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Microplastics Monitoring and Science Strategy for San Francisco Bay

2024 Revision

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Executive Summary

Microplastics are generally defined to include plastic particles that range in size from 1 nm–5,000 micrometers, though definitions vary. Microplastics also consist of a wide range of synthetic polymeric materials, such as polypropylene, polyethylene, polystyrene, tire rubber, cellulose acetate, and can include cotton and other cellulosic fibers used in apparel and textiles to which synthetic additives have been added. Microplastic can be categorized as a primary microplastic or secondary microplastic. Microplastics are a unique class of contaminants of emerging concern (CECs) because this category is inclusive of such a wide diversity of plastic particle sizes, morphologies, and polymers, and because risks are associated with both the physical particles and the chemicals they contain, resulting in new cross-disciplinary scientific challenges.

In 2016, the RMP convened the first RMP Microplastics Workgroup (MPWG), which includes representatives from stakeholder groups, government agencies, local scientists, and expert advisors. Together, the workgroup strives to protect the health of the Bay by addressing guiding management questions (MQ), revised in 2023.

> MQ1: What are the levels of microplastics in the Bay? What are the risks of adverse impacts?
>
> MQ2: What are the sources, pathways, processes, and relative loadings leading to levels of microplastics in the Bay?
>
> MQ3: Are microplastic levels changing over time? What are the potential drivers contributing to changes?
>
> MQ4: What are the anticipated impacts of management actions?

As microplastics science is rapidly developing, it is critical that the MPWG strategy continues to keep up with the developing field and apply the best available science to informing MQs.

The RMP MPWG supported the completion of landmark investigations that evaluated microplastics in Bay surface water, sediment, prey fish, bivalves, and adjacent ocean water; the study also evaluated microplastics in wastewater effluent and urban stormwater runoff, which are important pathways to the Bay. This effort led to the breakthrough discovery that concentrations in urban runoff were significantly higher than wastewater effluent, based on monitoring of stormwater from 12 small tributaries and treated wastewater effluent from 8 publicly-owned treatment works in the Bay region. Using a simple model to extrapolate loadings, SFEI estimated that annual microplastics discharges to the Bay were on the order of trillions of microplastics per year, and loadings from urban stormwater runoff were two orders of magnitude greater than from wastewater effluent. Additionally, the vast majority of particles observed in urban stormwater runoff were tire wear particles and fibers. The San Francisco Bay Microplastics study remains one of the most comprehensive regional studies of microplastics in the world, and this rich dataset provides the foundation for our understanding of microplastics in the Bay and statewide.

Subsequent findings emphasize the importance of characterizing tire wear particles in microplastics monitoring moving forward. Follow-up monitoring of urban stormwater runoff, in collaboration with researchers at University of Washington Tacoma, revealed that Bay Area stormwater contains a highly toxic chemical (“6PPD-quinone”) derived from vehicle tires at levels that are lethal to Coho salmon and may pose risks to local steelhead. Using available science, tire market and vehicle travel data, SFEI scientists estimated that 15-18 million kg of tire wear particles are generated in the Bay Area from cars and trucks driving on the road. While many of these particles may be entrained in pervious surfaces like soils or removed, SFEI’s first order calculations estimate that on the order of a million kg per year of tire wear particles are transported to the Bay annually.

The RMP has categorized Microplastics as a Moderate Concern for the Bay within the RMP’s tiered risk-based framework for CECs. There is definitive evidence that microplastics can cause harm to aquatic organisms through both physical mechanisms and chemical exposure. However, due to the diversity of physical and chemical characteristics that fit within the category of microplastics, there is still high uncertainty in our understanding of potential impacts and risks. Microplastics toxicity likely depends on multiple factors, particularly particle size and the specific chemicals that the particles contain and release. The RMP Microplastics Strategy and CECs Strategy represent coordinated efforts to investigate exposure and risks from microplastics, plastic additives, tires, and tire-derived chemicals. The multi-year plan for tires and tire-derived chemicals are centralized within the RMP’s Contaminants of Emerging Concern Strategy and Multi-Year Plan.

Understanding risks from microplastics (i.e., MQ1) is further confounded by analytical challenges. Currently, enumeration and identification of microplastics using FTIR and Raman spectroscopy remain the most widely accepted and used methods for environmental microplastic scientific studies. While spectroscopy methods are resource intensive, they provide particle-level characteristics that are important for informing both MQ1 and MQ2. Pyrolysis GC-MS is increasingly being used to complement spectroscopy analysis, and has especially useful application in the analysis of tire wear particles, which are difficult to analyze with spectroscopy methods. Pyrolysis GC-MS is a different analytical approach that can provide information about polymer composition in samples on a bulk mass basis. Current MPWG special study proposals recommend partnering with research laboratories using spectroscopy methods to analyze microplastics and prioritizing the analysis of smaller microplastics (between 10 µm –125 µm) that are challenging to characterize but also are critical data gaps in our understanding of microplastics. We also recommend complementing analysis with pyrolysis GC-MS to quantify tire-wear particles.

There are still many questions as to how best to collect microplastics in the field in a manner that is representative, practical, and cost-effective. Microplastics include such a wide range in particles sizes, densities, and shapes that can impact the fate, transport, and bioaccumulation of microplastics in abiotic and biotic matrices. This Strategy includes recommendations to pilot and improve upon previous field sampling approaches, which will inform future monitoring in the Bay.

High priority data gaps identified in this Strategy include monitoring ambient water, sediment, and urban stormwater to address MQ1 and MQ2, with a focus on addressing small microplastics and tire wear particles that were data gaps in previous monitoring efforts and where analytical methods have improved in recent years. The MPWG coordinates closely with the Emerging Contaminants Workgroup (ECWG) and Sources, Pathways, and Loadings Workgroup (SPLWG) to inform MQ1, MQ2, and MQ4, which cross workgroup focus areas. Since stormwater monitoring is an important data gap in the Microplastics Strategy, MPWG will continue to work closely with both RMP's ECWG and SPLWG to leverage their experience and staff in stormwater monitoring and modeling.

The RMP Microplastics Strategy also reflects broad coordination with regional, state, and federal efforts on microplastics. The California Ocean Protection Council (OPC) is a key agency leader in developing a vision for statewide microplastics monitoring to inform mitigation efforts as required by California Senate Bill 1263 (Portantino, 2018). While efforts to develop a statewide microplastics monitoring strategy are in the early stages of development, the RMP findings and experience can provide important lessons and context to inform and support statewide monitoring. Many of the concepts embedded in the RMP MPWG management questions are also key to management questions statewide. The SFEI microplastics team is also actively advising and collaborating with various other microplastics workgroups, researchers, and agencies to collaboratively identify key data gaps to inform management actions and develop appropriate strategies to address those data gaps. Examples of key partnerships include engagement with OPC, Southern California Coastal Water Research Project, the Moore Institute of Plastic Pollution Research, the Ocean Litter Strategy workgroup coordinate by National Oceanic and Atmospheric Administration and OPC, the California Water Quality Monitoring Council Microplastics Subcommittee, and the Pacific Northwest Consortium on Plastic Pollution Research led by Oregon State University. Knowledge gained from these external efforts will further inform RMP Microplastics Strategy and monitoring priorities moving forward.

1. Introduction

1.1 Microplastics in San Francisco Bay

In 2020, the California State Water Resources Control Board (SWB) became the first agency in the U.S. to adopt a formal definition of microplastics in drinking water, which are defined as ‘solid polymeric materials to which chemical additives or other substances may have been added, which are particles which have at least three dimensions that are greater than 1 nm and less than 5,000 micrometers (µm). Polymers that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded (California State Water Resources Control Board, 2020).

SWB adopted a broad definition of microplastics, citing the ubiquity and toxicity potential of this contaminant class and the rapidly evolving science and evolving analytical methods to understand and measure microplastics. The California Ocean Protection Council adopted this definition in the Statewide Microplastics Strategy (OPC, 2022), which focuses on microplastics in the environment. The ubiquitous nature of plastics means they are composed of a wide range of polymer types, including polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polyurethane (PU), polyethylene terephthalates (PET), polystyrene (PS), acrylonitrile butadiene styrene (ABS) and many more. Other materials, such as rubbers, cellulose acetate from cigarette filters, and cellulose-based fibers, such as rayon with synthetic additives, can fall under the broad category of microplastics. Microplastics are also characterized by their diversity in size, morphology, and color. Often, they are assigned to a morphological category that include fibers, fragments, and spheres (Rochman et al., 2019). This broad definition of microplastics is an important approach to investigating microplastics as our understanding and scientific methods improve.

In 2019, SFEI, in partnership with the University of Toronto and the 5 Gyres Institute, completed the first comprehensive regional study of microplastic pollution in the world (Sutton et al., 2019). Microplastics were monitored in the San Francisco Bay and adjacent marine sanctuaries, as well as wastewater and urban stormwater runoff pathways. This study provided a rich dataset that continues to inform our understanding of microplastics in the San Francisco Bay and major pathways to the Bay.

One of the most significant findings is the importance of the urban stormwater runoff pathway. Most microplastic studies have focused primarily on investigating wastewater as a pathway for microplastics to the environment, but our study highlighted that loadings from urban stormwater runoff can be significantly greater than from wastewater to receiving waters. This is based on the San Francisco Bay Microplastic Study (Sutton et al., 2019) findings that average microplastics concentrations in urban stormwater runoff were two orders of magnitude greater than average concentrations in wastewater, and extrapolated loadings from urban stormwater runoff were two orders of magnitude greater than expected loadings from wastewater effluent to the San Francisco Bay. The importance of urban stormwater runoff is especially important in California and in the western U.S., where stormwater collection systems discharge directly to receiving waters without treatment. Another pivotal finding was the importance of tire wear particles, which composed approximately half of the particles identified in urban runoff samples. The importance of tire wear particles as one of the dominant sources of microplastics is supported by estimates of annual tire wear emissions amounting to ~2 kg/capita in the Bay area (Moran et al., 2023) as well as other scientific studies indicating that tire wear particles are a major component of total microplastics entering the environment (Boucher & Friot, 2017; Hann et al., 2018; Kole et al., 2017; Sieber et al., 2020). In recent years, the RMP Emerging Contaminants Workgroup (ECWG), has also been leading efforts to measure several tire ingredients in urban stormwater runoff and in the Bay, as scientists have identified toxicity of various tire ingredients and transformation products, particularly the acute toxicity of 6PPD-quinone to Coho salmon (Tian et al., 2021). RMP monitoring priorities for tires and tire ingredients are described in the RMP's CEC Strategy Revision and Tires Multi-Year Plan (Sutton et al., *in preparation*).

