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Microplastic Strategy Update

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Microplastic Strategy Update

On behalf of the Regional Monitoring Program for Water Quality in San Francisco Bay

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Executive Summary

Based on the detection of microplastics in San Francisco Bay surface water and Bay Area wastewater effluent in 2015, the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) convened a Microplastic Workgroup (MPWG) in 2016 to discuss the issue, identify management information needs and management questions (MQs), and prioritize studies to provide information to answer these management questions. The MPWG meets annually to review on-going microplastic projects and to conduct strategic long-term planning in response to new information in this rapidly evolving field.

The MPWG guiding management questions are:

- MQ1: How much microplastic pollution is there in the Bay and in the surrounding ocean?
- MQ2: What are the health risks?
- MQ3: What are the sources, pathways, loadings, and processes leading to microplastic pollution in the Bay?
- MQ4: Have the concentrations of microplastics in the Bay increased or decreased?
- MQ5: Which management actions may be effective in reducing microplastic pollution?

In 2017, the RMP's Microplastic Monitoring and Science Strategy for the San Francisco Bay (Sutton and Sedlak 2017) outlined a multi-year plan identifying the need for studies including: developing robust methods; monitoring biota such as prey fish, bivalves, and sport fish; monitoring water and sediment; characterizing sources, pathways, loadings, and processes including stormwater and effluent monitoring; developing a transport model; evaluating policy options; assessing chemical composition of microplastics; and presenting the findings to scientists and managers.

In this nascent field with new findings published almost daily, the Strategy is designed to be a living document that is updated periodically. This Strategy Update includes a short summary of recent findings from the San Francisco Bay Microplastics Project - a major monitoring effort in the Bay - and an updated multi-year plan based on the newly acquired knowledge and current management needs.

In addition, one of the goals of the Microplastic Strategy, as well as the RMP's Contaminants of Emerging Concern (CECs) Strategy (Sutton et al. 2017), is to prioritize pollutants based on relative risk. (Microplastics are considered a class of CECs.) The RMP prioritizes CECs observed in the Bay via a tiered, risk-based framework, using available ecotoxicity thresholds and other information. This prioritization framework serves as a decision-making guide for future monitoring activities and management actions. Prioritizing chemicals into risk-based tiers allows us to focus our resources on contaminants that present the highest risk to the Bay.

The European Union (EU) has recently proposed a determination that there is no safe threshold for the release of microplastics into the environment. Based on this EU risk assessment, the difficulty in remediating this type of pollution, and the upward trend in plastic production and detection in the environment, this Update presents the rationale for elevating microplastics from Possible Concern to Moderate Concern for the Bay in the tiered, risk-based framework. The MPWG approved this change in classification at the May 2019 Microplastic Workgroup meeting.

1. Introduction

1.1 Definition of Microplastics

Microplastics are commonly defined as plastic particles smaller than 5 mm in at least one dimension (Thompson et al. 2009; Masura et al. 2015; GESAMP 2016). The lower size limits of microplastics are often operationally defined, with surface water trawl samples typically limited to particles between 5 mm and 0.355 mm (a typical mesh or sieve size), while other methods may be able to detect smaller particles. Particles smaller than 0.0001 mm are generally defined as nanoparticles (Thompson et al. 2009); these tiny particles are beyond the scope of this document.

There are considerable analytical challenges associated with determining whether microscopic particles recovered from environmental samples are, in fact, plastic. To provide a clear and transparent indication of the level of certainty regarding the composition of these particles, in this Update and other materials we use two different terms:

- **Microparticles** - particles identified visually as likely to be plastic. Many early microplastic studies used microscopy alone to identify and quantify microplastics. Subsequent studies have indicated that such visual techniques can result in misidentification of some non-plastic particles as plastics, demonstrating the need for additional analytical approaches to confirm the composition of particles.
- **Microplastics** - particles that have been confirmed to be plastic through techniques such as Raman or Fourier Transform Infrared (FTIR) spectroscopy. Due to the high numbers of particles detected and resource constraints, we were not able to perform spectroscopic analysis on every microparticle collected as part of the San Francisco Bay Microplastics Project. The need to communicate transparent and robust findings based on all *microparticles* as well as the subset of spectroscopically confirmed *microplastics* led to development of these definitions.

Microplastics are a chemically and physically diverse contaminant class. Differences in the characteristics of individual microplastics can affect the way they move through the environment, and may affect their potential for toxicity (Wright et al. 2013). For example, the term “plastics” encompasses materials made up of a broad range of polymers, including polyethylene (PE), polypropylene (PP), polystyrene (PS), nylon (polyamide), polyethylene terephthalate (PET or polyester in the case of fibers), acrylic, polyvinyl chloride (PVC), and natural and synthetic rubber (Hidalgo-Ruiz et al. 2012; GESAMP 2016). Many of these polymers have chemical additives to enhance the performance of the plastic, including flame retardants and plasticizers. Plastic polymers and monomers, as well as plastic additives, are the chemical components of microplastic contamination (Fries et al. 2013).

Microplastics come in a broad range of shapes (Figure 1). Particles are commonly classified in five different shape or particle type categories, which can provide insights as to the source of individual particles (Free et al. 2014; McCormick et al. 2014):

- Fragment – irregular, non-spherical particle; may result from the breakdown of larger plastic debris;
- Fiber – thin or fibrous plastic; may originate from textiles as well as fishing gear and cigarette filters; may be found in a bundle of fibers of similar or differing chemical composition and color;
- Sphere/Pellet – hard, rounded, or spherical particle; may originate from pelletized pre-production material for plastic, or from microbeads intentionally added to consumer products;
- Film – thin plane of plastic; may result from breakdown of larger plastic films, such as plastic bags and wraps; and
- Foam – lightweight, sponge-like plastic; may come from breakdown of foam plastic debris.

