Microplastic Monitoring and Science Strategy
FOR SAN FRANCISCO BAY

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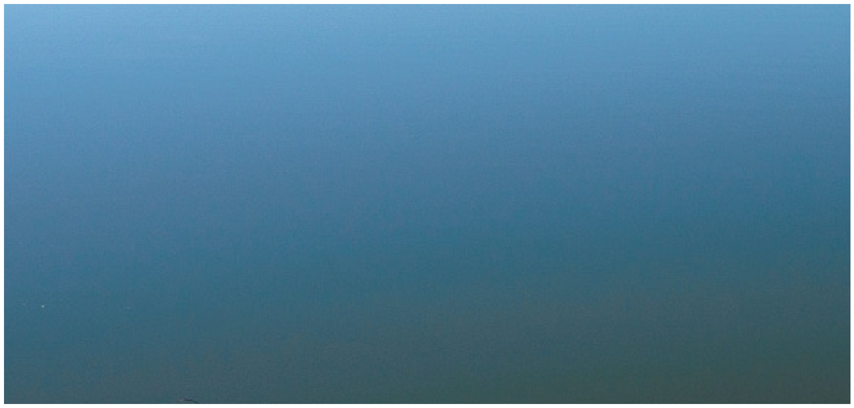

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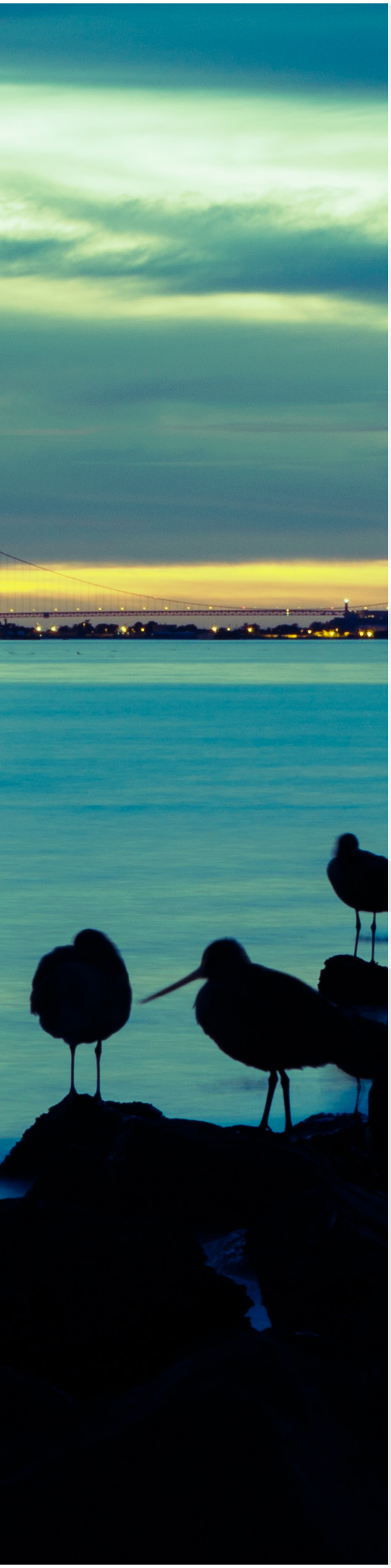
SF Bay, Shira Bezalel (SFEI)



Executive Summary

Microplastic is commonly defined as plastic particles smaller than 5 mm. In 2015, the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) conducted a special study to measure microplastic in treated wastewater effluent and Bay surface water. Bay surface water appeared to have higher microplastic levels than other urban water bodies sampled in North America, such as the Great Lakes and Chesapeake Bay. Microbeads derived from personal care products and tiny fibers, a portion of which were likely derived from synthetic clothing, were recovered from all nine Bay sites. Tiny particles, primarily fibers, were also detected in treated effluent from Bay Area facilities; not all of these particles are known to be plastic. These findings received considerable media attention and catalyzed state and federal policy shifts.

In 2016, the RMP authorized a special study to develop a strategy for continued study of microplastic in San Francisco Bay. To form this strategy, the RMP convened stakeholders to articulate management questions specific to microplastic pollution, and then conducted a one-day workshop that brought together stakeholders and microplastic experts to develop an understanding of the state of the science on this emerging contaminant, and determine consensus priorities for future work.

The resulting strategy document provides:

- *an overview of microplastic science relevant to San Francisco Bay,*
- *the management questions that will guide future work,*
- *a summary of available sampling and analysis methods, and*
- *a multi-year plan for studies that would provide answers to the management questions.*

The monitoring and management of both macro- and microplastic are issues that extend beyond the scope of the RMP. In this document, we seek to identify data gaps, next steps, and strategic partners who can help provide information and resources to inform management decisions. This Microplastic Strategy will be refined and adjusted in years to come based on advances in understanding and changes in the sources and management of plastic pollution.