Understanding the sources, environmental fate, and toxicity of microplastics continues to be a rapidly developing science, and while significant progress has been made, there are still significant science data gaps crucial to informing management questions for the RMP, California, and beyond. Scientists and practitioners are continuing to improve and harmonize microplastic sampling and analysis methods, which is a significant challenge considering the diversity and complexity of microplastics. For example, the monitoring approach in the San Francisco Bay Microplastic Study (Sutton et al., 2019) emphasized the use of manta trawls (using a 355 µm net), which, at the time, was the most widely used method for monitoring microplastics in surface water. Today, microplastic science is increasingly emphasizing the importance of smaller microplastics that manta trawl sampling are not designed to capture, as well as other types of microplastics that present analytical challenges, such as tire wear particles (Thornton Hampton et al., 2022).

The large scope of the San Francisco Bay Microplastics Study was made possible by generous funding from the Gordon and Betty Moore Foundation. Since the completion of this study, there are now significantly more scientists, environmental organizations, and environmental agencies, engaged in microplastics studies. Looking to the future, the RMP has many collaborators and partners in California and around the world to help identify and address the most important science questions needed to inform key management questions and decisions for the region. The California Ocean Protection Council is taking a leadership role in the state and internationally in developing a vision for California state agencies and external partners to work together to monitor and reduce microplastic pollution. The RMP can leverage opportunities to collaborate and coordinate with initiatives led by OPC and other science partners.

1.2 Report Objectives

This RMP Microplastics Strategy document has been revised as part of a continuous effort to refine approaches for supporting the management of microplastics in San Francisco Bay. The specific objectives of this report are to:

- Define the management questions that guide the RMP studies on microplastics (Section 1.3)
- Summarize the current state of the science and priority data gaps on topics most relevant to informing RMP management questions (Section 2)
- Provide recommendations for priority monitoring and data needs summarized in a multi-year plan (Section 3)

1.3 RMP MPWG Management Questions

In 2015, the RMP embarked on a small screening study to evaluate microparticles in surface water from nine Bay sites and in effluent from eight Bay Area wastewater treatment plants (Sutton et al., 2016). The detection of microparticles (Identified here as “microparticles” rather than “microplastics” because particles were visually identified without secondary spectroscopy confirmation) in Bay water and effluent galvanized interest in microplastic pollution and led the RMP to convene a workshop on the topic and to form the RMP Microplastics Workgroup (MPWG). The Workgroup is composed of representatives from RMP stakeholder groups, SFEI scientists, state and federal government agencies, nongovernmental organizations, an advisory panel of expert scientists, and interested industry representatives, including textile and garment manufacturers and consultants. The Workgroup developed management questions (MQs), which identify scientific needs and assist in the prioritization of studies that will provide information to answer these questions (Sutton & Sedlak, 2017). In 2023 the MPWG revised and approved the management questions below.

All management questions acknowledge the unique issues of microplastic quantification by using levels as the quantifying term instead of concentration, as microplastic quantities can be described in different ways (e.g., mass or particle count per unit volume or mass). Additionally, microplastic evaluations must account for the diversity of different types of microplastics, which can include descriptions of morphology (e.g., fiber, fragment, film, foam, sphere), size, and polymer type.

MQ1: What are the levels of microplastics in the Bay? What are the risks of adverse impacts?

Management question one grounds the RMP’s microplastic monitoring activities to inform risk screening evaluations for potential adverse impacts to San Francisco Bay ecosystems and other beneficial uses of the Bay. Monitoring of Bay water, sediment, and biota are needed to quantify the levels of microplastic exposure to Bay ecosystems and human health from ingestion of shellfish and fish from the Bay. As noted above, microplastics are very diverse, and evaluations of various microplastic characteristics (e.g., morphology, size, polymer type) are important for providing information about their upstream sources and toxicity. Quantification of microplastic levels in the Bay may be followed by risk screening evaluations by comparing measured levels with scientifically established ecological thresholds. There is still significant uncertainty in comparing monitoring data in the Bay with available ecological thresholds, as the toxicity data are limited to inform thresholds (See Section 2.2). Moreover, methods previously used for quantifying levels in the Bay have limitations due to collection methods and analytical data gaps (e.g. smaller sized particles and tire wear particles). Risk screening evaluations led by the RMP are scientific evaluations and are separate from regulatory decisions or risk management decisions.

MQ2: What are the sources, pathways, processes, and relative loadings leading to levels of microplastics in the Bay?

Management question two reflects the goal of tracing microplastics back to their upstream sources and pathways, providing information to guide control measures, such as source control. The RMP has developed conceptual models of microplastic transport to the Bay based on monitoring investigations and literature review, and additional information about sources, pathways, and breakdown processes is important to continue to improve the conceptual models. The process of degradation and fractionation of larger macroplastics to microplastics and microplastics to smaller size particles in Bay pathways and within the Bay may be important factors for particle transport, organism exposure and toxicity, and particle source identification and control measures. Understanding the relative loadings of different microplastics to the Bay is important to help the RMP prioritize monitoring and investigation efforts on the most important sources, pathways, and processes to utilize RMP resources efficiently.

MQ3: Are microplastic levels changing over time? What are the potential drivers contributing to changes?

Management question three explores the historical trends of microplastic levels in both pathways and the Bay. Such temporal trends may be influenced by management actions, plastic substitutions by manufacturers, and other policies; or drivers such as climate, population, socio-economic factors, and land- and water-use changes. The framing of this question acknowledges that microplastic levels may or may not increase or decrease, and compositions may or may not change. Additionally, the particle size fractions included in the evaluation can influence findings as larger particles may break down into smaller particle sizes over time. Understanding the likely causes behind trends can inform more actionable management strategies in the future.

Separate studies may be needed to answer the first and second parts of this question. While trying to understand the drivers of measured changes is important to inform future management actions, it may not always be possible to conclusively link changes in monitoring data with a specific driver when management actions and human responses may be interacting in complex ways.

MQ4: What are the anticipated impacts of management actions?

Management question four draws on qualitative and quantitative predictions of future contamination or changes in contamination levels resulting from management actions proposed by water quality managers and policy-makers. Predictions will be focused on management actions proposed and discussed by water quality managers and policy-makers and should not include hypothetical actions because it is not the role of the RMP to recommend management actions. Forecasts may be based on conceptual and numerical models and further informed by historical trends. This question is written broadly, as management actions can have positive, neutral, or negative impacts.

While forecasting future contamination from anticipated management actions is important to inform decisions, there may be significant uncertainty in predictions as future changes may be influenced by many other factors, including independent changes in manufacturing and use, population growth, and market responses that could include “regrettable substitution,” when a chemical or product is replaced by another product with problematic properties.

Figure 1: Storm flows into bioretention rain garden in San Francisco. Photo courtesy of Shira Bezalel.

2. Priority Science Updates

The purpose of this section is to briefly summarize important science developments most relevant to informing MPWG management questions. MPWG members agreed through consensus in 2023 that the high priority MPWG MQs were MQ1 (*What are the levels of microplastics in the Bay? What are the risks of adverse impacts*?) and MQ2 (*What are the sources, pathways, processes, and relative loadings leading to levels of microplastics in the Bay?*).

2.1 Improvements in Microplastic Sampling and Analytical Methods and Current Data Gaps

Considering the diversity and complexity of microplastics, as well as our expanding definition and understanding of microplastics, it is expected that methods for sampling and analyzing microplastics continue to develop and that various studies have adopted a diversity of sampling and analytical approaches. While different study objectives and resources may require different sampling and analytical methods, this also presents significant challenges in evaluating and comparing microplastic data across studies to evaluate geographic or temporal trends. OPC has prioritized support for the development of standardized approaches for sampling and analyzing microplastics as part of a broader vision of building monitoring capacity to assess microplastic pollution statewide (OPC, 2022).

2.1.1 Field Sampling Methods

Currently, there are no standardized methods for microplastic sample collection in ambient waters, sediment, biota, and urban stormwater runoff. The Southern California Coastal Water Research Project (SCCWRP) is currently funded by OPC to evaluate and facilitate the standardization of microplastic sample collection methods for ambient water, sediment, urban stormwater, and tissue. The study designs for each matrix are currently in development, and project deliverables are expected to be in the form of standard operating procedures that provide guidance on best practices for microplastic sample collection for each method. The sampling guidance may incorporate an adaptive decision tree for users to identify the best sampling approach and procedures. The sampling guidance for each matrix is led by various science partners from various institutions, and the study design to evaluate sampling methods and approaches are currently in development, with deliverables anticipated in 2026.

Field methods for monitoring microplastics in urban stormwater runoff were identified as the highest priority matrix for the SCCWRP-organized study because this matrix has the most significant data gaps. Stormwater runoff conveyance systems include diverse habitats and engineered systems, in which water, suspended sediments, and microplastics are transported under dynamic and complex flow patterns. An important data gap is an understanding of the concentration profile of microplastics in the water column during storm conditions, which is important to informing field sampling and analysis methods and interpreting results. The evaluation and development of urban stormwater sample collection methods is being led by Dr. Andy Gray from UC Riverside, and evaluation will include laboratory flume experiments to evaluate the efficacy of different sampling approaches under divergent fluvial transport modes (e.g., surface transport, washload). Results from the flume experiments will be used to inform field sampling in large river channels, such as the Los Angeles River and Coyote Creek. SFEI is engaged as an advisor on this study, coordinating with UC Riverside on stormwater sampling approaches for the Bay and sharing lessons learned.