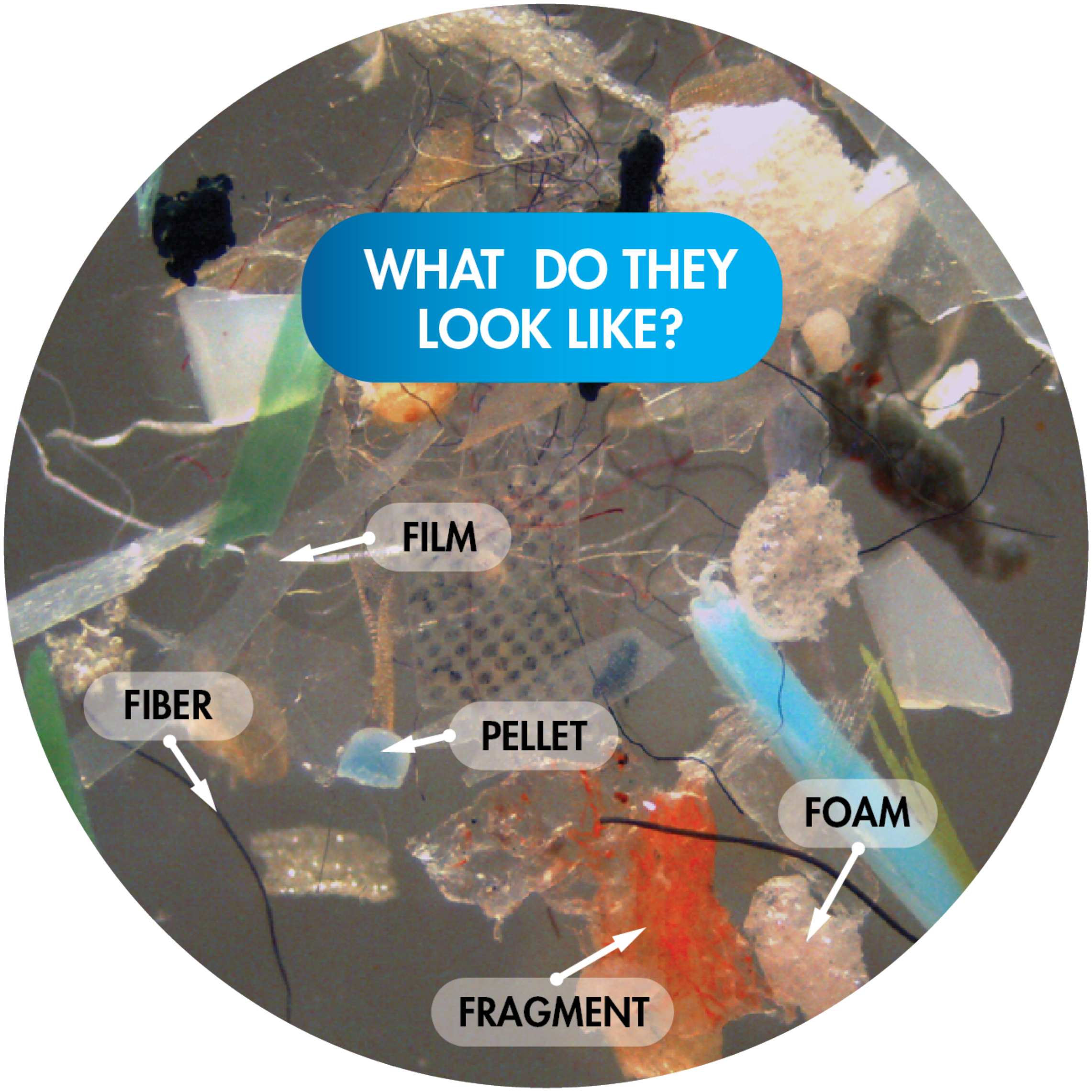

Figure 1. Microscope view of microplastic types collected from a single surface water sample in San Francisco Bay (Sutton et al. 2016). Photo courtesy of Dr. Sherri A. Mason.

1.2 Management Questions to Guide the Microplastic Strategy

In 2015, the RMP embarked on a small screening study to evaluate microparticles in surface water from nine Bay sites and effluent from eight Bay Area wastewater treatment plants (Sutton et al. 2016). The detection of microparticles, not all of which were known to be plastic because particles were visually identified without secondary spectroscopy confirmation, in the 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 Microplastic Workgroup (MPWG). The Workgroup is composed of representatives from RMP stakeholder groups, regional 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.

The MPWG guiding management questions are as follows.

- MQ1: How much microplastic pollution is there in the Bay and in the surrounding ocean?

This question encompasses two issues: firstly, the development of appropriate methods for characterizing microplastic pollution, including field collection methods and laboratory extraction and analytical procedures; and secondly, the presence and abundance of microplastics within the abiotic and biotic Bay and ocean environments. Based on the work to date, we have learned a great deal about successful field collection and laboratory methods and have begun to provide information to answer the question of how much microplastic pollution is in the Bay.

- MQ2: What are the health risks?

This question addresses risks to humans and aquatic life from microplastics. Risks to aquatic life include physical impacts such as blockages in the digestive tract, as well as impacts associated with chemical exposures from the constituents in plastic or from contaminants adsorbed to the plastic. Risks are likely to vary among species, and with plastic type, particle shape, and size. Limited information is available regarding toxicity thresholds for microplastics and there is an urgent need for this information to evaluate the occurrence data generated to date. A recent EU risk assessment suggests there is no safe level of discharge (ECHA 2019).

- MQ3: What are the sources, pathways, loadings, and processes leading to microplastic pollution in the Bay?

This question addresses potential sources, pathways, and processes by which microplastics are introduced to the Bay. To date, we have evaluated stormwater and wastewater effluent as potential pathways; however, it is likely that other pathways, including air deposition and the release of materials through spills or dumping, all contribute to microplastic loads in the Bay. Evaluating the potential sources and pathways of microplastics and their relative contribution may aid in identifying management actions.

- MQ4: Have the concentrations of microplastics in the Bay increased or decreased?

This question addresses long-term temporal trends, supporting the goal of understanding the forces that lead to any identified trends, including changes in sources (e.g., consumer use or product redesign) and management actions (e.g., bag bans or implementation of green stormwater infrastructure). Trends may vary with particle type, reflecting different sources or pathways. Recent monitoring establishes baseline levels that can be used to track trends in microplastic concentrations in the Bay and assess the efficacy of management actions.

- MQ5: Which management actions may be effective in reducing microplastic pollution?

This question explores alternatives for reducing contamination. Source control is typically found to be the most effective and least expensive pollution prevention option, and may be the primary tool applied to reduce microplastic pollution. The federal ban on plastic microbeads in rinse-off personal care products that was implemented in 2018 is one example of microplastic-specific source control.

However, the sources of microplastics to the environment are diverse, and different sources or particle types may be more amenable to source control than others. As part of the San Francisco Bay Microplastics Project (Section 1.3), the 5 Gyres Institute has developed a solutions document that identifies recommended management actions (Box and Cummins 2019). The solutions document is informed by the results of the Project's scientific studies.

In addition, the Project includes development of a Bay and open ocean transport model for microplastics. Future applications of the model may provide insights on the potential impacts of management actions.

