 4.

3.3 MP Quantification and Polymer Confirmation for Prepped Sweeping Materials

One milligram (0.0010 g) of dried, prepared samples—following density separation and/or chemical digestion—was stained using 2 mL of 10 µg/mL Nile Red dye in methanol and incubated at 30°C for 30 minutes. Duplicate samples were prepared. The stained samples were then visualized using a fluorescence microscope (Nikon), and polymer confirmation was performed using Fourier Transform Infrared Spectroscopy (FTIR) with an iN10 instrument (Thermo Fisher Scientific) at the Moore Institute for Plastic Pollution Research, Long Beach, CA, following the manufacturer's guidelines. Particles with an FTIR spectral fingerprint showing 67% or greater similarity to a known FTIR plastic spectral were confirmed as belonging to that polymer group. Figure 14 displays sample collection, preparation and analysis of sweeping samples.

A total of 11 different types of plastic polymers were detected in street sweeping materials collected from Fwy 405, Long Beach, CA. These included polyolefins (polyalkenes), 'other plastic', polyhaloolefins (vinyl halides), poly(esters/ethers/ diglycidyl ethers/terephthalates), polystyrenes (polyphenylethylenes, methylstyrene), poly(acrylamide/amid)s, polyacrylamides, polyesters, polysiloxanes, polyterephthalates, and polyurethane isocyanates, which are listed in order from the highest to lowest counts per milligram (mg) of treated samples, excluding 1,000 – 4,750 µm (Figure 15). More abundance of microplastic (MP) particles and a greater diversity of plastic types were found in the smaller-sized sweeping material samples as seen in all sets of 45 – 100 µm samples when the same 1 mg mass samples compared, except 1,000 – 4,750 µm sample (Figure 15). In contrast, only 'other plastic' and polyurethane isocyanates were detected in a single replicate of the 1,000 – 4,750 µm size range (Figure 15). Non-integer count values resulted from averaging duplicate analyses.

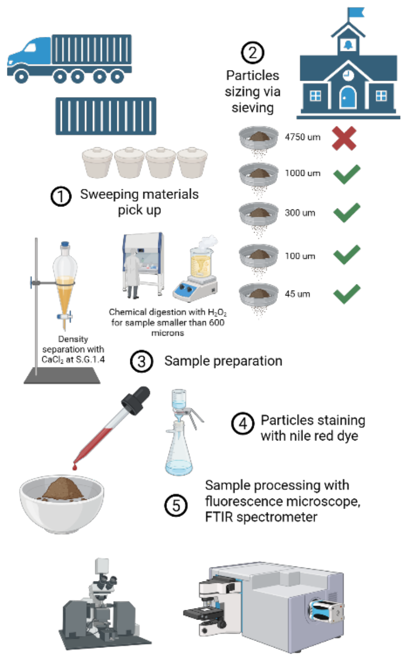


Figure 14. sample collection, preparation and analysis of sweeping samples

When plastic type data from FTIR analysis were combined with size distribution by mass results, four major polymer types—polyolefins (polyalkenes) (43.1%), 'other plastic' (17.2%), polyhaloolefins (vinyl halides) (15.9%), and poly(esters/ethers/diglycidyl ethers/terephthalates) (15.4%), which are collectively accounted for over 90% of all microplastic (MP) counts in the street sweeping samples (Figure 16a). Polyolefins (polyalkenes), which include widely used plastics such as polyethylene (PE) and polypropylene (PP), were the most abundant, representing 43.1% of all MPs per kg of street sweeping debris. These plastics are commonly found in packaging, automotive components, construction materials, textiles, medical devices, and recyclable beverage containers. Notably, both PP and PE have densities lower than water, which contributes to their environmental mobility. PP has a density ranging from 0.85 to 0.92 g/cm^3, making it the lowest-density common plastic, while PE ranges from 0.89 to 0.93 g/cm^3 (Frias et al., 2018). Their buoyant nature facilitates dispersion through air and water, which increases the likelihood of widespread environmental distribution as seen in Figure 9.

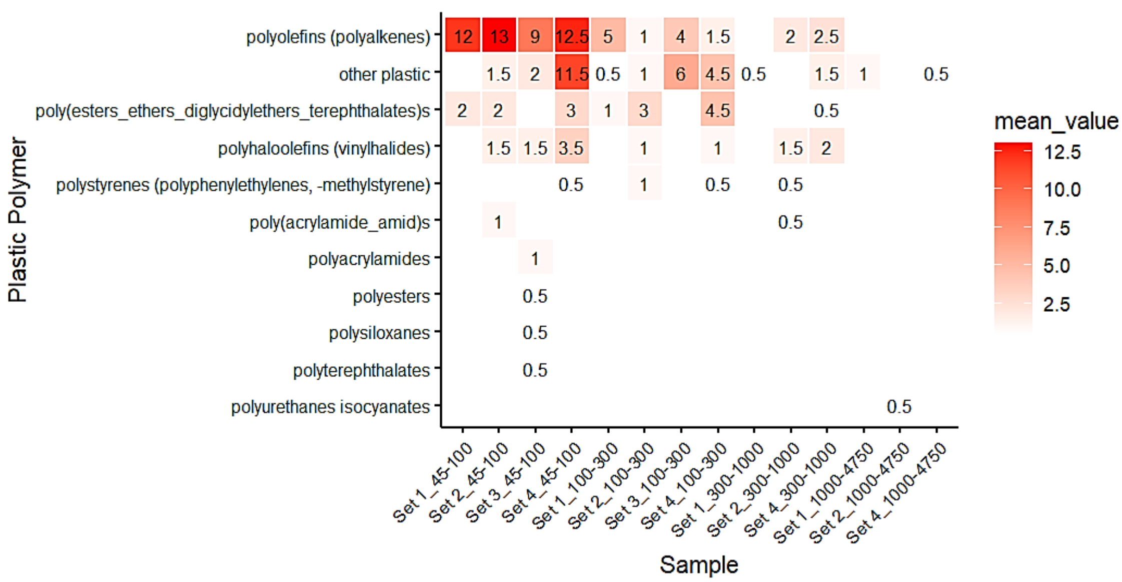


Figure 15. Mean MP abundance for each size and set for 1 mg processed sample, except 1,000-4,750 µm, after outliner data excluded (below)

The second most abundant category, labeled as 'other plastic,' made up 17.2% of the total MP count. This classification is used when FTIR analysis cannot conclusively identify a specific polymer type—typically when the spectral match falls below the 67% threshold required for confident identification. Polyhaloolefins (vinyl halides), commercially known as polyvinyl chloride (PVC) having the highest density of 1.38 – 1.41 g/cm^3 (Frias et al., 2018), were the third most abundant group at 15.9%. PVC is widely used in products such as floor tiles, wall linings, food packaging, pipes, hoses, and footwear. This was followed closely by poly(esters/ethers/diglycidyl ethers/terephthalates) having 1.38 g/cm^3 density, which accounted for 15.4% of MP counts. These polymers are commonly found in coatings, adhesives, sealants, elastomers, paints, textiles, automotive parts, and beverage containers. Other plastic types were detected at significantly lower levels than the dominant four and were primarily found in the 45 – 100 µm samples. Poly(acrylamide/amid)s were detected only in the 300 – 1,000 µm size range, while polyurethane isocyanates were found exclusively in the 1,000 – 4,750 µm samples. The results also report the absolute abundance of each MP group in the sweeping materials, totaling **~ 800,000** MP particles found in 1 kg sweeping debris. Iordachescu et al. (2024) conducted a study on MPs in spider webs and road dust, and reported a maximum of 4000 – 5000 MP counts per gram, 4 – 5 million MPs per kg, in a parking lot. This abundance is 5 folds higher than the counts per kg sweeping debris reported in this project due to smaller particle sizes of 10 µm or larger included. **Due to mass fraction of each particle size, 45 – 1,000 µm samples contained diverse polymer groups with large MP abundance. Given the presence of large MP in sweeping materials, effective MP management strategies must be implemented to prevent their release into the environment.**

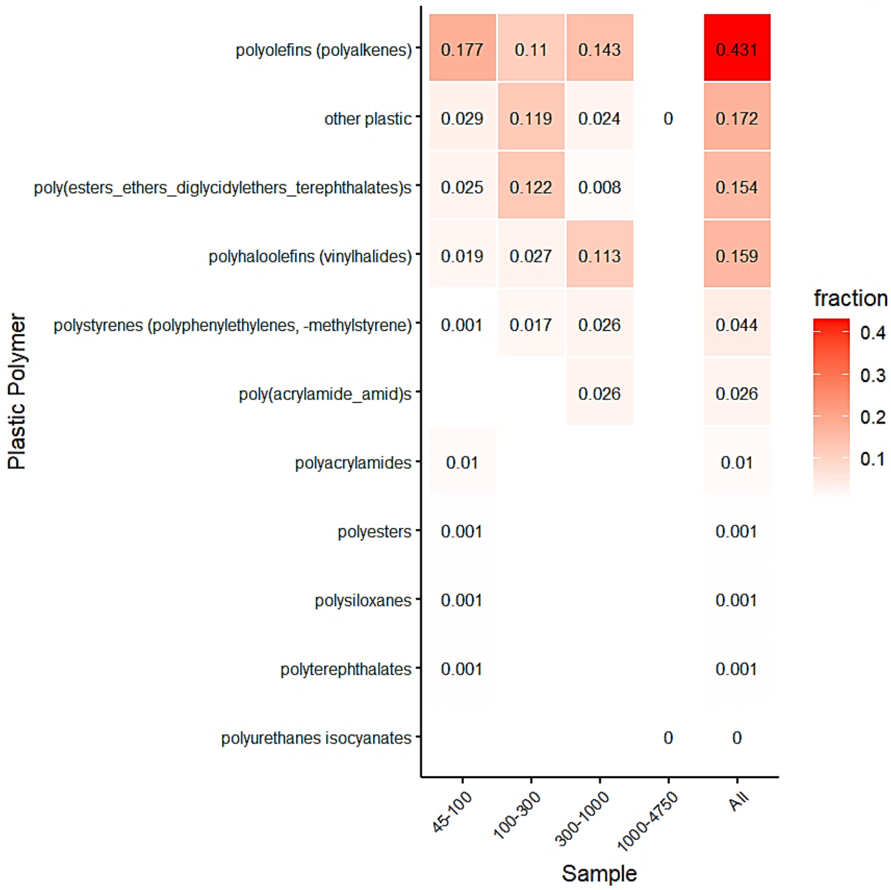


Figure 16. Fraction of each microplastic in 1 kg of sweeping materials

MP physical properties, including density, UV resistance, and physical durability were also obtained from available literatures and incorporated for data analysis to improve understanding of the factors influencing the presence of MPs in sweeping materials. (Table 2). The most abundant MPs were found to have either the lowest densities, such as polypropylene (PP) and polyethylene (PE), ranging from 0.895 to 0.965 g/cm^3, or the highest, such as polyvinyl chloride (PVC) and poly(esters/ethers/diglycidyl ethers/terephthalates), ranging from 1.38 to 1.40 g/cm^3. Other plastic groups, which appeared in smaller abundance, had densities between 1.0 and 1.38 g/cm^3. UV resistance and physical durability were considered indicators of a polymer's tendency to fragment, potentially contributing to the formation of fine MPs on-site. However, the analysis showed no clear influence of these physical properties on the abundance of MPs across size classes.