Ambient water, sediment, and tissue matrix sampling Standard Operating Procedures (SOPs) are anticipated to be developed based on literature reviews and experiences from participating scientists in each working group formed around each matrix. The ambient water sampling workgroup is led by Chelsea Rochman from the University of Toronto. Sediment sampling is led by SCCWRP and leverages current microplastic monitoring activities in the Southern California Bight in various habitats (e.g., inner shelf, ports, embayments, marinas, estuaries). Sediment cores are being evaluated for shallow, wadable waters; this approach enables better preservation of the top 5 cm of sediment and reduces disturbance and potential loss of microplastics as the sample is lifted from the water column. For deeper water sediments, a Van Veen grab sampler is being evaluated as the most widely used approach for sediment sample collection. Discussions are still ongoing in controlling for certain factors such as outside contamination, the use of plastic or plexiglass corers in place of steel corers, and the amount of material needed. Tissue sampling approaches will be led by SCCWRP and focus on fish and shellfish.

This SCCWRP/OPC effort will be important in summarizing the best approaches for each environmental matrix, and facilitate more harmonized sample collection approaches. However, there will still be significant data gaps for field sampling, particularly for the types of microplastics that still present analytical challenges, including tire wear particles and smaller microplastics in the low µm size range.

ASTM has published a standardized practice (ASTM D8332-20) for sample collection of water samples with varying levels of suspended solids. This method was used for wastewater sample collection in an OPC funded study implemented by SCCWRP to evaluate microplastics in California wastewater. While the ASTM method, which involves passing water through a stack of stainless-steel sieves of various sieve sizes, was successfully used to collect wastewater effluent, this approach was found to be challenging for influent samples due to the need to monitor sampling equipment over the 24-hour period to prevent clogging of the sieves from suspended solids. SCCWRP, in partnership with CASA and OPC, are evaluating whether composite samples collected using automated ISCO samplers of a few liters might be appropriate for influent sample collection.

Lara Dronjack of the University Rovira and Virgili, Spain, implemented a pro bono study to analyze archived Bay sediment samples as part of her PhD work and international exchange program with the California Department of Toxic Substances Control (DTSC). Density separation methods were adapted to extract denser tire and road wear particles

(TRWP), and microplastics ranging from 25 µm to 5 mm in size were quantified. Analysis of archived sediment samples collected from the 2018 Sediment Cruise (n=8) had an average of 6.2 microplastics/g_{dw}, and the highest concentrations were observed in the Lower South Bay compared to samples from other subembayments (Dronjak et al., 2023). Analysis of two archived sediment cores collected in 2020 in the Steinberger Slough Priority Margin Unit revealed increasing concentrations in the top layers of sediment, indicating increasing trends. All sediment samples contained a mixture of polymers, and the most abundant ones that could be identified via spectroscopy included polyethylene (PE), polypropylene (PP), polyester (PES), synthetic cellulose, and 45 polyamide (PA). Rubbery black particles suspected to be TWRP were frequently observed (Dronjak et al., 2023).

2.1.2 Analytical Methods

Due to the diversity of microplastic shape, size, and polymer type, as well as the diversity of environmental matrices, an array of methods have been developed for the detection, enumeration, and identification of microplastics in the environment (Adhikari et al., 2022). Visual microscopy, Fourier transform infrared (FTIR) spectroscopy, and Raman spectroscopy are the most common analytical approaches for microplastic identification and quantification (Adhikari et al., 2022). Previous studies by SFEI (Sutton et al., 2019) have utilized FTIR and Raman for the spectral identification of microparticles in San Francisco Bay samples. Other analytical methods for the assessment of microplastics and other microparticles are in development. This section will briefly explore current and developing methods for microplastic analysis using new and existing spectroscopy and thermal analytic spectrometric techniques.

2.1.3 Spectroscopy Methods

FTIR and Raman Spectroscopy

Fourier transform infrared spectroscopy and Raman spectroscopy are two of the most commonly used methods for plastic polymer identification in microplastic analyses. Both are vibrational spectroscopic techniques and can characterize particles through their spectral fingerprints on the basis of their polymeric chemical structure, which is compared to known references or a reference library (Adhikari et al., 2022; Käppler et al., 2016). These methods are non-destructive, can be applied with high accuracy, allow for the determination of particle size distributions, and contain large polymetric reference libraries (Elert et al., 2017). Because of this, FTIR and Raman have been incorporated as standard assessments for microplastics for many types of environmental samples.

The SWB has adopted standard operations procedures for the extraction and analysis of microplastics in drinking water using FTIR and Raman (Frond & Wong, 2021; Wong & Coffin, 2021). The Environmental Laboratory Accreditation Program now offers accreditation for the analysis of microplastics in drinking water utilizing these methods. Extensive FTIR and Raman spectral libraries that include diverse plastics including weathered plastics have been developed to increase the possibility of polymer spectral identification in environmental samples. For example, microplastics from the San Francisco Bay Microplastics Study were used to add to both FTIR (FLOPP) and Raman (SLOPP) spectroscopy databases ((Frond et al., 2021); (Munno et al., 2020).

While FTIR and Raman have proven to be the current leading form of microplastic particle identification in environmental samples, there are significant data gaps and challenges with using these methods to quantify the diversity of microplastics in the environment. One of the biggest issues is the limited particle size with which FTIR and Raman can realistically handle. Because spectroscopic measurements become more difficult as particle size nears the wavelength of probing light, the lower limit for analysis is 10 µm for FTIR and 1 µm for Raman (Käppler et al., 2016; Matsui et al., 2020). A blind study of 22 laboratories from across the globe found that particle recovery and positive identification of microplastics were affected by the particle size, with particles in the smallest size fraction of >20 µm being less likely to be identified by Raman and particles >50 µm less likely to be identified by FTIR (De Frond et al., 2022). The limitation of size means microplastics in the smallest particle fraction (less than <20 µm) are rarely studied in environmental samples, limiting our understanding of the levels of these microplastics in the environment. Spectral identification is also impacted by the presence of certain chemicals, such as dyes, which can mask the spectra of the particles (Zhu et al., 2021). Anthropogenic but non-plastic particles, such as cotton, and rayon (e.g., modal, or lyocell), can produce spectra showing they are derived from cellulosic materials, but more specific material identification is not possible (Sutton et al., 2019). Most crucially, tire particles cannot be spectrally identified due to their universally black color and the presence of carbon black as an additive (Baensch-Baltruschat et al., 2020; Rauert et al., 2022). Additionally, before microplastic identification with FTIR and Raman can be applied, environmental samples must undergo extensive pre-processing to remove interfering organic materials, and analysis of individual particles through FTIR and Raman can take a significant amount of time and skill, making these methods time-consuming and expensive (De Frond et al., 2022; Elert et al., 2017).

LDIR Spectroscopy

Laser Direct Infrared (LDIR) is a chemical imaging technique like FTIR. However, while FTIR uses microscopes using a focal plane array to spread light over an area and look at multiple particles simultaneously, LDIR uses a tunable quantum cascade laser as the IR source; this helps it to target and focus on particles while ignoring empty space (Cheng et al., 2022). LDIR can produce stronger signals faster than FTIR while also avoiding the use of liquid nitrogen, making it significantly safer. As a particle quantification and identification tool, LDIR can detect particles down to 20 µm and identify their chemical composition (Bäuerlein et al., 2023). The samples undergoing LDIR do not need as rigorous cleaning and separation as samples undergoing optical microscopy, which has significant cost savings (Bäuerlein et al., 2023). Methods for microplastic identification using LDIR are being developed for wastewater treatment (Bäuerlein et al., 2023) and drinking water (Bäuerlein et al., 2022). LDIR methodology has also been used for the evaluation of microplastic pathways and sources in river water (Fan et al., 2022). The largest issue with LDIR is that it is a fairly new technology;

therefore, rigorous testing of microplastic analysis methods have not been performed on LDIR to the extent of those performed on FTIR or Raman, and SOPs have not been developed. To our knowledge, LDIR microplastic analysis is currently being offered by a single commercial laboratory, Eurofins, in Melbourne, Australia (Eurofins, 2023a). However, these capabilities are not broadly available at this time.

Microscopy and Other Spectroscopy Methods

Other commonly used spectroscopy techniques are visual microscopy, scanning electron microscopy (SEM), atomic force microscopy-based infrared spectroscopy (AFM-IR), and optical photothermal infrared spectroscopy (O-PTIR). These techniques have their advantages, such as being cost-effective (visual microscopy), having the ability to get high-resolution images of the particles (SEM), and the ability to scan the particles at the nano-scale (AFM-IR). However, these techniques may lack the ability to inform polymer identity (visual microscopy, SEM) or require significant sample pre-processing (AFM-IR, SEM) (Adhikari et al., 2022).

Visual microscopy is the simplest, most cost-effective, and most commonly used methodology for microplastics identification (Prata et al., 2019). Visual inspection of the particles allows for the classification of the particles as plastic based on their physical characteristics, such as shape, color, flexibility, and opacity (Prata et al., 2019). Size can be a difficult barrier to overcome for microscopy analysis, particularly for particles <20 μm. An inter-laboratory comparison study found low microplastics recovery (average 32% recovery) for particles <20 um among 22 participating laboratories from six countries; and the study showed that more experience and training could significantly improve precision and accuracy (Kotar et al., 2022). Classification of a particle as plastic is often up to the observer's discretion, but there are image processing programs that can assist with the morphology and counting analysis (Adhikari et al., 2022; Cai et al., 2017).