1.3 San Francisco Bay Microplastics Project

Coincident with the development of the Microplastic Strategy in 2016 (Sutton and Sedlak 2017), SFEI and 5 Gyres received approximately $1 million in funding for a microplastic study, primarily from the Gordon and Betty Moore Foundation, with the RMP and others augmenting this grant. This funding enabled SFEI and 5 Gyres to undertake the first two years of the multi-year plan outlined in the Microplastic Strategy, including: baseline characterization of surface water, sediment, and prey fish; evaluation of wastewater and stormwater pathways; development of a Bay and coastal California transport model; and assessment of policy options.

In October 2019, SFEI and 5 Gyres presented findings from the study in a summary report; a solutions document, an action sheet, and at a symposium; scientific publications in peer-reviewed journals are forthcoming. Highlights from the San Francisco Bay Microplastics Project (Sutton et al. 2019) are presented in Section 2 to help identify data gaps and inform an updated multi-year plan.

1.4 California Initiatives on Microplastics in 2018

In the fall of 2018, Governor Jerry Brown signed two bills, the first one to monitor microplastics in drinking water, and the second to outline a microplastic research and monitoring strategy. Senate Bill 1422 (Portantino) requires the State Water Resources

Control Board (State Water Board) to develop methods to monitor public drinking water supplies for microplastics and to require testing and reporting of the results. Senate Bill 1263 (Portantino) directs the Ocean Protection Council to prepare a Microplastic Strategy for the State of California that includes: a prioritized research plan; development of standard methods for microplastic monitoring; characterization of microplastic concentrations in ambient surface waters; development of a risk assessment framework; and recommendations for policies to mitigate and reduce microplastic pollution. The Ocean Protection Council will collaborate with the State Water Board, the Office of Environmental Health Hazard Assessment, and scientists to develop the strategy.

The findings of the San Francisco Bay Microplastics Project (Sutton et al. 2019) are expected to inform both the science and policy recommendations of the Ocean Protection Council's forthcoming strategy document.

2. Recent Findings

2.1 Insights Regarding Field and Analytical Methods

The lack of standardized methods for the collection, extraction, analysis, quality assurance, and reporting of microplastics has been widely acknowledged as a significant challenge for the field (Brander et al. *in review*; Dyachenko et al. 2017; ECHA 2019; Lares et al. 2018; Rochman et al. 2019; SAPEA 2019; Simon et al. 2018; Wolff et al. 2019). In particular, field blanks, field duplicates, and other quality assurance/quality control (QA/QC) samples are largely absent from early microplastic studies, but are starting to be incorporated into study designs (Lares et al. 2018; Simon et al. 2018; Wolff et al. 2019).

Through the San Francisco Bay Microplastics Project (Sutton et al. 2019), we learned that some field methods are more appropriate for sampling microplastics than others. For example, in general, manta trawls work well for larger floating fragments; fibers may be more successfully collected using grab samples, although the volume should be sufficiently large to limit the influence of background contamination (Brander et al. *in review*). To date, microplastic laboratory analyses are very labor intensive, which makes it logistically infeasible to conduct spectroscopy on every microparticle collected. A number of new methods have been developed in conjunction with the San Francisco Bay Microplastics Project, including the magnetization of microplastics to facilitate more efficient extraction (Grbic et al. 2019), and staining techniques to more rapidly determine fiber composition (Zhu et al. 2018; Zhu et al. 2019 *in review*). These techniques are promising; however, there is an urgent need for greater automation.

Fibers were widely detected in Bay samples and in the field and laboratory blanks (Sutton et al. 2019). In some instances, the detection of fibers in the blanks could be traced back to a specific source (e.g., orange life jackets on board the sampling vessel or a curly black fiber mat on one of the sampling vessels [removed after the third day of field sampling]); however, in most instances, identifying the sources of the fibers was not possible, attesting to their pervasive and ubiquitous presence in the environment. Based on the field sampling to date, there are indications that these fibers may be transported through air deposition. This finding supports the need for collection of field and laboratory blanks as an essential element in future study design.

Recently, the Southern California Coastal Water Research Project (SCCWRP) has embarked on a goal to identify and standardize extraction and analytical methods for microplastics. SCCWRP is currently conducting a study to evaluate variations in microplastic measurements among different analytical methods and laboratories. The results of this project are scheduled to be available in 2020.

2.2 Surface Water

As part of the San Francisco Bay Microplastics Project, surface water samples were collected from 17 sites in the Bay, and 11 sites within the Monterey Bay, Cordell Bank, and Greater Farallones National Marine Sanctuaries located off the California coast (Sutton et al. 2019). Each site was sampled twice, once during the dry season and again during the wet season following rainfall events. Using a manta trawl, surface water samples were collected to provide a baseline of microplastic abundances in surface water, assess spatial distribution in the Bay and Sanctuaries, and evaluate the influence of season.

Microparticles were identified and characterized as fragments, foam, spheres, and film. Just over half of the samples were also analyzed for fibers. Microparticle abundance was higher in Bay surface water than in the marine sanctuaries. Microparticle abundance in one of the Bay surface water samples was one of the highest reported to date.

Microparticle abundance was higher in Bay surface water samples collected during the wet season than the dry season, which was statistically significant. This result suggests that wet weather may mobilize microparticles and microplastics from the surrounding Bay Area watersheds. A statistically significant seasonal effect was not observed in the sanctuaries, at least partially due to the low abundance of microparticles observed.

The dominant morphology of microparticles in surface water samples was fibers, followed by fragments. Of the microparticles that underwent spectral identification, approximately 53% of fibers were determined to be plastic, while 87% of fragments, 68% of foam, 97% of spheres, and 83% of film were determined to be plastic.

Average estimated plastic microfiber abundance within the Bay ranged from 270,000 to 340,000 microplastic fibers/km^2 (lower and upper bound values) for the wet season and 40,000 to 59,000 microplastic fibers/km^2 for the dry season. Average estimated microplastic abundance (excluding fibers) was 440,000 to 450,000 microplastics/km^2 (lower and upper bound values) for the wet season and 42,000 to 45,000 microplastics/km^2 for the dry season.

Manta trawl sample collection is not an ideal method for capturing fibers due to their elongated shape and thin diameter, which means depending on the orientation, some fibers can slip through the net mesh. Sampling methods designed to collect more representative levels of fibers, as well as particles smaller than the sieve size used as part of manta trawl sample collection (0.355 mm), were deployed at some sites to test their effectiveness. Evaluation of these samples suggests the need to sample larger volumes (e.g., three to four liter grabs) to be well above the background levels of contamination, and provides further evidence of the impacts of background contamination from fibers on data quality.