Table 2. Physical properties of MPs ranking from highest to lowest abundance reported in sweeping samples

Plastics	Density	UV Resistance	Physical Durability	MP Abundance (%)				
				MP Size (µm)				
				45-100	100-300	300-1,000	1,000-4,750	Total
polyolefins (polyalkenes) - PP, PE	0.85-0.98	Fair	Excellent	17.7%	11.0%	14.3%	0.0%	43.1%
other plastic				2.9%	11.9%	2.4%	0.0%	17.2%
polyhaloolefins (vinylhalides) - PVC	1.38-1.41	Moderate	Moderate	1.9%	2.7%	11.3%	0.0%	15.9%
poly(esters_ethers_ diglycidylethers_terephthalates)s	1.38	Moderate	Moderate	2.5%	12.2%	0.8%	0.0%	15.4%
polystyrenes (polyphenylethylenes,-methylstyrene)	1.06	Fair	Fair	0.1%	1.7%	2.6%	0.0%	4.4%
poly (acrylamid_amid)s	1.3	Fair-Moderate	Fair-Moderate	0.0%	0.0%	2.6%	0.0%	2.6%
polyacrylamides - PAM	1.3	Fair	Fair	1.0%	0.0%	0.0%	0.0%	1.0%
polyesters	1.38	Moderate	Moderate	0.1%	0.0%	0.0%	0.0%	0.1%
polysiloxanes	1	Excellent	Excellent	0.1%	0.0%	0.0%	0.0%	0.1%
polyterephthalates - PET	1.38-1.41	Moderate	Moderate	0.1%	0.0%	0.0%	0.0%	0.1%
polyurethane - PU	1.20-1.26	Moderate	Moderate-Excellent	0.0%	0.0%	0.0%	0.0%	0.0%

Note: MP abundance is the same in Figure 16a. Density of PS, PP, PE, PU, PET and PVC (Frias et al., 2018)

3.4 Conclusion and Recommendations

1. Analysis of four duplicate samples revealed that a single grab sample of sweeping debris contained over 800,000 microplastic (MP) particles per kg of sweeping debris. This high MP numbers indicate a significant accumulation of MPs on roadways. These findings underline the critical need for proper collection and disposal of sweeping debris to prevent the environmental release and further spread of MPs. Järlskog et al. (2020) evidence street cleaning can remove a large amount of tire and bitumen wear MPs (TBMPs), and weekly sweeping schedule is recommended to prevent further transport of TBMP to the receiving water body. Moreover, the elevated MP load poses a risk of overwhelming existing stormwater treatment systems during rainfall events because these systems are typically not designed to capture fine non biodegradable particulate pollutants like microplastics. Therefore, it is essential to develop and implement stormwater treatment technologies specifically engineered for microplastic removal to mitigate their transport into surrounding ecosystems.

2. The sweeping debris contained four primary types of plastics, including polyolefins (e.g., polyethylene and polypropylene), 'other plastic', polyhaloolefins (e.g., polyvinyl chloride), and polyesters/ethers/diglycidyl ethers/terephthalates, while other plastic

types presented in smaller proportions. Most of the identified plastics were thermoplastics, including polypropylene, polyethylene, polyvinyl chloride, polystyrene, polyethylene terephthalate, and polycarbonate, which are commonly associated with transportation-related sources. However, the current dataset does not allow for precise source attribution of these MPs. Specifically, thermoplastic stripping paints and tire wear, which contain large of blended plastic types, but the primary plastic content is less than 67%. This results in poor FTIR signal obtained. Hence, thermoplastic stripping paints and tire wear are identified as non-plastic. Microscopy analysis must be performed to manually characterize thermoplastic stripping paints and tire wear in the environmental sample. Moreover, the plastic property such as low density (e.g., PE and PP) along with their size (< 1,000 µm), and abundance are factors influence their potential to be dispersed to the environment. As a result, targeted preventative strategies cannot yet be formulated and will require further investigation, including source-tracking studies and expanded sampling efforts.

3. Based on the results from the sample pretreatment step (Section 3.2), a large fraction of particles in the sweeping materials are non-MPs. If all sweeping debris was washed away by stormwater runoff, the primary solid constituents would not be MPs. Therefore, MP loads are unlikely to interfere with the existing stormwater management units. Instead, operational difficulties and failure of the existing stormwater treatment systems are more likely caused by existing particles.

4 COMPARISON OF MICROPLASTICS IN STORMWATER AND SWEEPING MATERIALS

Dust and debris left on roadways can be washed away during storms, entering the environment and potentially overwhelming existing stormwater treatment systems, which are not originally designed to specifically handle microplastics loads. Moreover, the fine debris can be dispersed into the surroundings by strong winds. The statistical analysis of overall MPs composition percentage and their polymer type shows a significant correlation between microplastic composition between the sweeping debris and the March runoff sample ($r = 0.79$, $p < 0.05$, $n = 11$), and a weaker correlation between both stormwater samples ($r = 0.58$, $p = 0.06$, $n = 11$), regardless of MP sizes. However, there is no significant correlation between sweeping materials and February runoff sample. The coexist of MPs in sweeping debris and stormwater runoff solids can be influenced by freeway cleaning schedule, storm pattern such as intensity and duration, sampling time (at the beginning of the rainfall or middle of the rainfall) and sampling location, for example.

Our findings provide critical insights into MP pollution originating from transportation-related activities. A comparison of MPs found in stormwater runoff and street sweeping material samples, as detailed in Sections II and III, highlights key considerations and offers actionable recommendations for improving MP best management practices.

4.1 Diversity of Plastic Types

A greater variety of plastic polymers was identified in sweeping debris (11 types) compared to stormwater runoff samples, which contained 5 types per storm event, or 6 types combined across both events. Since stormwater runoff samples were collected from a single outlet receiving runoff from a particular tributary area from the Fwy 605 south in Long Beach City. Sweeping debris obtained from a Caltrans sweeping truck was integrated from a long distance of the Freeway. Moreover, the sweeping materials and stormwater sampling locations were from different freeways (Fwy 405 and Fwy 605) in the City of Long Beach, CA. This may result in more diverse MP groups reported in sweeping sample materials. Hence, more diverse MP groups can be reported from other stormwater runoff locations.

4.2 Abundance of 'Other Plastic'

'Other plastic' emerged as a notably abundant microplastic (MP) category across multiple sampling events. It was the most prevalent MP type during the February storm event, with a concentration of 58 MPs/L, and the second most prevalent in the March storm event, at 51 MPs/L. In sweeping debris, 'other plastic' ranked as the second most abundant category, accounting for 17.2% of the total MP count in sweeping samples. This consistent presence across different environmental matrices emphasizes the significance of the 'other plastic' group in the overall microplastic profile. However, its exact composition and polymer identity remain unknown, as these particles could not be characterized using Fourier Transform Infrared Spectroscopy (FTIR), the most widely adopted technique for plastic identification. This limitation suggests that 'other plastic' may consist of complex, degraded, or composite materials that fall outside the detection capabilities of current analytical methods. Tire and bitumen wear were reported as one of the potential MPs from roadways (Järlskog et al., 2020), composed of polybutadiene and styrene-butadiene rubber (Rogers 2020). However, these specific polymer groups were not showed on our FTIR analysis. It is unlikely that our reported MPs include tires due to less than 67% of tire compositions are plastics. The FTIR analysis will confirm when at least 67% of the spectra matches the plastic control. From our experience, tire wear analysis results from FTIR produced poor signal due less than 67% of spectra matched the standard spectra. However, for particles with a size range of 300-1,000 µm and 1,000-4,750 µm of sweeping materials in this study, several tire wears were visualized by naked eyes.

The high abundance of this unidentified group raises concerns about potentially overlooked sources and behaviors of MPs in the environment. This points out the need for advanced analytical techniques and further research to uncover the nature and origin of these particles. Understanding this group is essential for developing comprehensive MP management strategies and improving the accuracy of environmental risk assessments.

4.3 Dominance of Polyolefins (polyalkenes)

Polyolefins (polyalkenes), primarily polyethylene (PE) and polypropylene (PP), was the most abundant microplastics (MPs) in sweeping debris, accounting for 43.1% of the total MP counts. They were also the predominant type in the March stormwater runoff, with a concentration of 69 MPs/L, closely followed by 'other plastic' at 51 MPs/L. However, during the February storm event, polyolefins were detected at only 5 MPs/L, approximately 12 times lower than the concentration of 'other plastic'. This discrepancy is likely due to the storm pattern and timing of sample collection. There were two storms within 48 hours before February sampling. Moreover, the February samples were collected later in the storm, by which time these low-density plastics, which are lighter than water, may have already been washed away during the initial runoff. Both PE and PP have densities below 1 g/cm^3, making them highly mobile in aquatic environments and prone to early transport during rainfall events.

Given their high abundance in sweeping materials and potential for rapid environmental dispersion, polyolefins (polyalkenes) should be closely monitored. Further research is recommended to better understand their source, transport dynamics, source pathways, and environmental fate, particularly during different phases of storm events. This knowledge is essential for designing effective mitigation strategies and improving stormwater management practices.

4.4 Presence of Less Abundance Plastics

Although polystyrenes (polyphenylethylenes,methylstyrene), polyterephthalates, polyesters, po lysiloxanes, and polyurethane isocyanates were detected in sweeping debris at relatively low concentrations, these plastic types were also present in stormwater samples, where they constituted a notable fraction of the total microplastic (MP) count. Their presence in both debris and runoff samples suggests that the less abundant plastics depicted in sweeping debris were readily mobilized by stormwater, contributing to the diversity and complexity of MPs released to the environment. Despite their lower quantities, their persistence and potential toxicity can pose a significant environmental threat, particularly as they may degrade into smaller, more bioavailable fragments. These findings highlight the urgent need to intercept and immobilize these plastics at their source before they are transported into aquatic ecosystems. Effective source control measures and targeted treatment technologies are essential to reduce their environmental footprint and mitigate long-term ecological impacts.

4.5 MP Size of Concern

While the most abundant MPs in sweeping samples were smaller than 1,000 µm size range, our findings indicate that smaller MPs (< 300 µm) are more easily transported by rainfall compared to larger particles. This suggests that stormwater runoff preferentially mobilizes finer microplastics, which may escape conventional capture methods. To address this, the evidence from this work recommends that stormwater MP treatment systems be designed to effectively target particles in the 45 – 300 µm range, where the risk of environmental transport is highest. In contrast, larger MPs (>300 µm) can be more efficiently managed through routine street sweeping and debris collection, which serve as critical first-line defenses in preventing MP pollution.

The presence of MPs debris and stormwater samples provides compelling evidence of the fate and transport pathways of these micropollutants within urban environments. This co-occurrence illustrates how MPs accumulate on road surfaces and are subsequently mobilized by stormwater runoff, potentially entering storm drainage systems and nearby water bodies. To address this issue, the implementation of Best Management Practices (BMPs) can play a pivotal role in interrupting the transport of MPs from roadways to aquatic ecosystems. By integrating these practices into transportation infrastructure planning and maintenance can significantly reduce MP pollution and protect downstream environments.

4.6 Study Limitations

Due to the need for FTIR analysis to distinguish MPs, defined as particles with a ≥67% match to surrogate plastic spectra, from non-MPs (<67% match) in mixed environmental samples, thermoplastic paints were likely identified as non-MPs in this project. This is attributed to the high content of non-plastic components commonly found in striping paints. Specifically, thermoplastic striping paints typically contain glass beads (30–35%), and titanium dioxide (10%, per ASTM D476 Type II for white striping), while binder content (18%) is plastic, which leave less than 67% of the composition as resin (Caltrans, 2020). This is similar to tire wear, which produces poor FTIR signal matching plastics. FTIR has limitations in identifying blended plastic materials, which presents a gap in this study. A control sample of thermoplastic striping paint was not obtained, and its spectrum was not recorded for reference during the project period.