SEM uses a high-intensity electron beam and scanning of particles' surface that can obtain clear, high-resolution images of particles in the micro-sizes; paired with energy-dispersive X-ray spectroscopy (EDX) it can also be used to characterize a particle's chemical composition (Prata et al., 2019). However, additives, weathering, and surface coating due to environmental exposure can cause SEM-EDX to misidentify the chemical composition (Adhikari et al., 2022). SEM-EDX is typically used to supplement other spectroscopy methods, including visual microscopy, FTIR, and Raman spectroscopy.

AFM-IR uses an atomic force microscope to scan the surface of a particle and generate an image with a high spatial resolution as low as 50 nm, providing a possible approach for quantifying nanoplastics. AFM-IR analysis is typically used to supplement analyses using infrared spectroscopy to identify the chemical composition of a particle (Adhikari et al., 2022; Ivleva, 2021). AFM-IR has been used extensively to characterize nanoscale samples such as engineered nanoparticles, soils, and polymeric membranes (Mariano et al., 2021). However, AFM-IR is not widely used for microplastics analysis, and there are currently no standard methods for microplastic analysis using AFM-IR (Covalent Metrology, 2023).

O-PTIR is a novel molecular spectroscopy technique that allows for the nondestructive analysis of chemical information from organic and inorganic samples at the submicron level (Marchetti et al., 2022). Because the spatial resolution is determined by the visible light laser (532 nm) and not limited by the longer IR wavelength range (780 nm–1 mm), O-PTIR can achieve submicron analysis (Olson et al., 2020). Due to its contactless, nondestructive nature, O-PTIR has been used to characterize single cancer cells (Shaik et al., 2023), archeological items (Marchetti et al., 2022), atmospheric particles (Olson et al., 2020), and microplastics (Böke et al., 2022). However, O-PTIR is not widely used for microplastics analysis, and there are currently no standard methods for microplastic analysis using O-PTIR.

2.1.4 Thermal Analytical Spectrometric Methods

Pyrolysis GC-MS

Pyrolysis GC-MS methods are being developed to quantify microplastics in environmental samples, particularly to confirm black tire wear particles that are challenging to confirm via FTIR and Raman spectroscopy. Pyrolysis gas chromatography-mass spectrometry (pyrolysis GC-MS) works in a similar manner to standard GC-MS, except the sample is first introduced to a heated environment where it is heated to temperatures 500-800℃ and polymers and chemical compounds are broken into smaller stable fragments/components (Eurofins, 2023b). Polymer products are then analyzed via GC-MS, and the polymer types are identified based on the characteristic decomposition products. This approach provides information about the bulk polymer composition in the sample, and results are provided on a mass basis of quantified polymers. A key advantage of this approach is that that samples can be more rapidly analyzed in “bulk”. However, this approach does not provide particle-level information, which may be important for risk evaluation that may be based on particle counts and particle sizes. Applying both pyrolysis GC-MS and spectroscopy methods in combination to a study design can provide more comprehensive characterization of microplastics by providing data on particle and mass-based characteristics.

Pyrolysis GC-MS analysis is ideal for polymer and additive identification, such as for butadiene-based polymers, making it a perfect candidate for tire particle analysis (Unice et al., 2012).

However, pyrolysis GC-MS methods to analyze microplastics are still under development, and there are still important limitations to quantifying diverse microplastics in environmental samples. Microplastic identification is hindered by insufficient polymer data in reference libraries and interference with environmental matrices (Jung et al., 2021). Additionally, quantification of polymers requires calibration solutions for target analytes and polymers. Another significant limitation is that the instrumentation limits sample amounts to very small mass (0.1-0.5 mg) and volume (standard pyrolysis capillary diameter ~ 0.1 mm), which limits the ability to analyze bulk samples (Duemichen et al., 2019; Woo et al., 2021). Non-homogenous samples may give variable results as the distribution of particles may not be representative in comparison to the small sample size (Dierkes et al., 2019). Additionally, it is a destructive technique

(Duemichen et al., 2019; Eurofins, 2023b), so samples cannot be re-analyzed with a different method. Because Pyrolysis GC-MS outputs are on a mass basis, it can be difficult to compare to particle-based outputs common in FTIR and Raman methodologies (Hermabessiere & Rochman, 2021). The current lack of widespread use, standards, and the cost of instrument use make pyrolysis GC-MS analysis currently less feasible than FTIR and Raman for general microplastic identification and quantification.

The most promising and rapidly developing application of pyrolysis GC-MS in the field of microplastics is to identify and quantify tire-wear particles released into the environment (Rødland et al., 2022). The complex nature of tire components, additive mixtures, and the need to choose an organic marker to quantify tire particles have made method consensus difficult. During a tire's lifespan, the tire tread is abraded, forming heteroaggregates with road materials and other particles, forming tire and road wear particles (TRWPs) (Goßmann et al., 2021; Klöckner et al., 2019). Although standardized techniques for the determination of TRWP mass concentrations in soil/sediment (ISO, 2017b) and ambient air (ISO, 2017a) have been developed for pyrolysis GC-MS, the accuracy of these methods is under debate. Specifically, these ISO methods use 4-vinylcyclohexene as a marker for synthetic rubbers, styrene-butadiene rubber (SBR), and butadiene rubber (BR) concentrations (More et al., 2023). However, 4-vinylcyclohexene has been determined not to be a suitable marker, as evaluation of its concentration in comparison to SBR/BR showed no correlations (Rauert et al., 2021). Assumptions made by the ISO technical specifications assume the composition of tire tread, which could drastically under-report TRWP concentrations due to diverse tire markets and potentially diverse formulations (Moran et al., 2023; Rauert et al., 2021). This mass-based assessment of tire particle concentrations relies on assuming the composition of tire treads, which differ depending on the manufacturer and may be transformed or compounded from environmental exposure (Rødland et al., 2023). However, improving the ISO standard methods and controlling for uncertainties in tire composition could help improve concentration estimates using pyrolysis GC-MS analysis (Rødland et al., 2022). The lack of accredited TRWP standards or consensus on tire particle assessment using pyrolysis GC-MS also makes the quantification of tire wear particles in samples challenging. Currently, pyrolysis GC-MS is not widely used for microplastics analysis. While there is currently no standardized methods the analysis of microplastics in environmental samples using pyrolysis GC-MS, an ASTM International committee is working to develop standardized methods, which could expand the viability of using this method in the future.

TED GC-MS

Thermal extraction desorption coupled to gas chromatography-mass spectrometry (TED GC-MS) is another one of the most commonly used thermal desorption techniques in microplastic and tire particle identification and quantification. TED GC-MS is a mass-based method that allows for a relatively larger amount of sample to be processed (up to 100 mg) in comparison to pyrolysis GC-MS, although detection limits are lower(Ivleva, 2021). Sample processing and concentration of target microplastics may improve detection limits. TED GC-MS utilizes a thermogravimetric analyzer for sample pyrolyzation under an inert gas (usually nitrogen) and has controlled temperatureramped conditions up to around 650℃. Unlike in pyrolysis GC-MS, during the volatilization process in TED GC-MS, volatile compounds are released and then retained on a selective adsorbent filter, and only the retained compounds are introduced to the chromatographic systems, avoiding other compounds that may be present in the matrix (Sorolla-Rosario et al., 2023). However, organic matter in the sample matrix can interfere with polymer identification due to the use of the entire temperature range from 25 - 650℃, and sample processing time using this technique can be very long, making this a costly method (Ivleva, 2021). TED GC-MS is not widely used for microplastics analysis, nor are there standardized methods.

2.2 Ecotoxicity of Microplastics and Current Data Gaps for Risk Evaluation

RMP MPWG MQ1 (*What are the levels of microplastics in the Bay? What are the risks of adverse impacts?)* is the key driver for the RMP microplastics monitoring in the Bay.

The recommended approach for microplastics risk evaluation within the RMP is to be consistent with the RMP CEC Strategy (Sutton et al., 2017). For contaminants of emerging concern known to occur in the Bay, the RMP establishes priorities using a tiered risk-based framework that guides future monitoring studies and management actions. Findings from these studies then provide key data to update evaluations of potential risk and to understand the efficacy of management actions. The RMP assigns each CEC or CEC class to a tier in the prioritization framework primarily based on a risk quotient derived from available Bay occurrence data and toxicity information. A risk quotient is calculated using the 90th percentile concentration (to be protective while limiting the influence of outlier measurements) of the contaminant in a specific Bay matrix, divided by the best available toxicity threshold for this matrix. Additional human health risk quotients are also calculated for CECs that have available fish consumption thresholds. Resulting risk quotient values are compared to specified cutoff values to inform CEC placement among four tiers of concern within the risk-based framework: Very High Concern, High Concern, Moderate Concern, and Low Concern. Where lack of robust toxicity thresholds, limited occurrence data, and/or insufficient analytical method sensitivity limits the ability to calculate a sound risk quotient, contaminants are placed in a Possible Concern tier. While categorization in the tiered risk-based framework is primarily based on calculated risk quotients, additional characteristics such as persistence in relevant matrices, cumulative impacts, trends in production and use of the CEC or CEC class, and trends in Bay concentrations over time also influence the level of concern associated with each CEC or CEC class.

Microplastics are ubiquitous in San Francisco Bay water, sediment, prey fish, and bivalves, as well as in pathways to the Bay (i.e., stormwater runoff and municipal wastewater) (Sutton et al., 2019). Within the RMP's tiered risk-based framework for CECs, microplastics were initially classified as Possible Concern based on uncertainties regarding toxicity (Sutton & Sedlak, 2017). However, they were later elevated to Moderate Concern–despite continued uncertainty regarding hazard thresholds–because of several secondary factors (Sedlak et al., 2019). These secondary factors included the EU's decision to classify microplastics as a non-threshold contaminant (meaning any discharge poses a risk) for risk assessment purposes (European Chemicals Agency, 2019), the upward trend in both plastic production and environmental detection of microplastics (Azoulay et al., 2019; Jambeck et al., 2015; Lebreton et al., 2018), and the extreme persistence of microplastics in the environment and difficulty of clean up (European Chemicals Agency, 2019). This protective rationale has also been adopted by others. A working group of scientific experts convened by the California Ocean Science Trust on behalf of the California Ocean Protection Council to develop a risk assessment framework for microplastics also recommended a precautionary approach to assess the risk from microplastics and inform management and source reduction activities based on a similar rationale (Brander et al., 2021). Another example is the Science Advice for Policy by European Academies, which states that while it is unlikely that current exceedances of risk thresholds are geographically widespread, with expected increases in exposure to microplastics (Lebreton & Andrady, 2019), widespread ecological risk may arise within the next century (Science Advice for Policy by European Academies, 2019).