Shira Bezalel (SFEI)

1 Introduction

Plastic is a way of life. Annual global plastic production was estimated to be 299 million tons in 2013 (Gourmelon 2015); nearly a third of plastic production (75 to 80 million tons) is used for plastic packaging including single-use items (Andrady and Neal 2009). The characteristics that make plastic so desirable—it is inexpensive, versatile, and durable—are also the characteristics that make plastic pollution a major environmental issue worldwide. Anti-litter campaigns and trash regulations have focused on larger debris, overlooking smaller pieces of plastic, less than 5 millimeters, referred to as microplastic. Recent studies indicate that these microplastic particles occur widely in aquatic ecosystems, but the ecological and human health impacts of their presence are poorly understood. Public concern on this issue is high, and has led to actions to ban certain uses of one kind of microplastic - microbeads.

This strategy document provides an overview of the microplastic issue, presents the management questions that will guide future work, summarizes available sampling and analysis methods, and outlines a multi-year plan for studies that would provide answers to the management questions. The monitoring and management of both macro- and microplastic is an issue that extends beyond the scope of the RMP. In this document, we seek to identify data gaps, next steps, and strategic partners who can help provide information to guide management decisions.

2 Overview of the State of Science on Microplastic

2.1 DEFINITION OF MICROPLASTIC

Microplastic is commonly defined as plastic particles smaller than 5 mm (Thompson et al. 2009; Masura et al. 2015). The lower-bound size limit of what is considered microplastic is often operationally defined, with surface water trawl samples typically limited to particles between 5 mm and 0.355 mm, while other methods may be able to detect smaller particles. Particles smaller than 100 nm are classified as nanoplastic, and beyond the scope of this document.

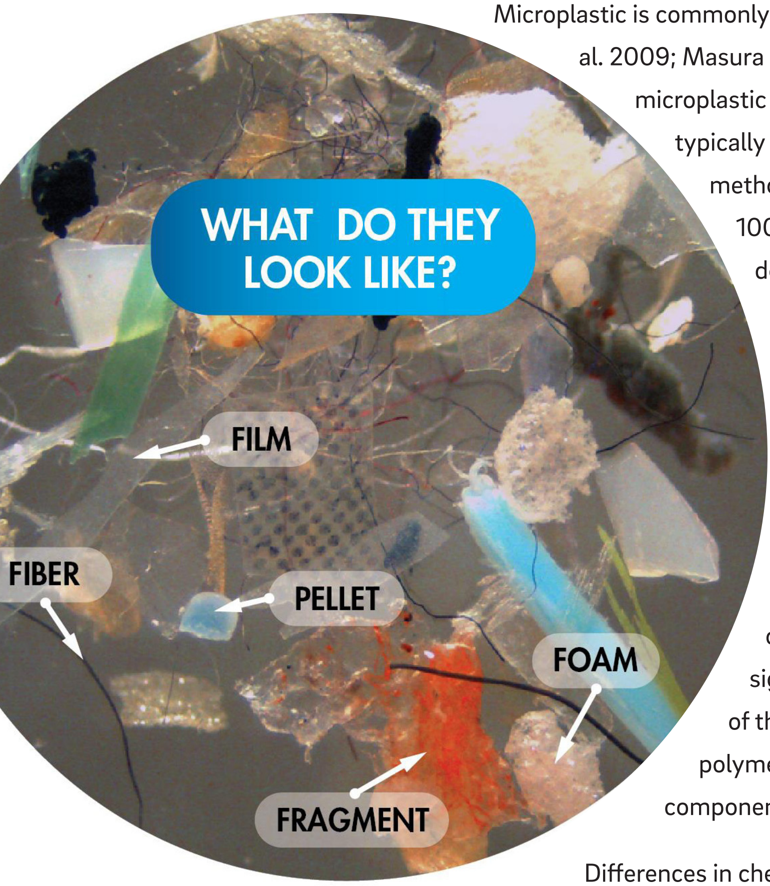


Figure 1. Microscope view of microplastic particle types collected from a single surface water sample in San Francisco Bay. Photo courtesy of Sherri A. Mason.

Microplastic is a chemically and physically diverse contaminant. The term plastic encompasses materials made up of a broad range of polymers including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyamide (nylon), polyethylene terephthalate (PET or polyester), polyacrylonitrile (PAN or acrylic) and polyvinyl chloride (PVC) (Hidalgo-Ruiz et al. 2012). Cellulose acetate (i.e., rayon), a non-plastic polymer, is also commonly observed (Andrady 2011). Many of these polymers have significant levels of 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).

Differences in chemical properties can affect the transport of particles through different environmental matrices. For example, polypropylene and polyethylene are positively buoyant, and can float on the surface of the water; polyvinylchloride, polystyrene, polyester and polyamide are high density plastics that are negatively buoyant, likely to sink to the sediment (Anderson et al. 2016).