5 PERFORMANCE OF VORTEX SEPARATOR FOR MICROPLASTICS REMOVAL

The concept of a vortex grit chamber was adopted to optimize the system design for microplastics (MP) removal. Since most plastics have a density slightly greater than that of water, and due to the centrifugal force generated by the flow regime, particles with higher momentum than the surrounding fluid are removed through tri-axial motion. These particles will settle at the bottom of the vortex separator, known as the underdrain, due to their inertia. The vortex separator is limited to removing only particles with a density greater than that of water. Therefore, MPs with lower densities such as polyethylene (PE) and polypropylene (PP), as shown in Table 2, cannot be removed by this unit. To address this limitation, an additional treatment component (e.g., a core settling compartment) is required to capture MPs with densities lower than water after the vortex separator. This vortex separator design minimizes the footprint of the unit operation while achieving higher removal efficiency comparable to that of a traditional horizontal velocity grit chamber, which relies on two-dimensional settling of solids. The objective of this scope is to design, test and assess the vortex separator to remove MPs from synthetic stormwater runoff.

5.1 Design of Vortex Separator

Vortex separator sizing was calculated using a capacity required for bioswale design from a 25-year storm event over a 1-acre paved tributary area, which generated approximately 0.11 cubic feet per second (cfs) of runoff. The first vortex separator (design 1) was 25% scaled down to handle runoff with a design capacity of 0.0275 cfs, or approximately 12 gallons per minute (gpm), consequently doubling the capacity to 24 gpm for the enlarged vortex separator (design 2). The design applied principles of vortex grit chambers commonly used in wastewater treatment plants, specifically utilizing a typical hydraulic retention time (HRT) of 30 seconds (Metcalf & Eddy, 2014), yielding the total volume of 6.8 and 12.3 gallons for 12-gpm and 24-gpm vortex separator capacity, respectively. Literatures on vortex geometry was reviewed to establish the vortex separator's proportional geometry. The resulting vortex separator dimensions for flow rates of 12 gpm and 24 gpm are presented in Table 3 and illustrated in Figure 17 – 18.

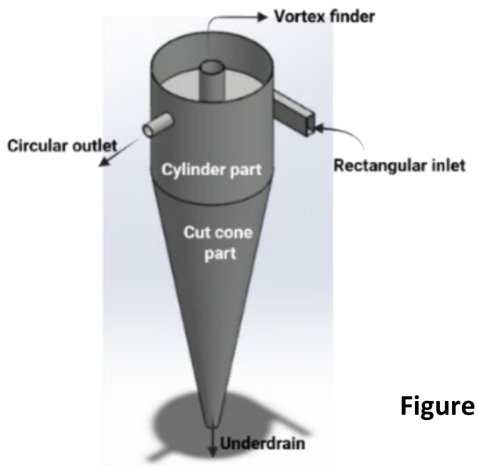
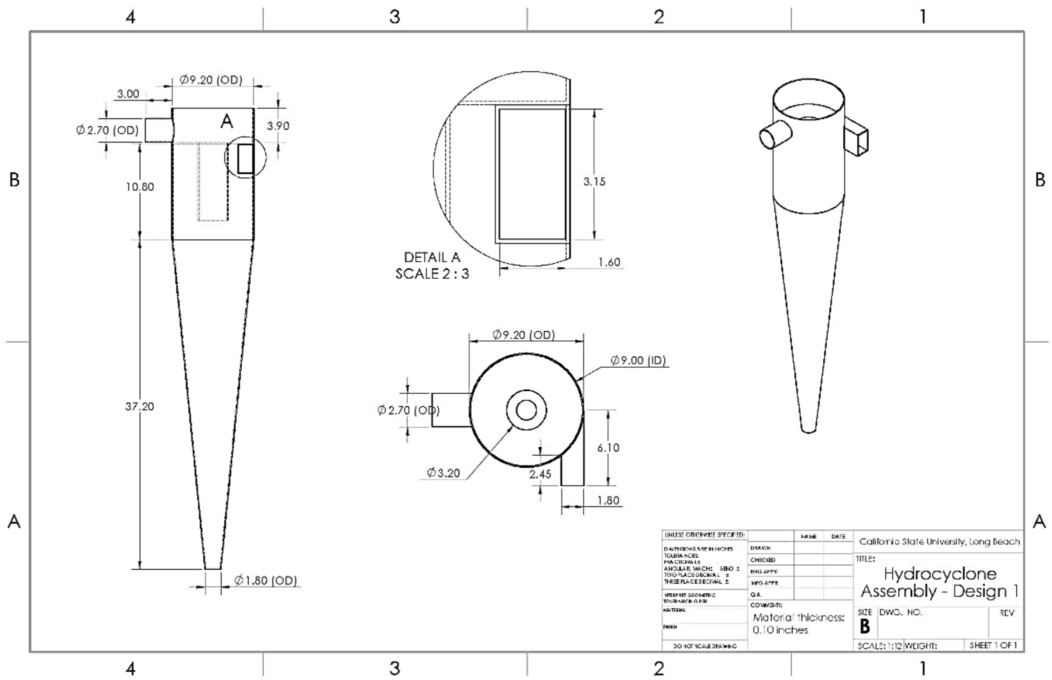


Figure 17. 3D vortex separator drawing with its features

Table 3. dimensions of developed vortex separators

	Feature	Design 1	Design 2	Remark
1.	Flow rate (gpm)	12	24	
2.	Total volume (gal)	6.8	12.3	
3.	Diameter of cylinder (in)	9.0	11.4	
4.	Diameter of underdrain (in)	1.6	1.9	Kyriakidis et al., 2018
5.	Diameter of vortex finder (in)	3.2	4.0	Hou et al., 2021
6.	Cylinder height (in)	10.8	13.6	
7.	Cut-cone height (ft)	3.10	3.88	
8.	Total height (ft)	4.0	5.0	
9.	Included angle of the cone	20°	20°	
10.	Inlet dimension (W×H) (in)	1.6 × 3.15	1.9 × 4.0	Tang et al., 2017
11.	Outlet diameter (in)	3.0	4.0	

(a)



(b)

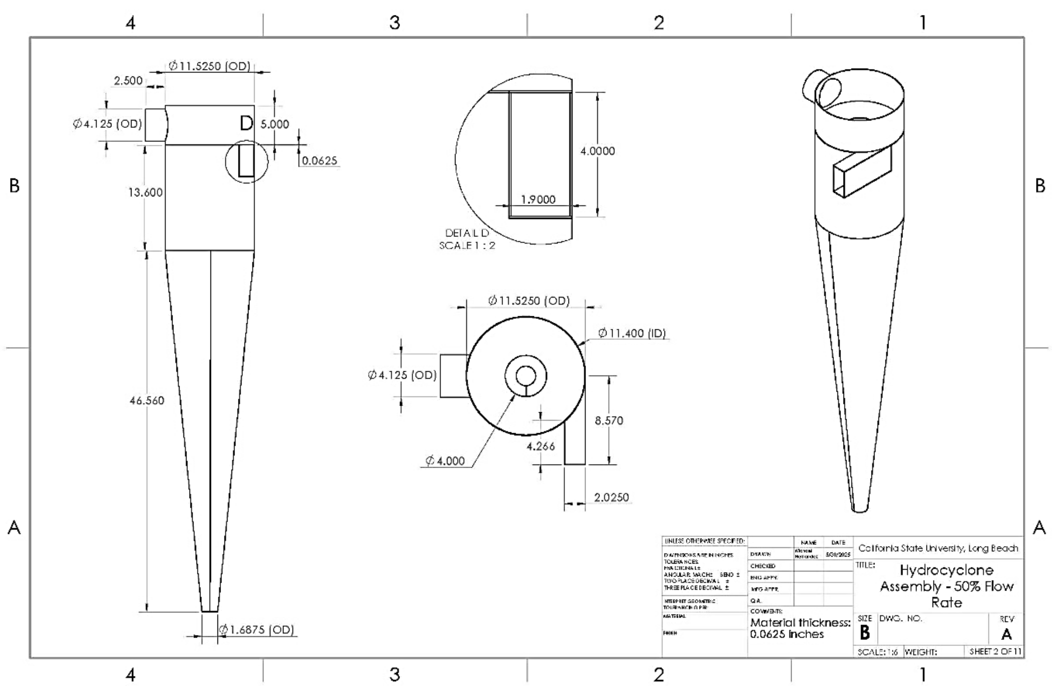


Figure 18. 2D vortex separator drawings (a) 12 gpm and (b) 24 gpm. Units in inches.

5.2 Vortex Separator System, Flow Calibration and Testing

Tap water filtered through a 45 µm metal sieve was used to fill the 294 gallon galvanized steel feed tank. Sweeping debris from Container 1 (Set 1) was then added to achieve the desired solids concentration prior to testing. The sweeping materials were thoroughly mixed in the feed tank for 5 minutes to ensure even dispersion of solids, and were mixed continuously and manually during testing using wooden paddles. Each debris size was tested separately in duplicate. Samples were collected using metal sieves at both the effluent and underdrain locations. Additional samples were taken from the bypass and system rinse to calculate the mass balance of the sweeping debris introduced into the system (Figure 19).

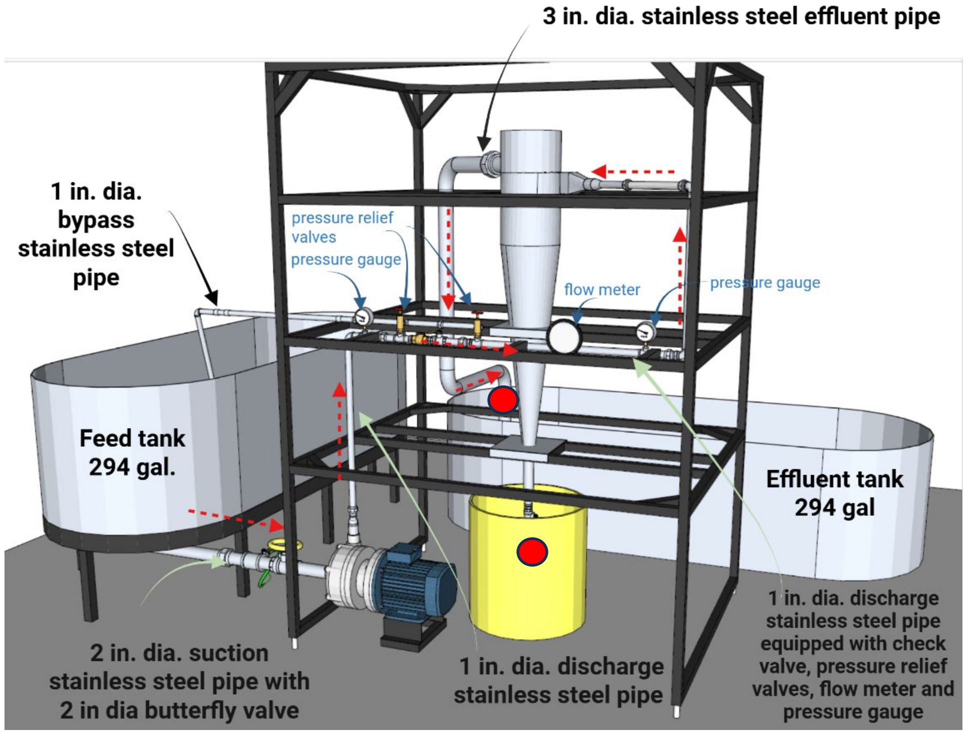
A stainless-steel centrifugal pump discharged flow rates of 12 gpm and 24 gpm at the required head. Flow rates were measured using both a flow meter and a stage-and-timer method during flow calibration and each test run. When the flow was found lower or higher than the set flow rate, the 1-inch diameter ball valve was adjusted.

In the lab testing, a pump was used to deliver various flow rates that simulate runoff generated from different storm events. It is important to note that the pump is not part of the treatment system but is instead used solely for the testing setup. Since runoff in the field flows under atmospheric pressure, the system's inlet must be redesigned for field application to ensure it can deliver the design flow rate to the treatment system with minimally required head.