There is definitive evidence that microplastics can cause harm to aquatic organisms through both physical mechanisms, such as physically blocking feeding structures, impairing respiration by clogging gills or causing lacerations, and chemical mechanisms, such as eliciting an adverse immune or stress response by causing the production of reactive oxygen species, inflammation, or cell damage. However, due to the diversity of physical and chemical characteristics (e.g., sizes, morphologies, polymer types, chemical additives, sorbed chemicals, and impurities) that fit within the category of microplastics, the many microplastics toxicity studies published to date do not yet paint a clear picture of microplastics concentrations likely to cause risk to aquatic ecosystems. Evidence demonstrated by numerous laboratory studies using different combinations of organisms and microplastics with varying characteristics, such as polymer type, size, shape, and associated chemical mixtures, indicates that microplastics toxicity likely depends on multiple factors (Rochman et al., 2019). There is currently sufficient evidence indicating particle size is a critical determinant of toxicological outcomes, particularly for the mechanisms of food dilution and tissue translocation, but the effects of other particle characteristics remain unclear (Thornton Hampton, Brander, et al., 2022). Understanding microplastics toxicity and risk is further confounded by the use of differing measures of microplastics concentrations (e.g., particle number or mass per volume, rarely both) and the lack of standardized reporting of microplastics characteristics in both toxicity studies and environmental monitoring.

Despite the difficulty in understanding and harmonizing microplastics toxicity data and environmental monitoring data for risk assessment, several ecotoxicity thresholds have been proposed in the literature. For example, Adam et al. calculated predicted-no-effect concentrations (PNECs) as the fifth percentile of probabilistic species sensitivity distributions of 7.4×10^5 particles per m^3 for freshwaters, based on 53 values from 14 freshwater species (Adam et al., 2019), and 3.84×10^6 particles per m^3 for marine waters, based on 46 values from 23 species (Adam et al., 2021). San Francisco Bay surface water microplastics levels (Sutton et al., 2019; Zhu et al., 2021) are several orders of magnitude below these thresholds. However, these thresholds have high uncertainty, as they are based primarily on highest observed no-effect concentrations

(HONECs), which are highly dependent on study design (i.e., tested exposure concentrations) and are not considered as reliable as toxicity dose descriptors calculated from dose-response curves such as ECx (the estimated concentration associated with x% effect on the tested endpoint). Furthermore, these thresholds are based on toxicity testing data with particles that are not representative of Bay microplastics: primarily spheres of only a few polymer types.

In response to the State of California legislative mandates for enhanced microplastics management, a group of microplastics experts proposed a risk management framework for aquatic ecosystems that identifies four critical management thresholds, ranging from low regulatory concern to the highest level of concern where pollution control measures could be introduced to mitigate environmental emissions (Mehinto et al., 2022). This expert effort also resulted in the development of the Toxicity of Microplastics Explorer (ToMEx), an open access database and open source accompanying R Shiny web application that enables users to upload, search, visualize, and analyze microplastics toxicity data (Thornton Hampton, Lowman, et al., 2022). All studies in ToMEx have been scored by two independent reviewers according to microplastics-specific technical and risk assessment quality criteria (de Ruijter et al., 2020). Proposed microplastics toxicity thresholds for two different effect mechanisms were developed using ToMEx, ranging from 0.3–34 particles/L (0.05–6 mg/L) for food dilution, relevant for particle sizes between 1 and 5000 µm, and from 60–4110 particles/L (10–676 mg/L) for tissue translocation, relevant for particle sizes between 1 and 83 µm (Mehinto et al., 2022). While the expert group participants expressed high confidence in the proposed multi-tiered management framework and the use of species sensitivity distributions and data alignment calculations to derive these hazard threshold values, they expressed low to moderate confidence in the actual threshold estimates due to insufficiencies in the available toxicity data (Mehinto et al., 2022). San Francisco Bay surface water microplastics levels (Sutton et al., 2019; Zhu et al., 2021) sampled via manta trawl are below these thresholds, while noting that the manta trawl data only includes particles greater than 355 µm due to the 355 µm mesh net. The Bay surface water wet season microplastic average abundance was 0.003 particles/L, with a range of 0.0002 to 0.020 particles/L (Sutton et al., 2019).

Microplastic toxicity is dependent on particle size, with greater toxicity generally associated with smaller particles (Thornton Hampton, Brander, et al., 2022), yet most microplastic surface water monitoring data are based on particle sizes greater than 355 µm (the pore size of widely used manta trawl nets). Smaller microplastic particles of sizes down to 1 µm are hypothesized to be exponentially more abundant than larger microplastics (Covernton et al., 2019; Kooi et al., 2021), so current monitoring data may not accurately reflect the true exposures of aquatic organisms without being corrected for size. Particle size distribution models to extrapolate environmental monitoring data to smaller sizes not captured in environmental sampling have been proposed (Koelmans et al., 2020; Kooi & Koelmans, 2019). However, these proposed size re-alignment methods have large amounts of uncertainty, as the size distribution models are based on very limited data sets in which data were partly picked to fit the model, had limited to no QA/QC, and were relatively limited in geographic scope. Most importantly, the environmental monitoring data underlying these size distribution models were limited to

>100 µm particle sizes yet were used to extrapolate to much smaller sizes. Therefore, the current size distribution models used to rescale manta trawl data to assess microplastic risk may not accurately represent environmental microplastics, and the validity and uncertainty of using these models to conduct risk characterization is currently unknown.

These size re-alignment models were recently used to extrapolate microplastic concentrations down to 1 µm particle size from existing monitoring data for microplastics in San Francisco Bay that had a 355 µm particle size based on the manta trawl mesh size (Sutton et al., 2019; Zhu et al., 2021) to assess microplastic exposure risk using the proposed microplastics risk management framework for aquatic ecosystems (Mehinto et al., 2022). Using this approach, as well as additional rescaling to estimate fibers that were not quantified in the manta trawl samples, more than three-quarters of samples exceeded the most conservative food dilution threshold, while no samples exceeded any tissue translocation threshold with statistical significance (Coffin, Weisberg, et al., 2022). Both the particle size rescaling and fiber count adjustment introduces significant uncertainty in the estimated microplastic concentrations in the Bay and associated risk characterization. This comparison was cited in the Draft 2024 California Integrated Report, which recommends placing three waterbodies (San Francisco Bay [Lower and Central] and San Leandro Bay) in Category 3 (insufficient data and/or information to make a beneficial use support determination but data and/or information indicates beneficial uses may be potentially threatened) and four waterbodies (San Francisco Bay [South], San Pablo Bay, Suisun Bay, and a segment of the Pacific Ocean off the coast of Marin County) in Category 2 (insufficient data and/or information to determine core beneficial use support) (California State Water Resources Control Board, 2023). The draft report states that current thresholds are not suitable for assessing beneficial use support for listing a waterbody as impaired on the 303(d) list due to the uncertainty regarding input data, but there is a scientific basis to use them to inform Clean Water Act 305(b) water quality condition reporting (California State Water Resources Control Board, 2023).

New microplastics toxicity studies that could potentially help improve the quality of ecotoxicity thresholds are constantly being published. An update to ToMEx is currently underway, and the authors expect to release ToMEx 2.0 and publish associated manuscripts in peer-reviewed journals by spring 2024*.* SFEI is involved in this update. Since it was first released in the spring of 2022, the database has roughly doubled in size, as measured by the number of publications, the number of toxicity data points, and the number of species. However, the increase in data does not correspond to a significant improvement in the amount of dose-response data (as opposed to studies that use just a single exposure concentrations) or quality criteria scoring (how the publications are fit for purpose for risk assessment). New thresholds calculated from ToMEx 2.0 will still likely have to be based on no/lowest observed effect concentrations (NOECs/LOECs) rather than ECx values (this is not ideal because NOECs/LOECs are highly dependent on study design and are not as robustly comparable as ECx values). There is also still very little data on many types of particle polymers/morphologies and on more environmentally realistic exposures of weathered particles or particle mixtures. Additionally, even with these updates and improvements, some key data gaps will still remain for microplastics risk characterization because, fundamentally, the size distribution and types of microplastic particles for which there exist toxicity data are different from the microplastics that have been monitored in the environment.

Toxicity of non-microplastic particles may also be important to consider, especially in the case of fibers. Fibers are frequently the most common particle morphology detected in environmental matrices, and field studies assessing microplastics in freshwater biota have reported that fibers are the predominant particle type ingested (O'Connor et al., 2019). Natural-based anthropogenic fibers (e.g., cotton) may be just as important a driver of risk as synthetic (i.e., plastic) fibers if toxicity is driven by particle morphology or chemical additives such as dyes (Remy et al., 2015). Quantifying natural cellulosic or protein-based fibers, as well as plastic fibers, in environmental samples is therefore important due to their widespread detections (often more numerous than synthetic fibers) and potential toxicity due to their shape and associated chemical additives.