2.3 Sediment

Sediment samples were collected from 18 sites in San Francisco Bay and two sites in Tomales Bay (a reference site with minimal direct urban influence) to assess baseline conditions, and evaluate spatial distribution (Sutton et al. 2019). Within the Bay, the majority of samples were collected along the Bay margins, an area that has numerous discharge points for stormwater runoff and wastewater effluent and is desirable habitat for birds and Bay animals.

Microparticles were identified in sediment from all 20 sites. The highest concentrations of microparticles were measured in the Lower South Bay, which is strongly influenced by wastewater and stormwater discharges. Concentrations in sediment from the reference site were among the lowest observed. Microparticle and microplastic concentrations in Bay sediment were higher than those reported in the majority of other regions, mostly due to the high concentrations measured in the Lower South Bay.

Fibers were the most abundant type of microparticles in Bay sediment, followed by fragments. Bay microparticle concentrations ranged between 1 and 49 microfibers per gram dry weight (microfibers/g dw), and 0.1 and 11 non-fiber (i.e., fragments, film, spheres, foam) microparticles/g dw.

A subset of microparticles was analyzed using Raman or FTIR spectroscopy to establish whether or not they were plastic. The average concentration of plastic fibers analyzed in Bay sediment was between 1 and 2 microplastics/g dw. The average concentration of plastic non-fibers was 1 microplastics/g dw.

Black fragments that had a rubbery texture were frequently detected in sediment samples. Spectroscopy was unable to identify the composition; however, laboratory analysts reported that based on secondary characteristics, these particles were similar to particles that had been previously identified as rubber by FTIR spectroscopy. Similar black fragments with a rubbery texture were also identified in stormwater (Section 2.5).

2.4 Prey fish

As part of the San Francisco Bay Microplastics Project, ten fish each of two species (anchovy, *Engraulis mordax* and topsmelt, *Atherinops affinis*) were collected from six locations in San Francisco Bay and two locations in a reference area (Tomales Bay). To evaluate the uptake of microplastics into the food web, the digestive tracts of these prey fish were analyzed for microparticles.

Prey fish are important to assess because they are key species in the food web, provide information on spatial distribution and potential hot spots, represent an important link between abiotic compartments and the food web, and may be an indicator of exposure to higher trophic level organisms, including larger predators and humans.

Two different fish species were chosen to evaluate whether differences in preferred habitat and foraging behavior affected microparticle concentrations. While there was no significant difference in total microparticle counts between the two species, likely due to the high variability in the fiber counts, there was a statistical difference in non-fiber microparticles counts (i.e., fragments, film, spheres, foam), with topsmelt having higher levels of non-fiber microparticles than anchovies. Topsmelt are thought to reside closer to Bay margins, feeding primarily in shallow and benthic areas, as compared to anchovies that generally live and feed in deeper Bay channels and throughout the water column.

Laboratory blanks contained fibers, necessitating qualification of fiber counts. Nevertheless, at least 38% of fish from the Bay had microparticle counts exceeding the qualification threshold. Fibers represented 86% of microparticles present in fish. Of the fibers that were further analyzed via Raman spectroscopy, 23% were confirmed to be plastic, while 60% were classified as "anthropogenic unknown," primarily because dyes embedded in the microfibers interfered with the laboratory's ability to identify the polymer composition. Twenty-one percent of non-fiber microparticles analyzed by spectroscopy were confirmed to be plastic.

The estimated average number of non-fiber microplastics/fish in the Bay anchovies and topsmelt was between 0.2–0.9 microplastics/fish. The estimated average number of fiber microplastics/fish in Bay anchovies and topsmelt was between 0.6–4.5 microplastics/fish. The microplastic counts and detection frequencies in the Bay were comparable to counts reported in many other locations.

Microparticle levels in fish from San Francisco Bay were statistically higher than levels in fish from the reference area. A dietary study of Bay Area sport fish identified the presence of microparticles, indicating that microplastics are likely present in higher level trophic organisms (Jahn 2018); however, a more detailed study is necessary to assess occurrence in these higher trophic levels, including humans.

To date, there are no established ecotoxicological thresholds specific to prey fish. The magnitude and types of effects are difficult to predict because of the diversity of microplastic morphologies and compositions. Ecological effects studies at relevant environmental conditions are needed.

2.5 Pathways: Stormwater

As part of the San Francisco Bay Microplastics Project, 12 tributaries comprising 11% of the watershed drainage area to San Francisco Bay (i.e., 763 km^2 out of a total of 6,725 km^2) and 6% of the total flow to the Bay via small tributaries were sampled during storms to measure concentrations of microparticles. Geographically distributed throughout the Bay Area, these tributaries were selected based on watershed size, watershed characteristics (e.g., impervious surfaces) and land-use characteristics (e.g., commercial, residential, industrial, agricultural/open space).

Microparticles were identified in stormwater from all 12 tributaries, discharging between 1.3 and 30 microparticles per liter, with a mean of 9.2 microparticles per liter (Sutton et al. 2019). Fragments (59%) and fibers (39%) constituted nearly all microparticles sampled.

Black fragments that had a distinctive rubbery texture were abundant in stormwater samples and constituted nearly half of all microparticles in stormwater samples. Spectroscopic analysis were inconclusive as to the composition of these particles, but based on visual characteristics and similarity with particles that were confirmed to be rubber using spectroscopy, these particles are suspected to be rubber. A few of these fragments were further analyzed via an additional analytical technique, pyrolysis gas chromatography-mass spectrometry, and confirmed to be tire tread rubber (Rochman, personal communication).

Correlations among microparticle concentrations and land uses were evaluated, and the Regional Watershed Spreadsheet Model (RWSM), previously developed for legacy pollutants such as PCBs and mercury, was used to estimate loads discharged to the Bay. Based on modeled correlations, it appears that industrial land use may be associated with higher microparticle concentrations. The potential reasons for this are not clear and need to be further explored.

The RWSM model provided an annual estimate of microparticle load of 11 trillion microparticles to the Bay per year from small tributaries. Based on the subset of microparticles that underwent spectroscopy and were identified as microplastics, and assuming similar distribution for the remaining microparticles not analyzed, potentially two thirds of these microparticles could be microplastics. The estimated microplastic loading from stormwater is 7 trillion microplastics to the Bay per year.

2.5.1 Rain Gardens

The San Francisco Estuary Partnership provided funding to evaluate the efficacy of rain gardens to reduce microplastics entering stormwater systems as part of a larger study evaluating their efficacy with respect to removal of legacy contaminants. This study was conducted during the wet season of 2016; influent into the garden and effluent after percolation through the garden were sampled over the course of three storms and analyzed for microparticles and microplastics (Gilbreath et al. 2019). The small catchment (approximately one acre) is located along a major urban transit corridor.