When water was reused, water in the effluent tank was filtered again through a 45 µm metal sieve before being returned to the feed tank. The system was rinsed after each run and cleaned before use. Debris in the feed tank was removed using a vacuum cleaner, followed by wiping with paper towels. All pump, pipes and fittings used were non-plastic materials. Figure 19 displays the vortex separator testing system. Synthetic stormwater runoff was prepared by sweeping debris from Container 1 spiked into 45 µm filtered tap water to achieve desired solid concentrations.

Flow calibration was conducted without plastics. Flow rates of 3 gpm, 6 gpm, and 12 gpm were calibrated. It is important to note that the capacity of the first vortex separator (design 1) was 12 gpm, so the maximum flow rate tested was 12 gpm. The data indicates that the median flow rates exceeded the desired values. For the 3 gpm and 6 gpm targets, the median values were slightly higher (Figure 20). However, at the 12 gpm target, the system exhibited significant fluctuations in flow rate across tests. Therefore, during each run, the flow rate was adjusted using a ball valve to minimize flow fluctuation.

(a)



(b)

Figure 19. Vortex separator testing system for (a) 3D model with red indicating sampling location and (b) actual system

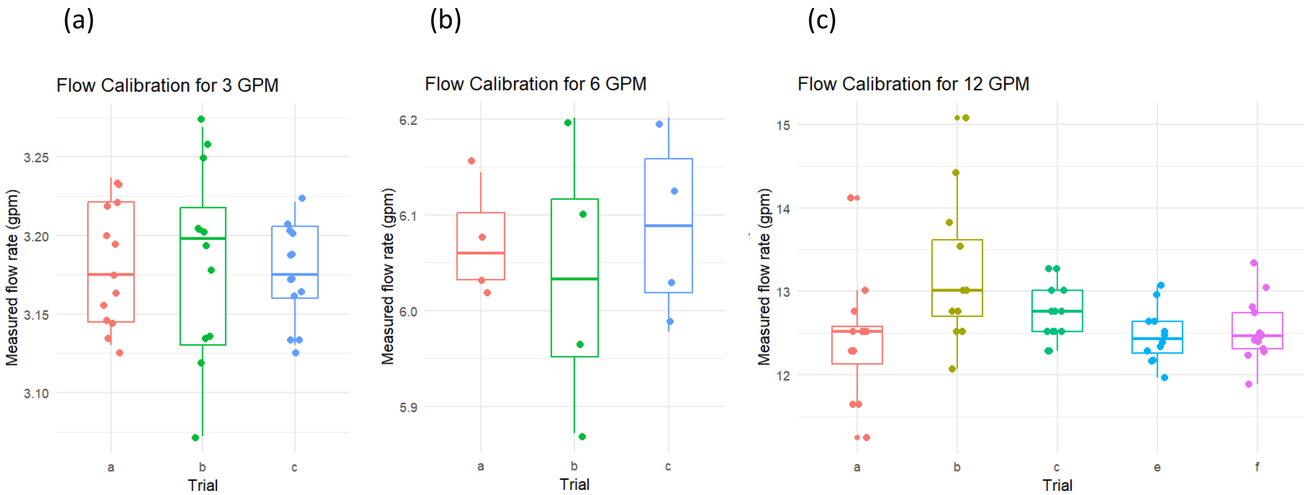


Figure 20. Vortex separator system flow calibration at (a) 3 gpm (b) 6 gpm, and (c) 12 gpm. Trial representing run replication

5.3 Nylon Microplastics Removal by Vortex Separator

Nylon microplastics (Goodfellow, PA) were sieved using various mesh sizes. The selected nylon microplastics (MPs), also known as polyamide, had a nominal size of 150 µm filaments and were introduced into the vortex separation system. The system was tested in duplicate at flow rates of 3 and 6 gallons per minute (gpm). The average measured nylon recovery from the system, defined as the sum of nylon found in the effluent and trapped particles, not removal, was 99.8% ± 13.0% at 3 gpm and 87.6% ± 3.5% at 6 gpm (Figure 21a). These results indicate that the cumulative mass input into the system closely matched the cumulative mass recovered at the output, with only a slight loss of material retained within the system's piping.

The average removal efficiency of the system was 65.7% ± 1.7% at 3 gpm and 24.4% ± 0.4% at 6 gpm (Figure 21b). At the flow rate of 3 gpm, the system nearly achieved the target removal efficiency of 70%. The nylon removal performance of the 6 gpm run was greatly below the desired removal threshold of 70%. Due to similar nylon density (1.14 g/cm^3) to water and its filament morphology, the nylon particles were not effectively removed using the vortex separator. This data proofs the system limitation of low-density MP filament removal. However, nylon (polyamide) MPs were absent in all stormwater samples, and sweeping materials discussed in Sections 2 and 3. Furthermore, the filament morphology was not the common MP shapes observed in sweeping debris and stormwater solids in this stormwater and sweeping samples (Figure 22). Nylon was selected for testing because it was the first commercially produced thermoplastic and is among the commonly reported polymer group found in the ocean (Andrady, 2011, Melville, 1949). The higher flow rate offers greater flow velocity, which promotes solid separation by a vortex separator. However, the results comparing 3-gpm and 6-

gpm show opposite outcomes. Further assessment for MP removal performance by the vortex separator, was also carried out using sweeping samples.

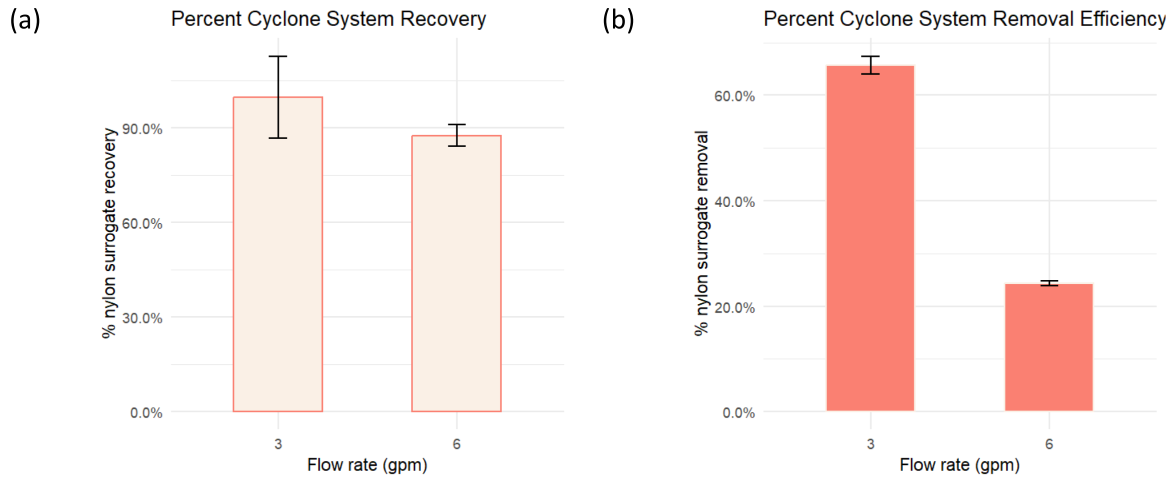


Figure 21. The cyclone testing with 150 µm nylon surrogates (a) recovery percentage and (b) removal percentage

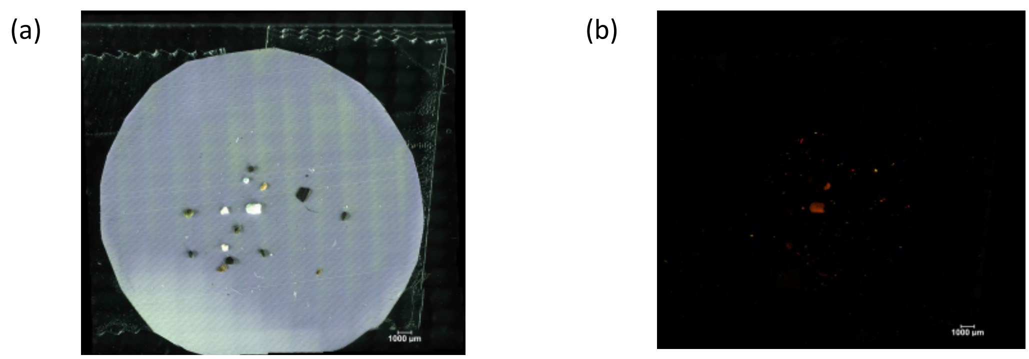


Figure 22. Bright field (a) and fluorescence (b) images of sweeping materials.

5.4 Sweeping Solids Removal Efficiency of the Vortex Separator

In this experiment, particle size, flow rate, and solids concentration were the three independent variables. Solids removal was assessed as a preliminary indicator of MP removal by the vortex separator, since MPs are a subset of solids. The average ± standard deviation solids recovery for all runs was 90.6% ± 22.8%. The results show that solids removal was influenced by particle size and flow rate (Figure 23). The vortex separator demonstrated higher removal efficiency for larger particles (> 300 µm) compared to smaller size ranges (45 – 100 µm and 100 – 300 µm). The highest removal efficiency, 97.9% ± 1.1%, was observed for the 300 – 1,000 µm sample, which was comparable to the solid removal efficiency of the 1,000 – 4,750 µm sample. The high solid removal performance of the large particles is likely due to the greater mass of these particles (Figure 23).

In general, higher flow rates enhanced the solids removal efficiency of the vortex separator, except for the smallest particles (45–100 µm). This trend is attributed to the increased centrifugal force and momentum differential between the solids and the surrounding water. Particles larger than 100 µm were effectively removed, with a minimum average removal efficiency of 80.2% ± 9.1% for the 100 – 300 µm range compared to 97.9% ± 1.1% and 97.5% ± 2.5% for 300 – 1,000 µm and 1,000 – 4,750 µm sample, respectively, for all flows (Figure 23). In contrast, the 45–100 µm particles showed a significantly lower removal efficiency of 38.2% ± 16.4%. These smaller particles accounted for only 6.2% of the total sweeping materials but contained the largest MPs abundance per 1 mg mass included in the testing. It is noted that Set 1 sweeping materials were used for all tests.

The 30 and 60 ppm were prepared to test samples that were smaller than 1,000 µm, while 1,000 – 4,750 µm samples were prepared only at 120 ppm due to their high mass per particle leading too few 1,000 – 4,750 µm particles per run at 30 ppm and 60 ppm. The linear regression models show sweeping materials at 30 ppm (mg/L) and 60 ppm concentration shared similar removal efficacy, but the 30 ppm was slightly better due to lower removal percentage of 60 ppm run for 45 – 100 µm samples, which suggested that high centrifugal force acting on small particles did not effectively enhance their removal due to small momentum (Figure 23 – 24). The combined solids removal efficiencies of various particle sizes at a specific flow rate cause low coefficient of determination (R^2). This finding suggests the modeling of solids removal by vortex separator required advanced multi-variable models to predict the system performance.