As the fiber example demonstrates, microplastic toxicity is complex and driven not just by exposure to the particles but also by the chemicals the particles contain and release. The RMP Microplastics Strategy, therefore, necessitates coordination with the CEC Strategy for understanding the impacts of chemicals in microplastics. This coordination is exemplified by the RMP's work on tire particles and tire-derived chemicals. Modeling studies estimate that tire wear may be one of the top sources of microplastic releases to the environment globally (Boucher & Friot, 2017; Hann et al., 2018; Kole et al., 2017; Sieber et al., 2020). In the San Francisco Bay Area, an estimated 1.9–2.4 kg per capita tire particles are released every year (Moran et al., 2023). These tire particles contain hundreds of chemicals, some of which are known or suspected to be toxic to aquatic organisms or to have toxic transformation products. Appropriate risk assessment of tire particles must therefore, include their known toxic chemical constituents and may need to be separate from risk assessment of other microplastics. When it rains, stormwater runoff carries micro and nano-sized tire particles—and the toxic chemicals associated with them—from outdoor surfaces to creeks and the Bay. RMP monitoring has detected tire particles and tire-related chemicals in Bay Area stormwater runoff and in San Francisco Bay during the wet season. This RMP data, in combination with new toxicity data on the tire-derived chemical transformation product 6PPD-quinone on multiple salmonid species, led the California Department of Toxic Substances Control (DTSC) to recently begin regulating motor vehicle tires containing 6PPD through their Safer Consumer Products Program (DTSC, 2023).

2.3 Linking Microplastics to Upstream Sources and Pathways

RMP MPWG MQ2 (*What are the sources, pathways, processes, and relative loadings leading to levels of microplastics in the Bay?)* is the key driver for the RMP microplastics monitoring strategy on sources and pathways, which leverages and takes a similar approach as the RMP's CEC Strategy. RMP science and monitoring can support microplastics management by informing source identification and control strategies. Microplastics can be generated from a variety of larger plastic items that can wear or disintegrate into smaller and smaller microplastics. In this context, the term source represents the original product or use from which contaminants are released, such as tires, synthetic textiles, cigarettes, and single-use plastic debris. The RMP prioritizes monitoring and investigation efforts on the most important sources, pathways, and processes to utilize RMP resources efficiently.

While tires are clearly one of the dominant sources of microplastics to the Bay and other receiving waters around the world, there are still key questions that remain about other major sources and pathways of microplastics. Identifying effective and creative control strategies for microplastics requires addressing these key data gaps on the major sources and pathways of microplastics. Here, we briefly summarize some examples of other efforts to identify the major sources of microplastics in other locations outside the Bay, which may help inform future RMP studies.

2.3.1 Identifying Microplastics Sources through Chemical Analysis

Foams such as expanded polystyrene, extruded polystyrene, polyisocyanurate insulation boards, and polyurethane spray are commonly used construction materials (Yücel et al., 2003). Release of these materials during the construction process can lead to the presence of foam from construction-related work into the environment, where it is prone to fragmentation and transport. Brominated flame retardants (BFRs) are commonly used additives to insulating construction foams and are easily identifiable in the field using X-ray fluorescence (XRF) spectrometry (Turner & Solman, 2016). Gao et al. (2023) used XRF to identify BFRs in foams in order to understand the relative contribution of foams from construction and packaging applications into the aquatic environment. Environmental samples were collected from a variety of sites across Toronto, Canada, including the quantitative and qualitative selection of foam debris greater than 2 cm x 2 cm in size from commercial streets, active construction sites, a recreational trail, a landfill, and three beaches boarding Lake Ontario. All suspected foam pieces and reference material were analyzed for the presence of bromine using XRF. Collected foam debris and litter were sorted based on their visual characteristics into distinct categories related to their suspected origin: construction, food packaging, consumer packaging, and unknown. Of the (n = 52) items in the construction category, all but one was confirmed to contain BFRs (Gao et al., 2023). For all three beach samples, a total of 372 macro-sized foam surveyed, 217 (58%) contained Br. Archived surface water and Lake Ontario water samples from 2014 underwent a similar examination for BRF foams, and of the microplastic foam particles, an average of 51% contained Br (Gao et al., 2023). Gao et al. (2023) used these results to suggest that nearly half of the plastic foam debris (macro and micro-sized) in Toronto-area waters and beaches could have originated from construction sites.

In addition to Br, other molecular signals may help identify sources of microplastics. Dr. Roxana Suehring (Toronto Metropolitan University) is leading an ambitious research effort to develop tools to identify microplastic sources using environmental forensic fingerprinting techniques. This highly interdisciplinary collaborative effort brings together international academic and industrial experts to develop an extensive analysis of microplastics using non-targeted and trace-analysis of organic plastic additives, trace-metal analysis, stable isotope analysis, and applying advanced forensic fingerprinting analysis, and the latest computational pattern recognition to identify microplastic sources. This research effort is in the proof-of-concept phase. Environment Climate Change Canada, SWB, and SCCWRP are project partners.

2.3.2 MP Sources and Pathways through Air

Microplastic research has predominantly focused on microplastic movement and effects in aquatic environments; less focus has been given to their atmospheric abundance and transport. This is an important data gap because short-range and long-range air transport is likely an important pathway for microplastics to enter and leave Bay watersheds and transport further to the Bay through urban stormwater runoff (Moran et al., 2021). Air is hypothesized to be a crucial pathway for microplastics most likely to be suspended in air, including fibers and small tire wear particles (Moran et al., 2021). To date, only three peer-reviewed studies have examined microplastic levels in ambient air within the United States; Gaston et al. (2019) and Yao et al. (2022) examined indoor and outdoor microplastic levels in Southern California and New Jersey, respectively, while Brahney et al. (2020) explored microplastic levels in remote National Parks. A comprehensive study of ambient air microplastic levels in urban areas within the United States has yet to be conducted.

Due to the lack of method harmonization for atmospheric microplastic sampling, the generation of comparable data is lacking (Nazima Habibi et al., 2022). Based on a review of 33 studies from around the world, Beaurepaire et al. (2021) concluded that microplastics in the atmospheric compartment are confirmed; however, the lack of standardization for sampling flow rates, the use of active or passive samplers, aerosolized versus dust deposition, and membrane filter pore size makes these studies only qualitatively comparable. Because of this and other factors, we do not have the data to evaluate trends for microplastics in ambient air.

Atmospheric deposition of microplastics has been profiled in remote “pristine” environments like the Pyrenees mountain region (Allen et al., 2019), the rural western periphery of Europe in remote coastal Ireland (Roblin et al., 2020), remote and protected national parks in the United States (Brahney et al., 2020), glaciers on the Tibetan Plateau (Y. Zhang et al., 2021), subterranean caves (Balestra & Bellopede, 2023), and the Arctic (Bergmann et al., 2019). Long-range airborne transport of microplastics is widely considered to be the cause of microplastic contamination in these remote, uninhabited, or low-population pristine environments (Allen et al., 2019; Bergmann et al., 2019). Particles measured in the Weser River catchment in Germany showed that particle size was a factor in their ability to be transported, with smaller particles more likely to be transported long distances than larger particles (Kernchen et al., 2022). Ambient marine aerosol samples (n=46) were collected during the Atlantic stretch of the *Tara Pacific* expedition (FL, USA to UK) and were analyzed using Raman spectroscopy for microplastics (Flores et al., 2020; Trainic et al., 2020). Particle residence time was calculated, and it was found that particle shape can also affect their transport; irregular and elongated shapes, such as fibers, can have long atmospheric residence times and be transported 1000s of kilometers (Trainic et al., 2020). In a survey of 21 sampling transects from the Pearl River Estuary to the South China Sea and East Indian Ocean, it was discovered that the long-range transport of microplastics in the oceanic atmosphere was dominated by fibers, with natural fibers making up the majority, suggesting that fibers are more easily suspended than other particle shapes during atmospheric transport and deposition (Wang et al., 2020).

There have also been evaluations of ambient air concentrations of microplastics in urban environments outside the United States. Assessment of ambient microplastic levels in London, UK (Wright et al., 2021); Beijing, Shanghai, and Dongguan City, China (Cai et al., 2017; K. Liu et al., 2019; P. Liu et al., 2022); Hamburg, Germany (Klein & Fischer, 2019); São Paulo, Brazil (Amato-Lourenço et al., 2022); Paris, France (Dris et al., 2017); and Mexico City, Mexico (Shruti et al., 2022) have found microplastics in most samples, with diverse particle types. Higher concentrations were observed closer to Beijing's urban center compared to urban peripheries (P. Liu et al., 2022; R. Zhang et al., 2023). Microplastic in atmospheric dustfall samples collected in a transect from north to south through Beijing's city rings, indicated that the densely populated central zone had 1.3 times the number of microplastics in the suburban southern zone and 9.2 times the number of microplastics in the suburban northern zone (P. Liu et al., 2022). In another study, atmospheric deposition (dry and wet) of microplastics from three ecological environments in Beijing (forest, agricultural, and urban) were measured from September 2021–February 2022 using passive samplers mounted 3–5 m from the ground (R. Zhang et al., 2023). Microplastic deposition ranged from 67–461 items/m^2-day, with the highest deposition rates happening in the urban areas and the lowest in the forest. Fibers were the most common type of microplastic, and textiles were hypothesized as their main source (R. Zhang et al., 2023). Wang et al. (2022) collected total suspended solids and atmospheric deposition samples from 32 sampling transects across the Pacific Ocean. They found that atmospheric microplastic concentrations decreased exponentially from the megacity of Shanghai, China, to the ocean. Synthetic and natural fibers were identified in many atmospheric samples, with some studies noting that natural fibers were more numerous than synthetic fibers (Cai et al., 2017; Gaston et al., 2019; Stanton et al., 2019; Wright et al., 2021).