Fibers composed 58% of particle counts. Of the fibers, 13% were positively identified as plastics, 9% natural-based cotton or wool, and the remaining could not be identified further other than being of anthropogenic origin due to the presence of dyes. Rubber and paint fragments made up 7% of particles, and 31% of the remaining fragments were positively identified as plastic. All the spheres identified in the rain garden study were made of glass, which are hypothesized to come from reflective paint on roads.

Based on a comparison of influent and effluent, the rain garden was able to remove more than 90% of the microparticles. These results suggest that rain gardens may provide additional societal benefits beyond removal of legacy contaminants. Further research on larger and alternative green stormwater infrastructure landscapes is necessary to understand efficacy and optimal performance with respect to microplastics.

2.6 Pathways: Wastewater

Microparticles were sampled in the effluent of eight Bay Area wastewater treatment plants that represent over 70% of the overall effluent flow to the Bay. The eight facilities were geographically distributed, varied in flow rates from 90 to 630 million liters per day (24 to 167 million gallons per day), and employed a variety of secondary and tertiary treatments. Effluent was sampled twice from each facility to assess variation.

Microparticles were identified in effluent from all eight facilities, discharging an average of 0.063 microparticles per liter (n = 16; range 0.008 to 0.2 microparticles per liter). Microparticles, particularly fibers, were also identified in the field blank (38 in total) and laboratory blanks (n = 5, average 17, range of 13 to 29). In the wastewater samples, fibers, followed by fragments, were the most frequently identified shapes (55% and 23%, respectively), a common observation in the literature.

Facilities employing tertiary treatment including dual media filtration had statistically lower microparticle concentrations than secondary treatment facilities, suggesting that enhanced treatment may have multiple societal benefits, including reduction in pollutants as well as microparticles. However, any microplastics captured through wastewater treatment is not expected to degrade within sewage sludge/biosolids or filtration media, and disposal of these materials may result in the transport of microplastics to other environmental compartments.

In aggregate, approximately 91 million microparticles per day were discharged to the Bay by the eight facilities (Sutton et al. 2019). Assuming a similar distribution among the remaining facilities, approximately 129 million microparticles were estimated to be discharged per day or approximately 47 billion microparticles annually. This estimate is substantially lower than the annual microparticle loads estimate from the small tributaries surrounding the Bay of 11 trillion microparticles.

Not all microparticles in effluent were plastic. Of the 91 million microparticles discharged per day by the eight facilities, based on Raman/FTIR spectroscopy for a subset of microparticles and information in the literature, it was estimated that the range of microplastics discharged to the Bay by the eight facilities was between 29 to 45 million microplastics per day, with a plausible estimate of 32 million microplastics per day (Sutton et al. 2019). This would translate to 46 million microplastics per day or 17 billion microplastics per year for the Bay Area municipal wastewater pathway as a whole (Sutton et al. 2019).

3 Reclassification of Microplastics from Possible to Moderate Concern

3.1 RMP's Tiered Risk and Management Action Framework for CECs

For those contaminants of emerging concern (CECs) monitored in Bay water, sediment, or biota, the RMP has developed a tiered, risk-based framework to assign appropriate levels of concern based on a CEC's potential to impact San Francisco Bay (Sutton et al. 2017). The degree of concern associated with a particular chemical or chemical class guides both monitoring activities and management actions (Table 1).

The risk-based tiers have been defined as follows (Sutton et al. 2017; Lin et al. 2018):

> High Concern – Bay occurrence data suggest a high probability of a moderate or high level effect on Bay wildlife (e.g., frequent detection at concentrations greater than the EC_{10}, the effect concentration where 10% of the population exhibits a response.
>
> Moderate Concern – Bay occurrence data suggest a high probability of a low level effect on Bay wildlife (e.g., frequent detection at concentrations greater than the PNEC (predicted no effect concentration) or NOEC (no observed effect concentration), but less than the EC_{10} or another low level effects threshold.
>
> Low Concern – Bay occurrence data suggest a high probability of minimal effect on Bay wildlife (i.e., Bay concentrations are well below toxicity thresholds and potential toxicity to wildlife is sufficiently characterized).
>
> Possible Concern – Uncertainty in toxicity thresholds suggests uncertainty in the level of effect on Bay wildlife. Bay occurrence data exist; in some cases, they may be constrained by analytical methods with insufficient sensitivity.

Secondary factors that may impact tier assignments include trends in use of the chemical or trends in Bay concentrations, as well as the potential for cumulative impacts.

Table 1. The RMP Tiered Risk-based Framework for San Francisco Bay. Once Bay monitoring data are available, a CEC may be classified within this framework (Sutton et al. 2017). Contaminants within the Moderate Concern category may merit additional resources for monitoring and to support management actions to control environmental concentrations.

	Risk Level Description	Monitoring Strategy	Water Quality Management Actions
High Concern	Bay occurrence data suggest a high probability of a moderate or high level effect on Bay wildlife.	Studies to support TMDL or alternative management plan.	303(d) listing.* TMDL or alternative management plan.* Aggressive control/treatment actions for all controllable sources.
Moderate Concern	Bay occurrence data suggest a high probability of a low level effect on Bay wildlife.	Consider including in Status and Trends monitoring. Special studies of fate, effects, sources, pathways, and loadings.	Action plan/strategy. Aggressive pollution prevention. Low-cost control/treatment actions.
Low Concern	Bay occurrence data suggest a high probability of minimal effect on Bay wildlife.	Discontinue or conduct periodic screening level monitoring in water, sediment, or biota. For CECs previously considered moderate concern, maintain Status and Trends monitoring for at least two cycles. Periodic screening level monitoring for chemical(s) detected in wastewater or stormwater to track trends.	Low-cost source identification and control. Low-level pollution prevention. Track product use and market trends.
Possible Concern	Uncertainty in toxicity thresholds suggests uncertainty in the level of effect on Bay wildlife. In some cases, analytical methods are inadequate.	Screening level monitoring to determine presence in water, sediment, or biota. Screening level monitoring for presence in wastewater or stormwater.	Maintain (on-going/periodic) effort to identify and prioritize emerging contaminants of potential concern. Track international and national efforts to identify high priority CECs. Develop biological screening methods and identify available analytical methods.