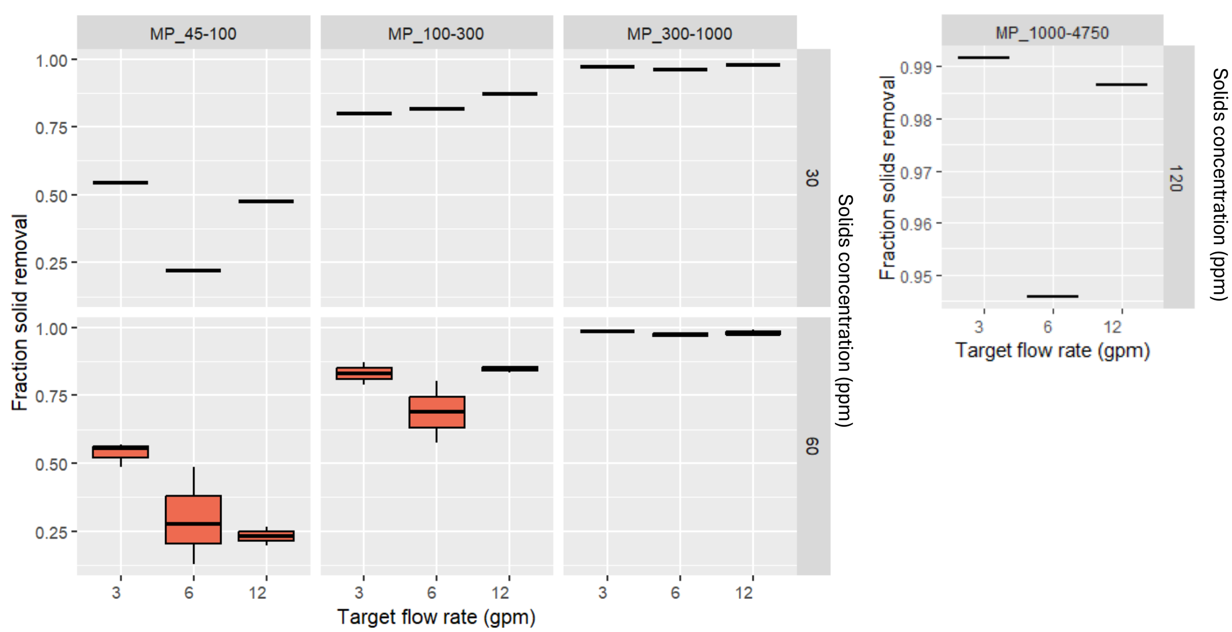


Figure 23. Solids removal efficiency tested at different solid concentrations and flowrates.

Note: The 1,000 - 4,750 µm tested at 120 ppm only due to fewer particles in 30 ppm and 60 ppm

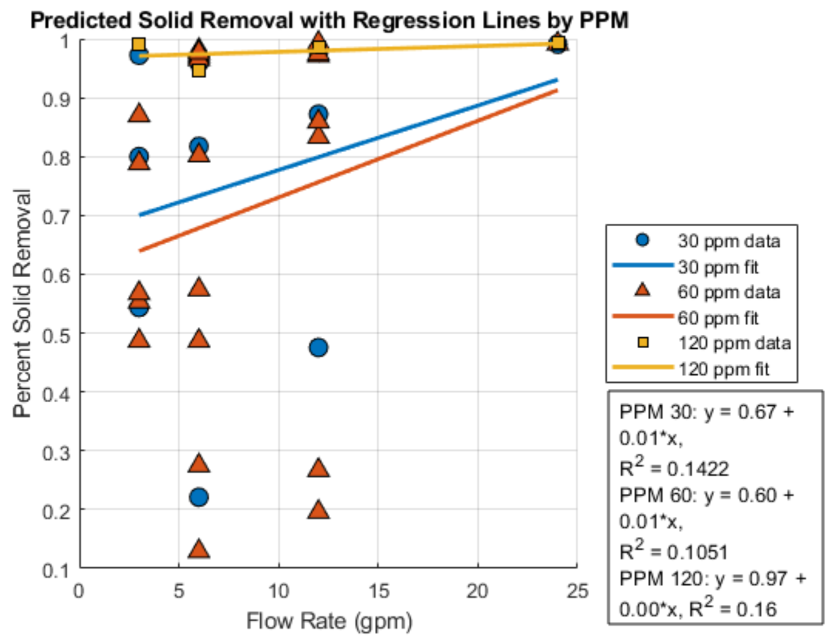


Figure 24. Linear regression model for solid removal for each solid concentration for all size ranges. **Note:** The 1,000 - 4,750 µm sample ran at 120 ppm only.

5.5 Microplastic Removal Efficiency of the Vortex Separator

Effluent and underdrain samples were collected after each run, dyed using Nile Red staining, and analyzed using fluorescence combined with FTIR microscopy techniques, as described in Section 3.3. Results indicate that MP removal means exceeded 70% for particles larger than 100 µm, with mean ± standard deviation removal efficiencies of 89.5% ± 14.6% for 100 – 300 µm, 99.5% ± 0.8% for 300 – 1,000 µm, and 78.3% ± 15.8% for 1,000 – 4,750 µm, across all flow rates and solids concentrations. These findings demonstrate the effectiveness of the vortex separator in removing larger (> 100 µm) MPs, where sufficient mass enables separation under the influence of centrifugal force. However, consistent with the low solid removal performance for 45 – 100 µm samples discussed in Section 5.4, the removal efficiency for this smallest MP size range was 14.0% ± 12.7% (Figure 25), which falls short of the desired 70% target. Based on the size fraction distribution by mass for Container 1 (Set 1) and MP counts per mass shown in Figure 3.3a, the overall MP removal across all runs was estimated at a marginal **69.7%.** The original purposed scope of work also includes MP removal using an additional unit operation, called a settling tank (Section 6), as well as a combined system integrating the vortex separator and settling compartment, which aims to achieve optimal MP removal of at least 70% from stormwater runoff.

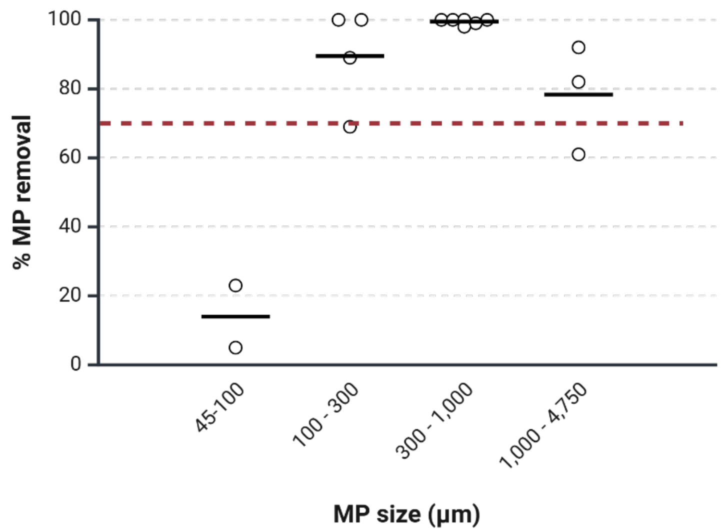


Figure 25. Microplastic removal efficiency across all particle sizes. The red dash line indicating the desired 70% MP removal performance

The multivariable linear regression model developed for the entire runs considering all available variables, suggests that the particle size parameter was the most influential predictor of performance, specifically for size ranges of 100 – 300 µm and 300 – 1,000 µm (*r* = 0.33 and 0.44; $p < 0.001$, respectively), while the solid concentration and flow rate variables demonstrated statistically insignificant governing the model. The equation to predict the vortex performance is displayed below:

$$\boldsymbol{MP\ fraction\ removal} = \mathbf{0.6704} + (\mathbf{0.0035} \times \boldsymbol{C}) + (\mathbf{0.0078} \times \boldsymbol{Q}) + \boldsymbol{K} \qquad \text{(Eq.1)}$$

When C = solid concentration as ppm or mg/L
Q = flow rate in gallon per minute (gpm)
K = coefficient for a certain solid size present
K is –0.35 for 1,000 – 4,750 µm MPs,
+0.1142 for 300 – 1,000 µm MPs,
0 for 100 – 300 µm MPs, and
–0.7363 for 45 – 100 µm MPs.

The model confirms that the medium size MPs (100 – 1,000 µm) are most effectively removed by the system, but the 45 – 100 µm MPs removal significantly reduces the system performance. This model produces the adjusted coefficient of determination (adjusted R^2) of 89.4%, which refers to the linear regression model confidently explains 89.4% of the variance. With the high adjusted R^2, the equation is a strong model. Furthermore, the F-statistic value of 24.53 (p = 5.4x10-5) confirms the model is statistically significant. This model has limitations to predict the MP removal efficiency for a single particle size at a time. Figure 26 displays the actual and predicted MP removal performance of the 12-gpm vortex separator.

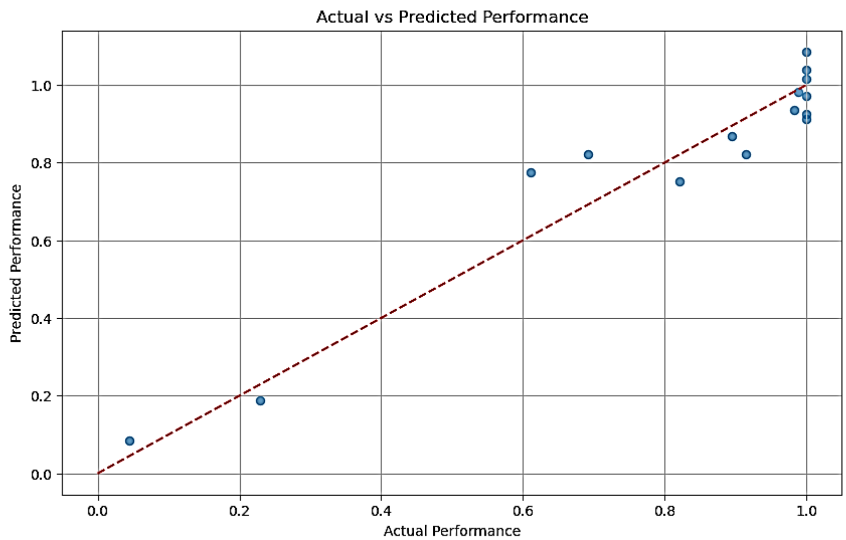


Figure 26. Actual and predicted (Equation 1) MP removal performance

5.6 Conclusion and Recommendation

High centrifugal force enhances momentum differentiation between sweeping particles and water matrix, which promotes solid separation through settling. Our findings confirm that larger particle sizes (>100 µm) and higher flow rates improve the removal of solids and microplastics (MPs) by the vortex separator. Additionally, MP removal efficiency observed in this project closely aligns with the system's solid removal performance. When solid removal was low, a higher concentration of MPs was detected in the effluent.

Furthermore, variations in solid concentrations whether low or high did not significantly affect the overall removal performance for solids and MPs because the amount of 1,000 — 4,750 µm samples included in the experiment was 120 ppm, which was not 30 or 60 ppm as used for other sizes. The nylon filament test further indicated that MP morphology, particularly filamentous shapes, may influence removal efficiency. Additionally, the nylon MPs removal data was not consistent with the environmental MPs removal results, which implies the MP removal mechanisms for both types of samples in the vortex separator were different. This finding suggests that vortex separators are less effective at capturing small MPs (<100 µm). This limitation arises because centrifugal force is insufficient to sufficiently increase momentum of fine particles from the water matrix.

The system was theoretically developed using the recommendations from peer-reviewed literature, which advocate for a smaller vortex separator diameter to maximize solid removal. Notably, the shortest distance a particle must travel to reach the vortex separator wall enhances its likelihood of removal. This design consideration results in an optimal separator depth slightly greater than 4 feet for 6.8 gallons capacity for a 12 gpm runoff capacity, which is equivalent to runoff from a 0.25-acre paved surface during a 25-year storm event. These findings suggest that optimizing the cyclone separator to be shallower could reduce construction costs while maintaining performance.

Several key findings from this project can be considered regarding the best operation practice for vortex separators. First, a greater number of particles, both MPs and non-MPs, are transported at the beginning of all storm events, regardless of storm intensity. Second, higher storm intensity, regardless of specific point of time, mobilizes more particles, especially larger ones. However, the proportion of non-MPs increases significantly. Third, most solids found in stormwater are non-MPs. Based on these findings, temporarily deactivating the vortex separation system at the beginning of heavy storms is unlikely to reduce overall MP removal efficiency due to the elevated presence of non-target particles. This approach can also help minimize maintenance requirements for the vortex separator. However, implementing such a control strategy would require an additional system for activation and deactivation, which introduces extra costs.