Sources of Microplastics to Air

Tire wear particles are a major source of microplastics to the Bay based on previous monitoring indicating that over half of microplastics measured in Bay urban stormwater runoff were likely tire wear particles (Sutton et al., 2019). Global dispersion modeling of roadway microplastic deposition (dominated by tire and brake wear particles) was estimated at 279 ± 125 kt/year, with an estimated 3–7% aerosolizing into the particulate matter with diameters greater than 2.5 µm ($PM_{2.5}$) size (Evangeliou et al., 2022). While acknowledging significant uncertainty in the input data, SFEI estimated that 15–18 million kg of tire wear is produced in the SF Bay Area (Moran et al., 2023), with a small fraction transported via urban stormwater runoff to the Bay. The significance of tire wear particles as one of the dominant sources of microplastic pollution has been confirmed by other microplastic emission inventories (Boucher & Friot, 2017; Hann et al., 2018; Kole et al., 2017; Sieber et al., 2020). Roadways are a known source of ambient air pollution (Zhang & Batterman, 2013), and tire particles have been found in the $PM_{10\text{-}80}$ (particle diameters <10 and <80) particle size range close to highways (Klein & Fischer, 2019; Sommer et al., 2018). However, the relative importance of short-range, mid-range, and long-range transport of tire wear particles and other roadway microplastics has not been explored.

In the San Francisco Bay microplastic study (Sutton et al., 2019), fibers were the second most common class of microplastic observed in urban stormwater runoff and were often identified as polyester or cellulose acetate. Household and commercial textile washing and drying in washing machines and tumble-vented dryers have been shown to release a considerable amount of both synthetic and natural fibers (Kärkkäinen & Sillanpää, 2021; Tao et al., 2022). SFEI scientists have hypothesized that tumble air dryers may be a significant source of microplastics to urban stormwater runoff. Currently, no appropriate studies are available to estimate the relative importance of tumble dryers as a source of microplastic fibers to ambient air. SFEI, with study partners at the Desert Research Institute and 5 Gyres Institute, was recently funded by the OPC and Sea Grant to implement a 2-year study to test this hypothesis. Results from this study are anticipated in 2025.

Several studies have assessed the difference in concentration between indoor and outdoor ambient air microplastic concentrations (Amato-Lourenço et al., 2022; Dris et al., 2017; Gaston et al., 2019; Liao et al., 2021; Yao et al., 2022) and found indoor microplastic concentrations to be far higher than outdoor levels. Microplastics indoors can be vented outdoors and become a pathway to microplastics outdoors (Moran et al., 2021).

Biosolids have also been hypothesized to be an important source of microplastic pollution to the air because biosolids contain high concentrations of microplastics and are often applied to agricultural soils (Crossman et al., 2020; Golwala et al., 2021). Crossman et al. 2020, examined agricultural biosolids application in Canada, estimated that 3.7 billion microplastics were introduced to a single field during one biosolids application. Air transport is hypothesized to transport microplastics from agricultural fields with biosolid amendments, although this has yet to be studied (Heerey et al., 2023).

Microplastics from the ocean ejected from the sea when trapped air bubbles burst are also being explored as a source of ambient atmospheric microplastics (Allen et al., 2020; Trainic et al., 2020). A pilot study by Allen et al. (2020) examining sea mist coming onshore from the Atlantic found microplastic coming from and going to the ocean. Further investigations are needed to see the net impact of these interchanges and the potential for the long-range transport and resuspensions of microplastics from the ocean.

Landfills (Loppi et al., 2021) and recycling centers (Brown et al., 2023) have been noted as potential additional sources for microplastic environmental discharge, but the magnitude of their contribution to atmospheric microplastic emissions has yet to be fully explored.

3. Strategy for Future Work and Multi-Year Plan

3.1 Coordination Strategy with Related Monitoring and Management Efforts

Collaborations and leveraging resources with key partners is an important and necessary component of the RMP strategy to address MPWG MQs, considering the significant resources needed to address major science data gaps to understand and manage microplastics contamination. There are scientists, state and federal agencies, and non-government organizations at the state, national, and international level engaged in microplastics research. This is a brief and non-comprehensive summary of relevant microplastics efforts and groups that SFEI is actively engaged with that is meant to provide a short sketch of the many efforts and discussions on microplastics, particularly within California.

SFEI staff and RMP MPWG stakeholders are closely engaged with the RMP Emerging Contaminants Workgroup (ECWG) and Sources, Pathways, and Loadings Workgroup (SPLWG) and working to identify opportunities to leverage efforts. For example, the ECWG and SPLWG are building up their monitoring and modeling capacity of CECs in urban stormwater runoff. We are identifying opportunities where these efforts can also inform microplastics monitoring in urban stormwater runoff. Monitoring of tire and roadway contaminants in urban stormwater runoff and in the Bay are incorporated in the CEC Strategy and Status and Trends monitoring, which will also inform MPWG's understanding of levels of monitored tire chemicals in the Bay. We also engage with leading microplastics scientists who serve as science advisors for the RMP MPWG.

SFEI is currently funded by OPC to facilitate the development of a statewide plastics monitoring strategy, which is in the very early stages of formulation. The guiding management questions and objectives for the strategy development are currently being identified through a half-year effort to gather feedback from state and federal agencies, a technical advisory committee, Tribes, non-government organizations, communities, and public individuals, to understand the priority management questions and information needs. After priority management questions have been identified in early 2024, SFEI and project partners will draft a written report that articulates a clear vision and framework for monitoring macro- and microplastics in the environment. Through this 2-year project, SFEI will be coordinating with state agencies and monitoring programs throughout the state to understand the information needs, resources, and expertise that can be leveraged for future implementation of the monitoring plan. State agencies that SFEI is coordinating with include the SWB, California Air Resources Board, California Department of Toxic Substances Control Safer Consumer Products Program, California Coastal Commission Marine Debris Program, California Department of Public Health, California State and Regional Water Boards, CalRecycle, Office of Environmental Health Hazard Assessment, Caltrans, and NOAA Marine Debris Program. These agencies actively participated in an August kick-off meeting for the project, and participating in this state advisory group continues to be open to engagement from other state agencies. SFEI will also engage with California Water Monitoring Council stakeholder groups, which already has an active stakeholder group collaborating and regularly sharing information and efforts on microplastics.

OPC is a key agency leader in developing a vision for a statewide microplastics strategy and establishing a goal of developing a future statewide plastics monitoring network. OPC, NOAA, and California Sea Grant have recently provided important research funding for microplastics. A recent microplastic funding opportunity jointly issued by OPC and California Sea Grant solicited proposals on research priorities. This was a rare opportunity for funding to investigate major sources and pathways of microplastics to inform management actions. SFEI and project partners Desert Research Institute and 5 Gyres Institute are funded to investigate whether clothing dryers are a major source of microplastics. OPC and NOAA also jointly organize the Ocean Litter Strategy (OLS) Workgroup that engages groups across the state to support the coordination of efforts most relevant to OLS priorities, which includes microplastics research gaps.

SCCWRP is an active leader in supporting SWB microplastics monitoring method development. SCCWRP led a microplastics inter-laboratory comparison study from which results were used to develop Standard Operating Procedures for analysis of microplastics in drinking water and other matrices (De Frond et al., 2022; Thornton Hampton et al., 2023). SCCWRP also led the health effects workshop that gathered experts from around the world to develop ecotoxicity and human health thresholds for microplastics (Coffin, Bouwmeester, et al., 2022; Mehinto et al., 2022). An important part of this effort included the development of the ToMEx open access database and web application for microplastics toxicity (Thornton Hampton, Lowman, et al., 2022); SCCWRP maintains ToMEx and is currently leading the ToMEx 2.0 effort. Currently, SCCWRP is funded by OPC and SWB to develop SOPs for field sampling microplastics (See Section 2.2.1). SCCWRP also funded by OPC on a project to measure microplastics in California wastewater. SCCWRP is also the coordinating and implementing organization for the Southern California Bight monitoring program. In 2023, for the first time, this monitoring program will be monitoring microplastics in Bight sediment and shellfish. SFEI is a collaborator or advisor on most of these efforts.

Oregon State University (OSU) is the lead on the Pacific Northwest Consortium on Plastics Pollution Research, an NSF-funded collaboration between regional scientists, regulators, and community coalitions to compile data on micro- and nanoplastics occurrence, transport, breakdown, and effects on aquatic species to support decision-makers. SFEI is a member of this consortium. OSU is performing cutting-edge toxicity research and actively engages in wide ranging work on microplastics, including actively engaging in MPWG meetings.

Moore Institute of Plastic Pollution Research (MIPPIR) has developed a state of the science laboratory to analyze microplastics and is on the path to becoming the first laboratory to be accredited by ELAP for microplastics in drinking water. MIPPIR is leading an important project to develop the first open-source data analysis and data-sharing portal in the state, which is meant to address a key challenge in sharing and reporting microplastics data that requires a large and complex multivariate dataset. The pilot phase of the Open Data Portal is funded by the Possibility Lab, and the data portal will be a central reporting hub for microplastics monitoring in drinking water source waters required by the SWB. The long-term ambitious vision for the Open Data Portal is to develop the portal for microplastics data for other environmental matrices so that government regulators, regulatees, academics, and the general public can use this platform to make sense of the prevalence of microplastics in their environment. SFEI and SWB are key partners in this effort.

SFEI has engaged with USEPA through various topics, including providing advice on tire research needs and providing comments on related microplastic reports, including the Draft Report on Microfiber Pollution (NOAA, 2011) and Draft National Strategy to Prevent Plastic Pollution[1].

3.2 Future Monitoring and Special Study Recommendations

MPWG members agreed through consensus in 2023 that the high priority MPWG MQs were MQ1 (*What are the levels of microplastics in the Bay? What are the risks of adverse impacts*?) and MQ2 (*What are the sources, pathways, processes, and relative loadings leading to levels of microplastics in the Bay?*). Table 1 shows an updated multi-year plan that emphasizes high-priority science needs to address MQ1 and MQ2 in the next few years. We will continue to develop a longer-term multi-year plan based on key findings from these short-term priorities as well as ongoing science developments and development of a statewide monitoring strategy (anticipated multi-year plan in 2026).

MPWG Strategy is crucial to supporting SFEI staff efforts to track the most relevant scientific information that will inform the RMP, responding to requests for information from the Water Boards and other stakeholders, and staying engaged with science partners and collaborators to identify the essential data gaps for informing management questions and leveraging activities and funding opportunities.