*Subject to Regional Water Quality Control Board action with public review

3.2 Rationale for Classifying Microplastics as Moderate Concern

Initially, microplastics were classified as a Possible Concern under the RMP tiered, risk-based framework because there is uncertainty as to effects due to lack of a toxicity threshold (Sutton et al. 2017). At the Spring 2019 Microplastic Workgroup meeting, microplastics were elevated to Moderate Concern based on the following: the recent classification of microplastics as a non-threshold contaminant in an EU risk assessment; available toxicity studies; the continued upward trend in plastic use and environmental detection; and persistence. Each of these factors is discussed in more detail below.

3.2.1 Microplastics as a Non-threshold Contaminant

Under the European Union (EU) regulation for Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), the European Chemical Agency (ECHA), which oversees the use of chemicals in the EU, aims to minimize releases and exposures of contaminants identified as PBT/vPvB (persistent, bioaccumulative, and toxic / very persistent and very bioaccumulative). These substances are recognized to require a precautionary approach, in which it is appropriate to take cost-effective action now, despite uncertainties.

In 2019, after an extensive review of the scientific literature on occurrence, fate, and effects of microplastics, and discussion with stakeholders and scientific experts, ECHA determined that risks arising from intentional uses of microplastics that result in releases to the environment are not currently adequately controlled. This is due to the lack of sufficient ecotoxicity data for calculation of risk thresholds, clear evidence of microplastic persistence, and uncertainty in regards to bioaccumulation potential. As a result, ECHA concluded that microplastics should be classified as a non-threshold substance for the purposes of risk assessment, with any release to the environment assumed to result in risk.

Specifically, ECHA concluded: *there is currently insufficient information to derive robust predicted no effect concentrations (PNECs) for microplastics, that could be used to justify a conclusion that risks are adequately controlled, either based on current exposures in the environment or exposures that are forecast to occur in the future* (ECHA 2019). Reclassifying microplastics as non-threshold substances means managing them in the PBT/vPvB framework.

This recommendation was due to a lack of data, and based on current exposures in the environment and exposures that are forecast to occur in the future. Also contributing to the non-threshold risk classification was the persistence of these compounds and the fact that they are exceedingly difficult to remove once introduced into the environment. Microplastics fragment into smaller plastic particles (e.g., nanoplastics) as they degrade. The half-lives of these materials are not known with certainty due to the wide variety of polymers in use and varying environmental conditions; however, it is widely acknowledged that these particles will be stable in the environment for hundreds, if not thousands of years (SAPEA 2019; Andrady 2011; GESAMP 2016).

Based on the non-threshold classification, ECHA has proposed a ban on microplastics that are intentionally added to products used by consumers and industries. They assessed the risk reduction potential and socio-economic impacts of several restriction options; the proposed restrictions are considered to be proportionate to the risk, with cost effectiveness similar to previously implemented REACH restrictions. The restrictions cover a broad range of microplastic uses in products, including agricultural controlled-release fertilizers, cosmetics (rinse-off and leave-on products), controlled-release medications, detergents (fragrance encapsulation), paints, construction materials, and oil and gas processing. The ban does not apply to microplastics that are generated as a result of secondary processes such as fragmentation or degradation of larger plastic items in the environment.

3.2.2 Recent Findings from Toxicity Studies

Microplastics can pose risks to aquatic life through physical and chemical mechanisms; this risk is discussed in more detail in the original Microplastic Strategy (Sutton and Sedlak 2017) and the San Francisco Bay Microplastics Project report (Sutton et al. 2019). Summarized here are findings from more recent literature relevant to fish, the organisms most recently studied in the Bay.

In general, microplastics may be ingested directly or indirectly within prey, or taken up through the gills. Ingested microplastic particles may be present in the gut, gills, and may even translocate to other tissues.

Assessing the risk to fish from exposure to microplastics is challenging due to the diversity of microplastics, and whether exposure occurs alone or in conjunction with exposure to other contaminants. Many studies have reported minimal effects, even when fish were exposed to relatively high doses (Ašmonaitė et al. 2018a, 2018b; Caruso et al. 2018; Foley et al. 2018; Jacob et al. 2019; Jovanović et al. 2018; LeMoine et al. 2018; Malinich et al. 2018; Messinetti et al. 2019; Tosetto et al. 2017). However, other studies report a variety of adverse effects caused by microplastics, from altered swimming and feeding behavior (Barboza et al. 2018; Critchell and Hoogenboom 2018; Mattsson et al. 2017; Yin et al. 2018) to altered reproductive success (Peixoto et al., 2019; Pitt et al. 2018) and decreased growth and body condition (Barboza et al. 2018; Critchell and Hoogenboom, 2018; Jabeen et al. 2018).

Fragments and fibers, especially those that have experienced environmental weathering, seem more likely to cause adverse effects (Choi et al. 2018; Jabeen et al. 2018). Microplastics also seem to increase the toxicity of other environmental contaminants, including heavy metals (Barboza et al. 2018; Rainieri et al. 2018; Wen et al. 2018), persistent organic pollutants (Pannetier et al. 2019a, 2019b; Rainieri et al. 2018), and emerging contaminants (Chen et al. 2017; Zhang et al. 2019).

Smaller microplastics tend to cause more adverse effects (Critchell and Hoogenboom 2018; Ding et al. 2018; Mattsson et al. 2017), possibly because they can more easily translocate from the gut into other tissues (Ding et al. 2018; Mattsson et al. 2017;

Messinetti et al. 2019).While most microplastics (>90%) ingested by fish will be excreted (Lusher et al. 2017), they may bioaccumulate if they translocate across the gut and into the tissues of the animal (Browne et al. 2008). Recent studies have shown that microplastics can translocate from the guts of bivalves (van Cauwenberghe and Janssen 2014) and fish, such as herring and anchovies (Collard et al. 2017), to other tissues where they may elicit an adverse immune response associated with inflammation and cell damage (Alimba and Faggio 2019; GESAMP 2016). This finding has particular relevance to the RMP categorization of microplastics because both anchovy and herring are found in the Bay; Pacific herring is one of the last commercial fisheries in the Bay.

The wide variation in results reported in the literature indicates a great deal of uncertainty and variation in sensitivity. Trying to ascertain how much of this variability is due to inconsistent methods, exposures, and analyses is a large task. In addition, many studies have been conducted in laboratories using high concentrations that are not representative of environmental conditions (GESAMP 2016; Bessling et al. 2018; ECHA 2019; SAPEA 2019). Furthermore, some plastics contain relatively high concentrations of other CECs on the Moderate and Possible Concern lists, meaning microplastics can act as an exposure pathway in addition to being a hazard themselves.

There is an urgent need for ecotoxicological studies that evaluate the effects of microplastics at environmentally relevant concentrations in organisms at multiple life stages. However, even with more ecotoxicological data, establishing risk thresholds may not be possible given the heterogeneous nature of the contaminant (and the wildlife that encounter it). Threshold values for a single contaminant in a given environmental medium are normally set to protect the most sensitive receptors, but in the case of microplastics, the adverse impacts are potentially more wide-ranging and species-specific.