Last but not least, the existing Caltrans problem statement highlights that MPs clog bioswales and reduce their efficiency. The results from this project partially support this claim, showing that MPs are present in stormwater and can accumulate in bioswales and settle in retention ponds. However, the findings also indicate that non-plastic particles which present in much greater abundance than MPs, are the primary contributors to clogging in bioswales and retention ponds. Having a vortex separator installed before a bioswale is ideal to prolong bioswale performance with minimal maintenance and remove MPs. Although the primary function of the vortex separator is to remove MPs, the system may also capture non-MPs with similar physical properties such as size, shape, density, etc. However, the accumulation of varying non-MPs can exceed the system's design capacity, leading to operational overload. Capturing non-MPs does not deteriorate the MPs removal of the proposed system. This project recommends having the vortex separator first followed by the bioswale for the most effective system to remove micropollutants.

6 PERFORMANCE OF CORE SETTLING COMPARTMENT FOR MICROPLASTICS REMOVAL

The theory of clarifiers, also known as sedimentation basins or settling tanks, design commonly adopted in primary and secondary treatment processes for water and wastewater, was referenced for the design of the microplastic (MP) settling compartment. The MP settling chamber relies on both horizontal and vertical flow motions to remove solids from water. The settling velocity of the target particles is used as a critical design parameter, referred to as the overflow rate. MPs with a density larger than water settle down in the compartment, and MPs with a density smaller than water float and trap inside the basin via undersurface outlet design. Due to a small footprint of the system required, plate settlers were incorporated into the design to enhance particle settling. The settling compartment can be used independently or in series with a vortex separator to maximize MP removal from stormwater runoff. Since neither the vortex separator nor the core settling compartment includes a filtration feature for MP removal, the system requires less maintenance. The aim of this task is to design and validate the MP removal performance of settling compartments. It is important to distinguish between the theoretical mechanisms of solid separation in vortex separators and gravitational settling systems. In a vortex separator, higher flow rates increase particle velocity and momentum. As a result, greater flow enhances removal performance due to stronger centrifugal forces. However, in gravitational settling compartments, high flow rates increase horizontal velocity, which leads to particle washed out, so the particle removal efficiency trends to decrease.

6.1 Design of Core Settling Compartment

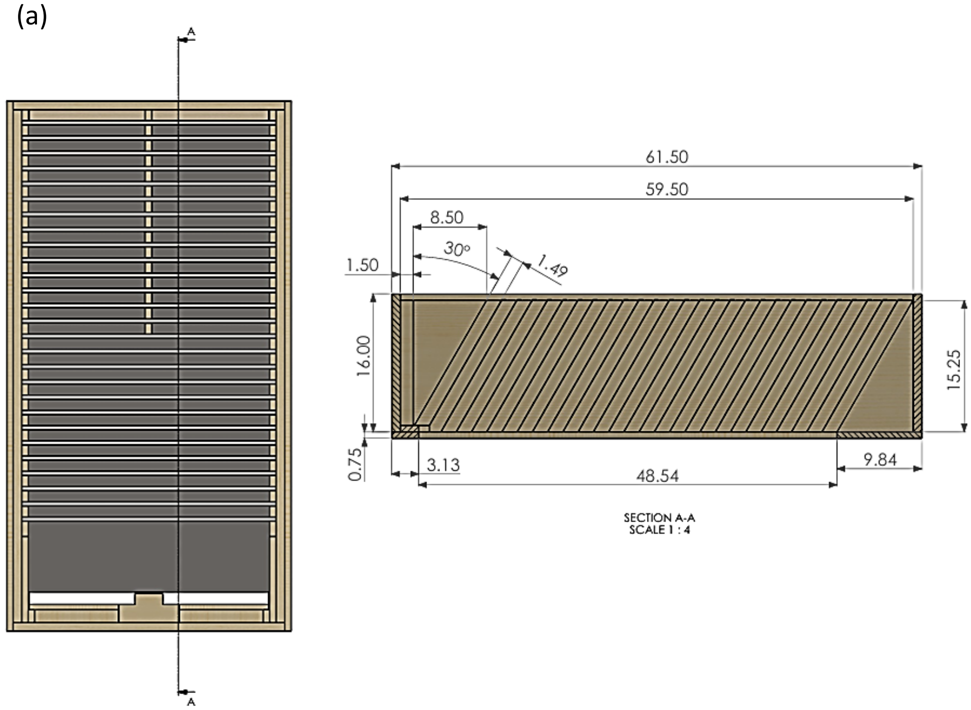
Microplastics (MPs) with a diameter of 100 µm and a density of 1.01 g/cm³ were selected as the critical particles targeted for removal through gravitational settling in water at 10 °C. The settling velocity under a laminar flow condition of these particles was calculated using Stokes' Law. Under these parameters, the settling velocity was determined to be 564×10^{-6} ft/s, which serves as the design overflow rate (OR) for the settling compartment.

To accommodate a consistent target flow rate of 12 gallons per minute (gpm), the required surface area (width × length) of the settling compartment was calculated to be 47.3 square feet of required settling area (ft²). The core settling compartment was designed with adjustable settling surface area capabilities, ranging from 15 ft² to 60 ft², to maintain flexibility while testing the 12-gpm design flow. With the final dimension of the 12 gpm settling compartment of 3 ft. × 5 ft. × 3 ft. (w × l x d) produces a hydraulic retention time (HRT) at approximately 34 minutes (Design 1). The effective depth of the compartment was maintained at 3 ft. Table 4 summarizes design criteria and dimensions for both the 12 gpm and 24 gpm core settling compartments. Figure 27 —28 illustrate the as-built drawing of 12 gpm core settling compartment. Figure 29 displays the design for 24 gpm core settling compartment.

Table 4 Design criteria and dimensions for core settling compartments.

-	Feature	Design 1	Design 2
1.	Flow rate (gpm)	12	24
2.	Settling velocity (ft/s)	564×10^{-6}	564×10^{-6}
3.	Overflow rate (gal/ft^2-d)	364.5	364.5
3.	Total volume (gal)	404	671
4.	Settling area width; w (ft)	3.0	3.5
5.	Settling area length; l (ft)	5.0	7.5
6.	Depth; d (ft)	3.0	3.0
7.	Number of plate settlers (plates)	27	40
8.	Angle of plate settlers	60°	60°
9.	Settling surface area (ft^2)	15 — 60	26.25 — 102
10.	Hydraulic retention time (mins)	33.6	27.9
11.	Tank length (ft)	7	8.9
12.	Inlet diameter (in)	3	3
13.	Outlet diameter (in)	4	4

(a)


A
A
61.50
59.50
8.50
30°
1.49
1.50
16.00
15.25
0.75
3.13
48.54
9.84
SECTION A-A
SCALE 1 : 4

(b)

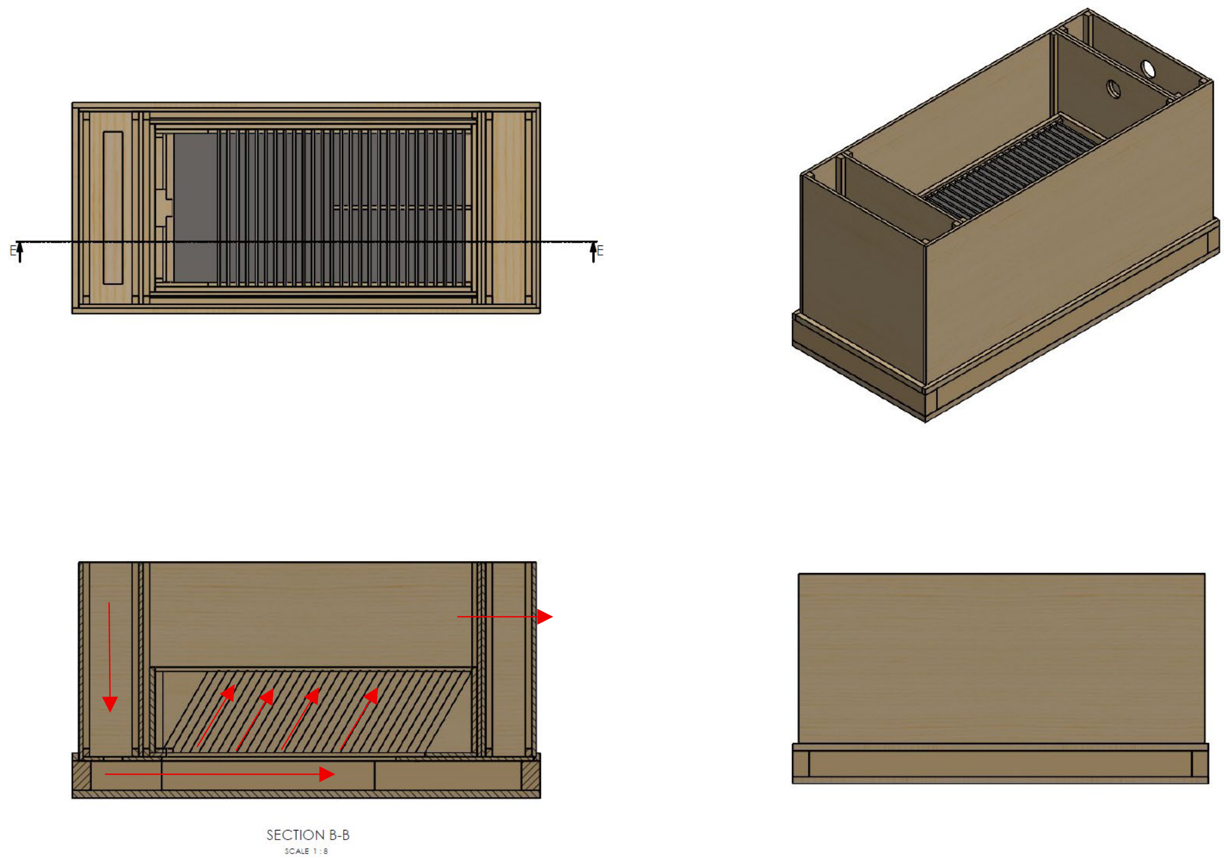
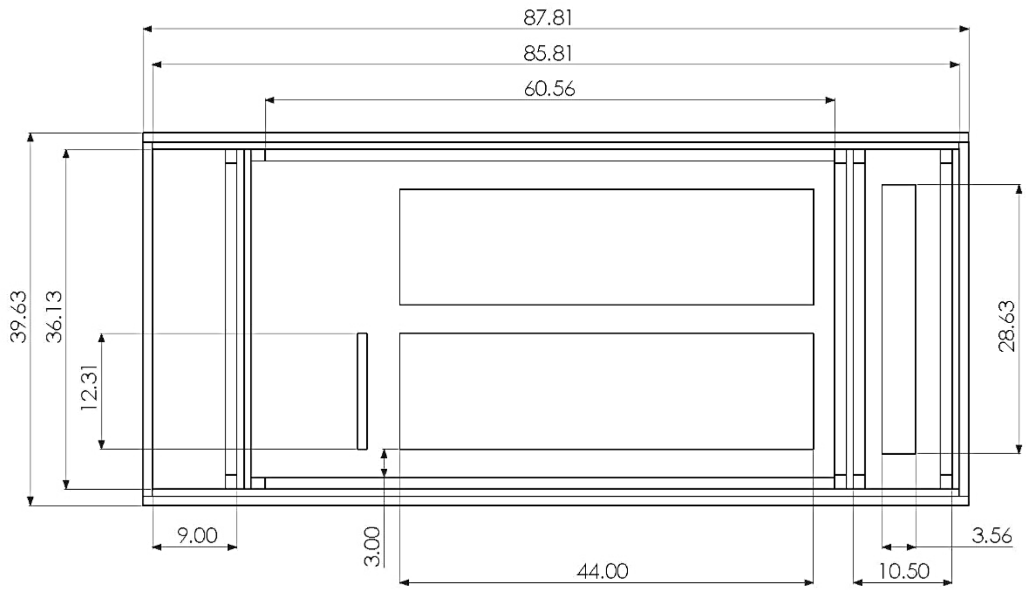


Figure 27. 3D as-built drawing of 12 gpm core settling compartment. (a) removable inclined plate settling unit, (b) entire core settling compartment, including core basin and inclined settling unit installed inside. Units in inches.