3.2.1. High Priority Data Gaps

Ambient Water Monitoring

Although our previous monitoring in San Francisco Bay (Sutton et al., 2019) remains one of the most comprehensive microplastics monitoring data sets, most of the Bay water monitoring were collected by manta trawl using 355 µm mesh nets, which underestimates the abundance of microplastics smaller than the mesh size. Science developments since then have highlighted the importance of the smaller size particles due to their relative abundance and potential toxicity compared to larger size particles. Due to the sampling and analytical challenges with accurately quantifying smaller microplastics (e.g., <100 µm), many environmental sample analyses continue to omit the smaller size fraction. Particle size distribution models to extrapolate environmental monitoring data to small sizes not captured in environmental sampling have been proposed by Koelmans et al. (2020) and Kooi and Koelmans (2019), but the datasets

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[1] https://www.epa.gov/circulareconomy/draft-national-strategy-prevent-plastic-pollution

used to fit these models were based on very limited data sets in which data were partly picked to fit the model, had limited to no QA/QC, and were relatively limited in geographic scope.

There is a significant need to evaluate microplastic particles smaller than 355 µm to address MPWG MQ1 (*What are the levels of microplastics in the Bay? What are the risks of adverse impacts?).* Analysis of particles smaller than 355 µm down to the smallest feasible size limit (e.g., 20 µm) is necessary to assess the validity and uncertainty of using these particle size distribution models to conduct risk characterization. Additionally, this data would improve our understanding of microplastic levels in the Bay and distribution of particle types by quantifying these smaller particles that were not evaluated previously. Understanding the particle size distribution will also help inform future RMP monitoring and study design and science needs. This study would also directly inform similar types of questions for the rest of California, and inform statewide monitoring questions and approach. We recommend a special study to collect and evaluate the size distribution of San Francisco Bay surface water microplastics to inform more accurate estimates of microplastic levels in the Bay and future exposure assessments. In addition, this study will help evaluate field sampling methods to better design future monitoring efforts. It is important to work closely with the analytical laboratory to quantify microplastics down to the smallest feasible size limit.

Sediment Monitoring

While previous sediment sampling in the Bay was not limited by mesh size, particles extracted for microplastic analysis in the laboratory were limited to 45 µm, which was the smallest sieve size used to wet sieve particles. Most importantly, sediment extraction procedures were not optimized for tire wear particle analysis, and methods (See Section 2.2.2) are currently in development to quantify tire wear particles. Despite these data gaps, there was an abundance of black fragments that were suspected to be tire particles.

We recommend a special study to collect and evaluate microplastics in San Francisco Bay sediment that includes quantification of tire wear particles and other microplastics smaller than 45 µm to inform more accurate estimates of microplastic levels in the Bay and future exposure assessments. Previous analytical methods underestimate the levels of microplastics in Bay sediment, and our understanding of the composition of microplastics in sediment could improve based on a more thorough investigation. It is crucially important to work closely with the analytical laboratory to quantify microplastics down to the smallest feasible size limit and include approaches appropriate for quantifying tire wear particles.

Stormwater Monitoring

One of the critical findings from the San Francisco Bay Microplastics Project was the identification of urban stormwater runoff as the major pathway for microplastics entering the Bay. More recent investigations on the sources and pathways of microplastics revealed that tire wear particles and other smaller microplastics were undercounted in previous investigations due to limitations in collection and analytical methods. In addition, while depth-integrated sampling was prioritized for the 2019 study to better characterize microplastics in the full water column, this approach requires considerable labor resources relative to stormwater samples collected at a single depth, which is a more likely sampling scenario for any kind of automated sampling program. There are currently important efforts underway to improve and inform our approaches for monitoring microplastics, including an RMP special study to pilot field collection methods and particle size distribution analysis of microplastics in urban stormwater, as well as a UC Riverside/SCCWRP led study to evaluate methods for monitoring urban stormwater (See Section 2.2.1). Simultaneously, the RMP is undergoing significant efforts to build up stormwater monitoring and modeling capacity for CECs. Depending on the results of these current sampling evaluation efforts indicating whether CEC stormwater monitoring approaches could be used for microplastics, this could open up many more opportunities to monitor microplastics.

Due to the importance of urban stormwater runoff as a pathway for microplastics to enter the Bay, we emphasize the importance of continuing to monitor microplastics in urban stormwater runoff to address MPWG MQ2 (*What are the sources, pathways, processes, and relative loadings leading to levels of microplastics in the Bay?).* Understanding the sources of microplastics, as well as their dominant transport pathways to the environment, is crucial to informing microplastics management strategies and policies to direct actions to reduce contamination. Data on microplastic characteristics such as polymer composition, color, size, and morphology are commonly collected to provide clues as to their potential sources.

We expect findings and lessons learned about microplastics in urban runoff in the San Francisco Bay can be extrapolated and inform our understanding of other dense urban areas in California.

3.2.4. Other Data Gaps

Tires

The multi-year plan for tires and tire-derived chemicals are centralized within the CECs Strategy and multi-year plan. The Tires Multi-Year Plan is guided by the priority Tires MQ: Do tire particles or chemicals have the potential to adversely impact beneficial uses in San Francisco Bay? Measurement of tire rubber and priority tire additives in stormwater, Bay water, and sediment would provide important information about the total amount of tire material in water and sediment. These data would make it possible to determine the relevance of the growing body of tire particle toxicity data indicating the potential for adverse effects to diverse aquatic organisms at concentrations that could potentially occur in the Bay ecosystem. Data on tire chemical indicators could be used for benchmarking purposes (comparison to other studies) and to explore more cost-effective options for future monitoring related to tires. Scientific methods for implementing this type of study are in development (See Section 2.1), and could build upon sampling and analytical methods applied to microplastic high priority studies identified above. This special study is incorporated in the ECWG Multi-Year Plan and not included in the Microplastics Multi-Year Plan.

Microplastic Additives

Science developments on microplastics, especially tire wear particles, have emphasized the importance of considering the impacts of microplastics due to their particle characteristics AND chemical ingredients. Microplastics can expose organisms to potentially harmful chemicals, especially plastic-associated contaminants, and additives such as flame retardants, plasticizers, or dyes (Fries et al., 2013; Rochman et al., 2019). Micro- and nanoplastics and the potentially harmful plastic chemical ingredients and additives they contain can also be transferred up food chains (Athey et al., 2020; Carbery et al., 2018; Chae et al., 2018; Chagnon et al., 2018; Farrell and Nelson, 2013; Mattsson et al., 2017; Setälä et al., 2014; Tosetto et al., 2017). Many plastic-associated chemicals of concern are also chemical classes prioritized for monitoring in the CEC Strategy. We recommend future special studies jointly study microplastics and associated plastic ingredients to evaluate the role microplastics play in the transport and exposure of priority CEC contaminants in the Bay.

Air Monitoring

Small microplastics, particularly fibers, are often transported in the air compartment via short-range and long-range transport before being transported to urban runoff via wet or dry deposition on the urban landscape. While air is increasingly recognized as an important transport pathway for microplastics, there are no peer-reviewed published studies of microplastics levels in air in California. Tire and road-wear particles, in particular, are likely subject to local and long-range transport and are an important source of airborne particulates. Agencies such as the California Air Resources Board are identifying research needs to understand exposure to airborne particulates, particularly tire-wear particles near roadways. We recommend a special study to evaluate the relative importance of long-range microplastic transport (e.g., carried in air currents from Asia and re-emitted from the ocean into coastal air) as compared to local sources to urban runoff. This is an important question to inform the impacts and efficacy of local, state, or international management actions to address microplastics.

MULTI-YEAR PLAN FOR MICROPLASTICS: September 2023

Microplastic studies and monitoring in the RMP from 2020 to 2026. Numbers indicate budget allocations in $1000s. Budgets in parentheses represent funding or in-kind services from external sources (e.g., SEP funds). Budgets that are starred represent funding that has been allocated within other workgroups. Bold boxes indicate multi-year studies. Items shaded in yellow are considered high priority.

Element	Study	Funder	Questions Addressed	2020	2021	2022	2023	2024	2025	2026
Strategy	Microplastic Strategy	RMP Patagonia/OPC	1,2,3,4	20 (30)	10	37	13 (50)	16 (100)	17 (50)	17
	Tires Strategy (ECWG)	RMP	1,2			25.5	10*	10*	10*	10*
Bay Monitoring	Bivalves	RMP	1,3							
	Fish	RMP	1,3							
	Sediment	RMP/OPC U. Rovira I Virgili	1,3		3.5		(15)			40
	Water	RMP/OPC	1,3						65	
Characterizing sources, pathways, loadings, processes	Wastewater	SCCWRP/OPC	1,2,3		(26)					
	Stormwater	RMP OPC	1,2,3					68	51	*(40)*
	Stormwater Conceptual Model	RMP OPC	1,2,4	30 (30)	30 (90)					
	Evaluating efficacy of rain gardens	SFEP/EPA	2,4			(62)	(62)	(62)		
	Investigating clothing dryers as a source	Sea Grant/OPC	2,4					(170)	(230)	
	Air monitoring	RMP OPC/Sea Grant/NOAA	1,2							(40)
	Assessing Information on Ecological Impacts	RMP NSF/CCCSD	1	(50)	18 (7.5+50)					
	Characterize microplastic additives	RMP ECWG	1,4						120*	
	Tire market synthesis to inform science (pro bono)	UC Berkeley	1,2,4			(20)				
			RMP-funded Special Studies Subtotal – MPWG	**50**	**61.5**	**62.5**	**13**	**84**	**133**	**57**
			High Priority Special Studies for Future RMP Funding						**116**	**40**
			RMP-funded Special Studies Subtotal – Other Workgroups				**10**	**10**	**130**	**10**
			MMP & Supplemental Environmental Projects Subtotal							
			Pro-Bono & Externally-funded Special Studies Subtotal	**110**	**173.5**	**82**	**127**	**332**	**280**	**80**
			OVERALL TOTAL	**160**	**235**	**144.5**	**140**	**416**	**413**	**137**

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