3.2.3 Projected Future Trends

Since the 1960s, plastic production has increased by approximately 8.7% annually (Jambeck et al. 2015). In 2016, 335 million tons of plastic were produced worldwide (Plastic Europe 2017), with future projections likely to double to 600 million tons around 2030 (Azoulay et al. 2019). Globally, 5 to 13 million tons are estimated to be disposed of in the ocean every year (Jambeck et al. 2015). Estimates of floating plastic debris in the Great Pacific Garbage Patch show a doubling in concentration in the last decade (Lebreton et al. 2018). Although recent policy actions may reduce some plastic use (e.g., straw, bag, and food-packaging bans) and discharge (trash control measures), the reservoir of plastics in use today is large and, without substantial management actions, is likely to result in continued discharge to the environment and the Bay.

3.2.4 Additional Support for Classification of Microplastics as Moderate Concern

Based on discussions with the Microplastic Workgroup and several of the Emerging Contaminants Workgroup advisors, the determination by ECHA that microplastics are a non-threshold contaminant for which no safe discharge exists, the ubiquitous detection of microplastics in Bay matrices, the suggestive findings of recent ecotoxicological studies of fish, the complexity and uncertainty in setting broadly applicable toxicity thresholds, and the projected trends of plastic use and presence in the environment, the Microplastic Workgroup was in consensus that microplastics should be moved to the Moderate Concern category under the RMP's tiered, risk-based framework for CECs.

The external advisors noted the following in additional support of this decision:

- Establishing a risk threshold is a massive undertaking given the confounding factors of polymer type, age of plastic, entrained plasticizer/additive toxicities, preferentially sorbed persistent organic pollutant toxicities, varying impacts related to size and shape of particles, exposure pathways varying by media and by receptor, etc.;
- Teasing out measurable and environmentally representative adverse impacts that can definitively be attributed to plastic exposure versus other exposures is very challenging and, with current methodologies, perhaps not possible;
- Deciding how many particles, of what type and size, and including what chemical components could constitute the "acceptable" lower boundary, and determining how to evaluate those threshold levels for adverse impacts to organisms as varied as phytoplankton, bivalves, sportfish, marine mammals and humans would be exceedingly challenging;
- Additives can be present in plastic at parts per thousand or percent levels. Several additives in plastic are already listed as Moderate Concern for the Bay (e.g., alkylphenol ethoxylates, bisphenols, organophosphate esters), while others are listed as Possible Concern (e.g., phthalates, alternative flame retardants).
- Microplastics pose the hazard of reduced nutrition for organisms and can also inhibit ingestion or respiration through blockage.

4 Future Monitoring Directions

Based on recent findings, we have revised the multi-year plan to include several new studies. The multi-year plan is provided at the end of this section (Table 2).

4.1 Microplastic Strategy (Annual)

Strategy funding is necessary to conduct core tasks including: tracking new information regarding microplastic occurrence and toxicity; responding to requests for information from the Water Board and other stakeholders; and, in collaboration with the Workgroup, identifying any essential data gaps for San Francisco Bay that could be filled by the RMP or others. Strategy funding also allows for important leveraging activities, such as the coordination of pro bono analyses by partners.

4.2 Stormwater Conceptual Model (New, 2020-2021)

As described previously, microparticles and microplastics were identified in stormwater from all 12 tributaries monitored, discharging between 1.3 and 30 microparticles per liter, with a mean of 9.2 microparticles per liter. Correlations between stormwater microparticle concentrations and watershed land use, as well as calibration of the

Regional Watershed Spreadsheet Model, suggested that industrial land use may be associated with greater discharges of microparticles and microplastics.

The RMP has funded the first year of a two-year study to develop a conceptual model that describes sources of microparticles and microplastics to stormwater, and identifies land uses and/or landscape attributes that could be linked to higher levels of discharge. A review of Bay data in the context of the scientific literature may suggest industrial land use, impervious surfaces generally, or proximity to roadways as key factors that may explain higher levels of discharge, and should be evaluated in future monitoring studies. Evaluating possible factors influencing microparticle and microplastic loads is important to identify potential sources, to better understand areas of uncertainty, and to identify key attributes that influence the generation of microparticles in stormwater, all of which can inform management actions.

This study will commence in 2020.

4.3 Assessing Ecological Effects (New, 2021)

With the detection of microplastics in small prey fish, it is important to understand potential risks that microplastics present to fish and to wildlife that consume fish. Microplastics have been shown to cause physical damage to small fish through the accumulation and blockage of the digestive tract of some organisms (Cole et al. 2013; Wright et al. 2013). In addition, exposure to microplastics has been associated with reduced feeding and growth rates, reduced reproductive fitness, and diminished mobility (ECHA 2019). However, very little is known about the mechanisms that cause these effects, and even more uncertainty is associated with the thresholds at which these effects occur. This information can help us develop management actions to protect the most vulnerable species.

Oregon State University researchers, working in conjunction with SFEI staff, have developed a proposal to evaluate the effects of microplastics on herring across multiple life stages. This study proposes to assess concentrations of microplastics in wild herring (San Francisco Bay and a reference site) and would use this information to inform a series of laboratory experiments to evaluate the impacts of microplastic on fecundity and health. In addition, the proposed study would evaluate fiber composition and additives. We are presently in the process of identifying potential funding opportunities from federal and state agencies and foundations for this work.

4.4 Air Deposition (New, 2022)

Air deposition of microplastics may be an important pathway for the introduction of microplastics into surface waters and stormwater; however, very little research has been conducted to date (GESAMP 2016; Boucher and Friot 2017; SAPEA 2019). Air deposition studies have occurred in Paris, France (Dris et al. 2015; Dris et al. 2016), in the urban Chinese city Dongguang (Cai et al. 2017), in a remote part of Mongolia (Free et al. 2014 in GESAMP 2016), in the French Pyrenees (Allen et al. 2019) and the Arctic (Bergmann et al. 2019). In Paris, atmospheric deposition of microparticles occurred in a range of 2 to 355 microparticles/m^2/day. The majority of the microparticles were fibers and nearly one-third of them were synthetic or a mix of synthetic and natural compounds (Dris et al. 2016). Similar airborne concentrations of microparticles were identified in Dongguang, China, with concentrations ranging from 175 to 313 microparticles/m^2/day (Cai et al. 2017). Fibers were also the dominant morphology identified.