(a)



(b)

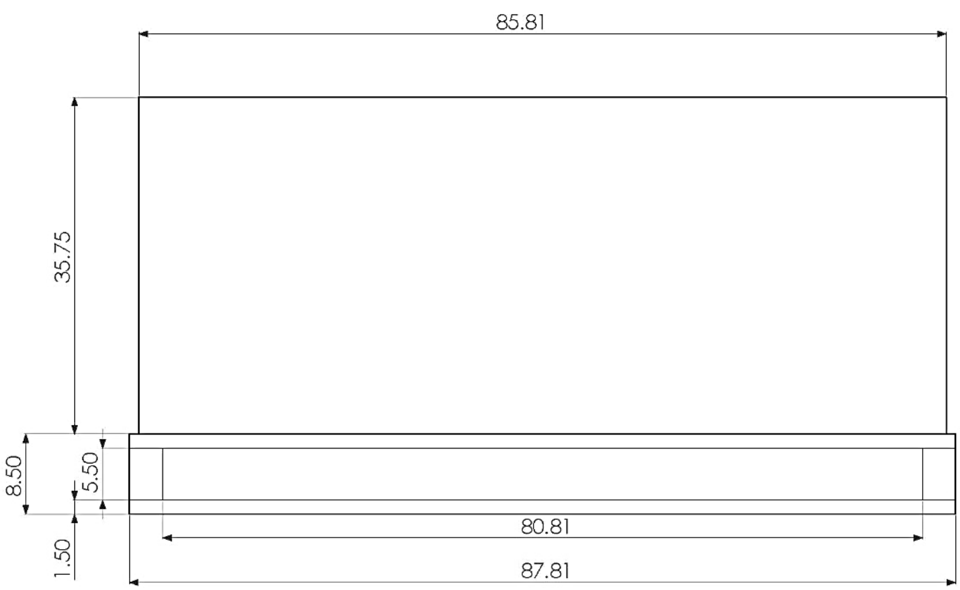
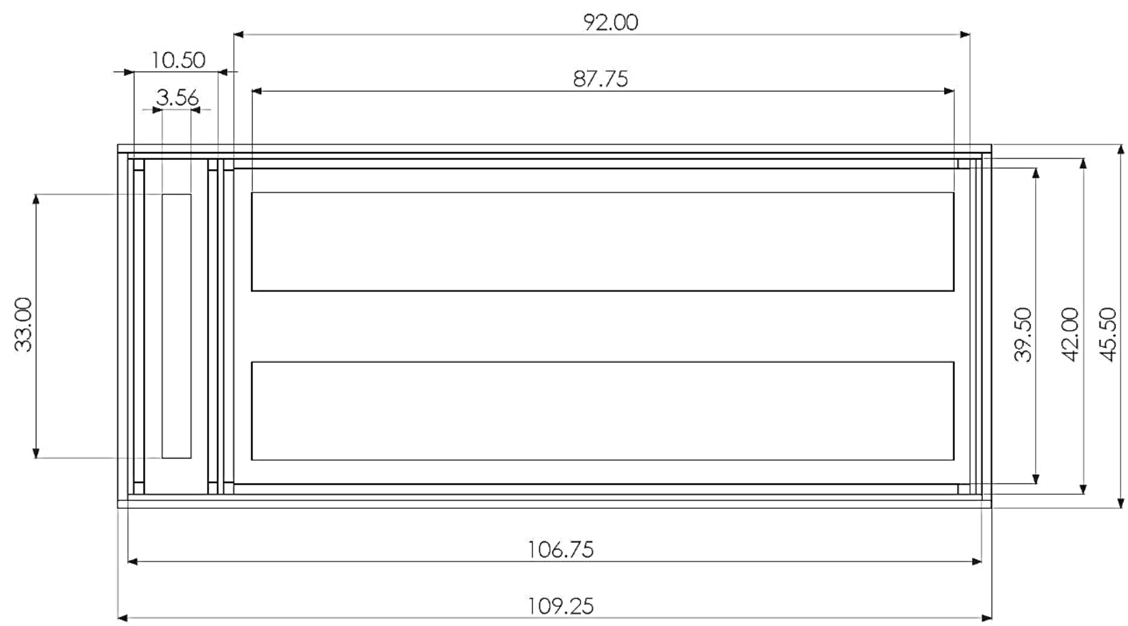
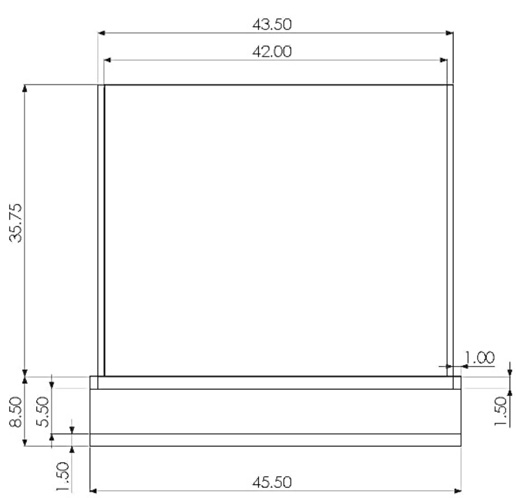


Figure 28. As-built drawing of 12 gpm core settling compartment (a) top view without plate settlers and (b) side view. Units in inches.

(a)



(b)



(c)

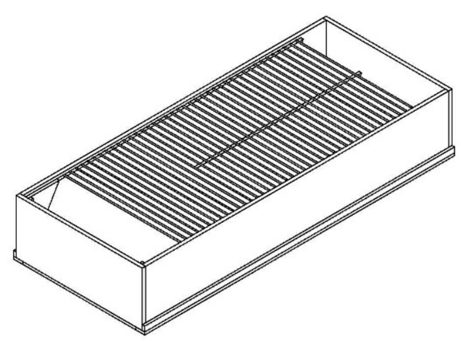


Figure 29. Drawing of designed 24 gpm core settling compartment (a) top view without plate settlers, (b) side view, and (c) the plate settler module. Units in inches.

6.2 Sweeping Solids Removal Efficiency of the Vortex Separator

The settling compartment was constructed using wood and plastic-free materials. The existing piping system from the vortex separator testing setup was used to deliver 45 µm-sieved tap water to the 12 gpm core settling compartment (Design 1). The sieved, debris-free water was pumped through the existing vortex separator and then directed into the core settling compartment. Flow rate was monitored using a flow meter.

Sweeping solids were manually added to the influent water at the inlet chamber throughout the testing period. Effluent water was collected in a tank and reused by pumping it back to the feed tank. Before entering the feed tank, the reused water was filtered through a 45 µm sieve. Sweeping debris from Container 1 was used for the test. Influent samples were collected from the inlet pipe at four different times, while effluent samples were taken after the water exited the settling compartment. Hydraulic retention time was monitored to ensure that the final particles had exited the tank. Figure 30 illustrates the settling compartment testing system.

Figure 30. 12 gpm settling compartment testing system. Red indicating sampling locations

Settling surface area, flow rate and particle size were independent parameters for the core settling compartment test. Only 30 ppm solids concentration was employed across sample size ranges, except 120 ppm for 1,000–4,750 µm samples. Due to the delay of the 12-gpm settling compartment construction, the system was tested for solid removal at 60 ft^2 settling area for all particle sizes and three flow rates (6 gpm, 12 gpm and 18 gpm). The flow rates tested were different than those of the vortex separation testing because 18 gpm was a value exceed the design flow. Thus, the performance of the core settling compartment was expected to be deteriorated.

The findings of the runs using a 60 ft² settling area demonstrated high removal efficiencies for particles larger than 100 µm. Specifically, removal efficiencies were 99.4% ± 0.0% for particles sized 100–300 µm, 99.0% ± 0.4% for 300–1,000 µm, and 99.8% ± 0.2% for 1,000–4,750 µm. In contrast, particles in the 45–100 µm range exhibited a lower removal efficiency of 95.7% ± 1.9% (Figure 31). However, this MP removal efficiency for fine particles (45–100 µm) by the settling compartment was considerably higher than those of the vortex separator of 38.2% ± 16.4%.

As flow rate increased, removal efficiencies for the 100–300 µm and 1,000–4,750 µm size classes showed a downward trend, indicating that higher flow rates contributed to particle washout. However, this trend was not observed for the 300–1,000 µm size class. Additionally, the smallest particle size group (45–100 µm) consistently showed lower and more variable removal performance compared to larger particles.

MP removal analysis for these samples and further testing of the core settling compartment (Design 1) are unavailable due to the project ending.

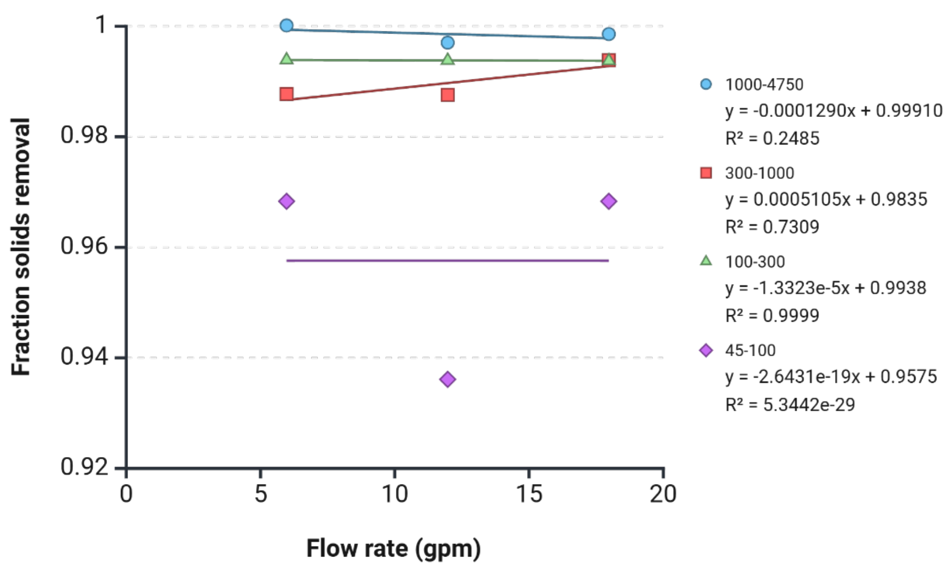


Figure 31. Solids removal efficiency tested at different and flowrates at 60 ft^2 of the core settling compartment (Design 1).

Note: The 1,000 - 4,750 µm tested at 120 ppm only due to fewer particles in 30 ppm and 60 ppm

7 Project Conclusion

Parts of the proposed scope of work were completed by the contract deadline. The available findings provide key insights to guide best practice for roadway MP management.