Some samples collected in remote areas have shown a surprisingly high concentration of microplastics (Bergmann et al. 2019). These studies suggest that even remote areas—far from sources or use—may be affected by microplastic contamination (Free et al. 2014).

We propose studying the air deposition of microplastics in various locations (e.g., nonurban, urban residential, industrial, and commercial sites) to better understand background concentrations, the potential airborne sources of microplastics, the magnitude relative to other pathways such as stormwater and wastewater, and the potential for mitigation.

4.5 Continuation of Stormwater Assessment (New, 2022)

Based on the findings of the stormwater conceptual model proposed for 2020, additional information from other watersheds may be needed to test resulting hypotheses and further evaluate the influence of factors such as land use, impervious surfaces, and transportation on the generation of microparticle loads in Bay Area watersheds.

4.6 Evaluation of Green Stormwater Infrastructure (New, 2022)

A pilot study of a rain garden in a small urban catchment suggested that rain gardens may be effective in removing microplastics, as well as the legacy contaminants they were designed to capture (Gilbreath et al. 2019). Further research on larger and more varied green stormwater infrastructure landscapes is necessary to understand efficacy and optimal deployment with respect to microplastics.

4.7 Trend Monitoring (2022/2023)

It will be important to periodically assess the status of the Bay and its contaminant pathways to evaluate trends with time and assess the efficacy of management actions (e.g., microbead ban). In addition, because microplastics are categorized as a Moderate Concern contaminant class for the Bay, inclusion of microplastic monitoring within RMP Status and Trends sampling may be appropriate.

4.8 Characterize Microplastic Additives to Assess Exposure (2023)

It is also important to understand the behavior of chemicals that are associated with microplastics and are released into the environment either through uptake into the food web or directly to sediment and water. Plastics are by definition a chemical polymer that may be composed of toxic monomers. In addition, they can contain a number of additives to enhance their performance, including plasticizers, flame retardants, pesticides, stain and/or water repellency coatings, and dyes. For example, polyvinyl chloride plastics can contain up to 50% phthalates (plastic additive) by weight

(Rochman et al. 2019). The role microplastics play in the release of pollutants to Bay surface water and aquatic life is currently unknown and is important for assessing risks.

4.9 Sport Fish (2023)

Microparticles were detected in the prey fish we sampled. A follow-up question is whether they are also detected in sport fish, which are consumed by apex predators such as seals and humans. It is important to quantify microplastics in sport fish because these contaminants can be an important vector for transferring chemicals such as flame retardants and plasticizers present in the plastic to the fish (Pannetier et al. 2019a, 2019b; Rochman et al. 2013), and because of the human and wildlife health risks associated with ingestion of plastic and contaminant exposures from fish consumption. In addition, there may be additional risk factors associated with small microplastic particles that have been shown to translocate from the guts of organisms into tissue.

Microplastics have been detected in sport fish from other locations (Compa et al. 2018; Collard et al. 2017; Neves et al. 2015; Rochman et al. 2015); however, to date, no study has quantitatively measured microplastics in Bay sport fish. In a study looking at the gut contents of four fish species (topsmelt, northern anchovies, white croaker, and shiner surfperch) from eight locations in San Leandro Bay, microparticles consisting of fibers, film and fragments were observed (Jahn 2018). Because the focus of the study was the dietary contents in the guts and, as such, standard procedures for microplastic analysis were not undertaken (e.g., dissection in a clean room and secondary confirmation with spectroscopy), these results should be viewed with caution. Nonetheless, the potential identification of microparticles in sport fish suggests that microplastics are likely to be present.

4.10 Evaluation of Microplastics in Land-applied Biosolids (2023)

Wastewater treatment facilities remove large amounts of microplastics, trapping them in biosolids that are often applied to agricultural fields for soil nourishment. As a result, we may be re-releasing microplastics to the ecosystem. Further work is necessary to assess biosolids-related microplastics.

MULTI-YEAR PLAN FOR MICROPLASTICS

Table 2. Microplastic studies and monitoring in the RMP from 2016 to 2023. Numbers indicate budget allocations in $1000s. Budgets in parentheses represent funding or in-kind services from external partners. Budgets with "x" values indicate unknown total funding. Italicized dollar amounts indicate external funds that are needed but not yet secured.

Element	Study	Funder	Questions Addressed	2016	2017	2018	2019	2020	2021	2022	2023
Strategy	Microplastic Strategy	RMP	1,2,3,4,5	25			15	20	10	10	10
	Additional funding for the Moore Foundation SF Bay Microplastics Project	RMP Others*	1,2,3,4,5		75 (40)		(50)				
Monitoring biota	Bivalves	RMP	1,2,4			46					
	Sport Fish	RMP					15				100
	Prey Fish	RMP Moore Foundation			(130)				50		
	Assessing Ecological Impacts	RMP	1,2						150		
Monitoring water and sediment	Open Bay and Margins Sediment	Moore Foundation	1,3,4		(100)						
	Surface Water: Bay and Sanctuaries	Moore Foundation Bay Keeper			(238)	(x)					
	Follow up Status and Trends Monitoring	RMP								50	50
Characterizing sources, pathways, loadings, processes	Stormwater and Wastewater Effluent	Moore Foundation	1,3,5			(90)					
	Continuation of Stormwater Monitoring	RMP External						*(50)*	*(50)*	50	
	Stormwater Conceptual Model	RMP External						30 *(100)*	30		
	Green stormwater infrastructure: Evaluating the efficacy of rain gardens	RMP SFEP			(10)				(100)	(50)	
	Model transport in Bay & ocean	Moore Foundation				(80)					
	Evaluate microplastics in biosolids	RMP									75
	Monitoring air deposition	RMP								100	
Evaluating control options	Options for source control/efficacy of microbead ban, foam bans	Moore Foundation	1,5			(40)					
	Characterize microplastic additives to assess exposure and identify sources	RMP								100	
Synthesis	Synthesize findings (e.g., report, factsheet, video), hold symposium	Moore Foundation	1,3,5				(290)				
RMP-funded Special Studies Subtotal – MPWG				**25**	**75**	**46**	**30**	**50**	**240**	**310**	**235**
High Priority Special Studies for RMP Funding									**190**		
RMP-funded Special Studies Subtotal – Other Workgroups				**0**	**0**	**0**	**0**				
RMP Supplemental Environmental Projects Subtotal				**0**	**0**	**0**	**0**				
Pro-Bono & Externally-funded Special Studies Subtotal				**0**	**518**	**210**	**340**	**150**	**150**	**50**	
OVERALL TOTAL				**25**	**593**	**256**	**370**	**200**	**390**	**360**	**235**

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