Critical MP size classes identified in environmental samples ranged from 45 to 1,000 µm, with particles smaller than 300 µm being more readily transported during storm events. Smaller samples contained a greater variety of polymer types. MP diversity in sweeping samples (11 polymer groups) was higher than in stormwater samples (5–6 polymer groups). A significant correlation was observed between MPs in sweeping debris and one of the stormwater runoff samples collected in March ($r = 0.79$, $p < 0.05$, $n = 11$), which indicates that roadway MPs were mobilized during the storm. Most plastic classes found in stormwater were subsets of those identified in sweeping debris. Additionally, MP diversity between the two stormwater samples was also closely aligned ($r = 0.58$, $p = 0.06$, $n = 11$). Variations in MP abundance and distribution between the stormwater samples may be attributed to storm patterns, freeway cleaning schedules, and sampling conditions. The reported MP concentrations in stormwater ranged from 83 to 157 MPs/L, with potential seasonal and spatial variability.

Furthermore, the first flush of stormwater yielded a peak concentration of fine MPs, while larger MPs arrived at the sampling location subsequently. Based on these findings, frequent roadway cleaning is recommended as a first practical step in mitigating ongoing MP pollution. Additionally, the volume of the first flush should be considered when designing MP removal systems. MPs of concern included polyolefins (polyalkenes), such as polyethylene (PE) and polypropylene (PP), as well as ‘other plastics’, which were present in large fractions in sweeping materials and were expected to be abundant in stormwater samples.

The 12 gpm vortex separator (Design 1) demonstrated a 69.7% MP removal efficiency from synthetic stormwater runoff, approaching the target MP removal goal of 70%. Higher flow rates enhanced solids separation for debris larger than 100 µm. However, the 45–100 µm size class exhibited the lowest MP removal performance, at 14.0% ± 12.7%. A multivariable linear regression model indicated that particle size was the most influential predictor of MP removal efficiency, rather than solid concentration or flow rate. These results suggest that the developed vortex separation system has limitations in removing MPs smaller than 100 µm.

The 12 gpm settling compartment (Design 1) was tested using a single settling area of 60 ft^2 under three flow rates. High removal efficiencies for particles larger than 100 µm were 99.4% ± 0.0% for 100–300 µm, 99.0% ± 0.4% for 300–1,000 µm, and 99.8% ± 0.2% for 1,000–4,750 µm. In contrast, the 45–100 µm size class had a lower removal efficiency of 95.7% ± 1.9%. When flow rates exceeded the design value, the removal performance declined for 100–300 µm and 1,000–4,750 µm size classes, while the 45–100 µm sample showed fluctuated solids removal. Unfortunately, additional settling compartment runs and downstream MP analyses for the 12 gpm core settling compartment combined with other proposed tasks could not be completed by the project’s conclusion.

The cost of laboratory construction differs significantly from field construction. In our project, plastic-free materials were used for lab-scale testing, including a stainless-steel vortex separator ($2,500) and a wooden core settling compartment ($5,000), excluding the pumping and piping systems. This led to high cost for both lab prototypes. In field applications, similar components can be constructed using materials commonly used for concrete manholes, which are considerably less expensive than the lab-scale prototypes. Concrete or cement was not used in the lab due to the need for mobility during construction and testing.

8 FINAL THOUGHTS & NEXT STEPS

MP Identification and Quantification

Blended plastics with a primary plastic content below 67% are likely to be misidentified as non-plastics, which underestimates MP abundance, particularly for mixed-material particles such as tire wear and thermoplastic stripping paints. To improve accuracy, microscopy should be complemented with FTIR, especially when identifying complex or blended plastic particles. However, microscopy has inherent size detection limits, which may further contribute to underreporting of smaller blended MPs.

Treatment System Performance

Testing results from both the vortex separator and core settling systems reveal a limitation in removing fine particles. This is a significant concern, as a large proportion of MPs are found in the smaller size range, directly affecting the system's overall MP count removal efficiency. To fully assess the system's effectiveness, the combined performance of the integrated system must be evaluated.

Non-target particles with similar physical properties (e.g., density and morphology) to MPs can also be removed by both systems. While this does not appear to interfere MP removal, it does increase the volume of settled solids, which may elevate maintenance and disposal requirements.

Plastic fiber surrogates (100% nylon, density 1.14 g/cm^3) showed lower removal efficiency in the vortex separator compared to environmental samples. This indicates a limitation in fiber removal, although fibrous MPs were rarely observed in the sweeping materials tested.

Particles of particular interest such as thermoplastic striping paint debris and tire wear particles should be separately tested to confirm the system's effectiveness in removing these common urban pollutants.

Lastly, the system footprint and configuration are preliminary and not fully optimized. Further calibration and testing are necessary to enhance performance, particularly under variable flow conditions and with diverse particle types of interest.

9 REFERENCES

9.1 Works Cited

ASTM International. (2006). *ASTM C136-06: Standard test method for sieve analysis of fine and coarse aggregates*. ASTM International.

Andrady, A. L. (2011). Microplastics in the marine environment. *Marine Pollution Bulletin, 62*(8), 1596–1605.

Boucher, J., & Friot, D. (2017). *Primary microplastics in the oceans: A global evaluation of sources*. International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2017.01.en

California Department of Transportation. *Specification for Thermoplastic Traffic Striping Material, Alkyd Resin Binder, White, and Lead-Free Yellow (PTH-02)*. California Department of Transportation, n.d., https://dot.ca.gov/-/media/dot-media/programs/engineering/documents/mets/pth-02alkyd-a11y.pdf.

California State Water Resources Control Board. (n.d.). *Microplastics in drinking water*. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html

Caltrans. (2012). *Biofiltration swale: Design guidance*. California Department of Transportation, Division of Environmental Analysis.

Cowger, W., Steinmetz, Z., Gray, A., Munno, K., Lynch, J., Hapich, H., Primpke, S., De Frond, H., Rochman, C., & Herodotou, O. (2021). Microplastic spectral classification needs an open source community: Open Specy to the rescue! *Analytical Chemistry, 93*(21), 8568–8576. https://doi.org/10.1021/acs.analchem.1c00123

Drobny, J. G. (2007). Fluoropolymers in automotive applications. *Polymers for Advanced Technologies, 18*(2), 117–121.

Frias, J., Beck, A., Regoli, F., Vollertsen, J., Ziveri, P., & Sempere, R. (2025). Sources, distribution and impacts of microplastics in the marine environment: An overview of the results of JPI Oceans projects.

Gigault, J., Halle, A. T., Baudrimont, M., Pascal, P. Y., Gauffre, F., Phi, T. L., El Hadri, H., Grassl, B., & Reynaud, S. (2018). Current opinion: What is a nanoplastic? *Environmental Pollution, 235*, 1030–1034.

Hou, D., Cui, B., Zhao, Q., Wei, D., Song, Z., & Feng, Y. (2021). Research on the structure of the cylindrical hydrocyclone spigot to mitigate the misplacement of particles. *Powder Technology, 387*, 61–71.

Iordachescu, L., Rullander, G., Lykkemark, J., Dalahmeh, S., & Vollertsen, J. (2024). An integrative analysis of microplastics in spider webs and road dust in an urban environment–webbed routes and asphalt trails. *Journal of Environmental Management, 359*, Article 121064.

Järlskog, I., Strömvall, A.-M., Magnusson, K., Gustafsson, M., Polukarova, M., Galfi, H., Aronsson, M., & Andersson-Sköld, Y. (2020). Occurrence of tire and bitumen wear microplastics on urban streets and in sweepsand and washwater. *Science of the Total Environment, 729*, 138950.

Kabir, S. M. A., Bhuiyan, M. A., Zhang, G., & Pramanik, B. K. (2024). Microplastic distribution and ecological risks: Investigating road dust and stormwater runoff across land uses. *Environmental Science: Advances, 3*(1).

Kyriakidis, Y. N., Silva, D. O., Barrozo, M. A. S., & Vieira, L. G. M. (2018). Effect of variables related to the separation performance of a hydrocyclone with unprecedented geometric relationships. *Powder Technology, 338*, 1022–1031.

Lares, M., Ncibi, M. C., Sillanpää, M., & Sillanpää, M. (2018). Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Research, 133*, 236–246.

Liu, F., Olesen, K. B., Borregaard, A. R., & Vollertsen, J. (2019). Microplastics in urban and highway stormwater retention ponds. *Science of the Total Environment, 671*, 992–1000.

Monira, S., Roychand, R., Bhuiyan, M. A., Hai, F. I., & Pramanik, B. K. (2022). Identification, classification and quantification of microplastics in road dust and stormwater. *Chemosphere, 299*, 134389.

Melville, H.W. (1949) The Science of Plastics. Nature, 163, 384–385.

Metcalf & Eddy, Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R., & Burton, F. (2014). *Wastewater engineering: Treatment and resource recovery* (5th ed.). McGraw-Hill Education.

Michielssen, M. R., Michielssen, E. R., Ni, J., & Duhaime, M. B. (2016). Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed. *Environmental Science: Water Research & Technology, 2*(6), 1064–1073.

Murphy, F., Ewins, C., Carbonnier, F., & Quinn, B. (2016). Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. *Environmental Science & Technology, 50*(11), 5800–5808.

Rodgers, B. (2020). *Tire engineering: An introduction*. CRC Press.

Österlund, H., Blecken, G., Lange, K., Marsalek, J., Gopinath, K., & Viklander, M. (2023). Microplastics in urban catchments: Review of sources, pathways, and entry into stormwater. *Science of the Total Environment, 858*, 159781.

Sadiku, R., Ibrahim, D., Agboola, O., Owonubi, S. J., Fasiku, V. O., Kupolati, W. K., ... & Ojijo, V. (2017). Automotive components composed of polyolefins. In *Polyolefin fibres* (pp. 449–496). Woodhead Publishing.

Southern California Coastal Water Research Project (SCCWRP). (2020). *Microplastic measurement methods evaluation study: Version 4.03 for participant use*. https://www.sccwrp.org/news/researchers-reviewing-data-from-international-microplastics-measurement-methods-study/

Talvitie, J., Heinonen, M., Pääkkönen, J.-P., Vahtera, E., Mikola, A., Setälä, O., & Vahala, R. (2015). Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. *Water Science and Technology, 72*(9), 1495–1504.

Vieyra, H., Molina-Romero, J. M., Calderón-Nájera, J. D. D., & Santana-Díaz, A. (2022). Engineering, recyclable, and biodegradable plastics in the automotive industry: A review. *Polymers, 14*(16), 3412.

Werbowski, L. M., Gilbreath, A. N., Munno, K., Zhu, X., Grbic, J., Wu, T., ... & Rochman, C. M. (2021). Urban stormwater runoff: A major pathway for anthropogenic particles, black rubbery fragments, and other types of microplastics to urban receiving waters. *ACS ES&T Water, 1*(6), 1420–1428.

Yano, K. A., Geronimo, F. K., Reyes, N. J., & Kim, L. H. (2021). Characterization and comparison of microplastic occurrence in point and non-point pollution sources. *Science of The Total Environment, 797*, 148939.

9.2 Preparer(s) Qualifications

Dr. Pitiporn Asvapathanagul is a professor in Environmental Engineering, Civil Engineering and Construction Engineering Management Department, California State University, Long Beach. She earned both her master's and Ph.D. degrees in Environmental Engineering from the University of California, Irvine, with a focus on water quality. Dr. Asvapathanagul started her academic career at her institute in 2012. In 2019, Dr. Asvapathanagul became a licensed Professional Engineer in the state of California. Since 2001, she has been actively engaged in the water and wastewater treatment design profession. Dr. Asvapathanagul' research centers around biological/chemical and physical pollution mitigation and water/wastewater processes.

Dr. Phil Gedalanga is an associate professor in the Department of Public Health at California State University, Fullerton. He earned his doctorate in Environmental Health Science and Policy in the laboratory of Dr. Betty Olson at University of California, Irvine and trained in biodegradation and bioremediation of groundwater contaminants as a postdoctoral scholar in the laboratory of Dr. Shaily Mahendra at University of California, Los Angeles. Dr. Gedalanga has over 20 years of experience in studying water pollution issues in both the natural and engineered environments.