Microplastic particles come in a broad range of shapes and sizes (Figure 1). Through visual observation with the aid of a microscope, particles are commonly classified in five different shape or particle type categories, which can in some cases provide insights as to the source of individual particles (Free et al. 2014; McCormick et al. 2014):

- ***Fragment*** – hard, jagged particle
- ***Fiber or line*** – thin or fibrous, straight plastic
- ***Pellet*** – hard, rounded, or spherical particle
- ***Film*** – thin plane of flimsy plastic
- ***Foam*** – lightweight, sponge-like plastic

Differences in size and shape can affect the way particles move through the environment, and may modify their potential for toxicity (Wright et al. 2013).

2.2 ECOLOGICAL AND HUMAN HEALTH CONCERNS

Microplastic poses a unique exposure risk to wildlife due to its physical properties. Wildlife commonly ingest microplastic particles (Wright et al. 2013). Microplastic particles are also small enough that they can be ingested by planktonic organisms and filter feeders (Browne et al. 2008; Cole et al. 2013). In addition to ingestion, microplastic may also be taken up through the gills by organisms such as crabs (Watts et al. 2014).

Ingestion of microplastic has been shown to cause a myriad of deleterious effects. Microplastic can cause physical damage such as accumulation and even blockages within the digestive tract of some organisms (Cole et al. 2013; Wright et al. 2013) and abrasions or ulcers from sharp fragments (Wright et al. 2013). Exposed organisms may exhibit reduced feeding and growth rates, reduced reproductive fitness, and diminished mobility (Cole et al. 2013, 2015; Wright et al. 2013; Watts et al. 2015), although this may not be exclusively due to physical impacts, as behavioral feeding adaptations to avoid further exposure to plastic particles have also been observed in some cases (Cole et al. 2015).

Ingested particles are primarily found within the digestive tracts of organisms, but translocation to other organ systems has been observed in some cases (Browne et al. 2008; Brennecke et al. 2015). Particles may also adsorb to wildlife or lodge within gills (Cole et al. 2013; Wright et al. 2013; Watts et al. 2014), potentially affecting organism health by blocking light and/or oxygen, or by inhibiting feeding or mobility.

Exposure to microplastics may result in greater exposure to plastic chemicals with toxic properties (Browne et al. 2013; Rochman et al. 2013, 2014a,b). Controlled experiments demonstrate transfer of plastic additives like triclosan and polybrominated diphenyl ethers (PBDEs) from microplastic particles to exposed organisms (Browne et al. 2013). In the marine environment, a correlation has been observed between PBDE levels in wild fish and microplastic levels in local surface waters (Rochman et al. 2014a). Several widely used plastic compounds are considered toxic to aquatic life; however, the relative role of direct exposure of wildlife via microplastic particles versus exposure to the same contaminants via ambient environmental sources is largely unknown.

Exposure to microplastics in controlled settings has been shown to disrupt hormone levels (Rochman et al. 2014b; Lu et al. 2016), disturb liver function (Rochman et al. 2013; Lu et al. 2016) and energy metabolism (Watts et al. 2015; Lu et al. 2016), trigger immune responses (von Moos et al. 2012; Lu et al. 2016), and affect reproduction (Sussarellu et al. 2016). The specific mechanisms that cause these impacts to different organisms are rarely readily identifiable. They may include a combination of physical and chemical harms, and be modified by behavioral adaptations.

In addition, plastic particles and associated chemical constituents may be transferred through the food web (e.g., Farrell and Nelson 2013; Rochman et al. 2014a; Setala et al. 2014). While microplastic-related impacts have been observed in laboratory and field studies of biota, no toxicity thresholds have been established that would permit an evaluation of the relative risk to wildlife associated with measured microplastic levels in the environment.

An additional concern relates to the capacity of microplastic particles to sorb persistent, hydrophobic pollutants from the surrounding environment, given their high surface area to volume ratio and relative hydrophobicity. Teuten et al. (2007) and others have hypothesized that exposure to microplastic could result in higher exposures to these persistent contaminants. However, evidence supporting this hypothesis is mixed (e.g., Besseling et al. 2013; Rochman et al. 2014b), and a recent review suggests that microplastic ingestion is unlikely to significantly increase exposure to persistent contaminants already present in the surrounding environment, relative to exposures via natural prey (Koelmans et al. 2016).

The impact of microplastic contamination of aquatic life on human health is currently unknown, and an active topic of research (Seltenrich 2015). Microplastic typically accumulates in the digestive organs of wildlife, and people are most likely to be exposed to these particles directly if they consume organisms whole, as with shellfish (Rochman et al. 2015). However, recent research indicating that microplastic particles can translocate from the gut to other organ systems suggests greater potential for bioaccumulation (Browne et al. 2008; Brennecke et al. 2015).

Of greater concern is the potential for human exposure to the toxic pollutants transferred by microplastic, which could occur from eating any part of an affected fish or shellfish (Seltenrich 2015). Contamination of the aquatic environment with plastic is suggested to be a factor in human exposures to toxic compounds, but the relative importance of this exposure when compared with other sources is unknown (Engler 2012; Seltenrich 2015). There are fish advisory tissue levels for some chemicals used as plastic additives (e.g., PBDEs; Klasing and Brodberg [OEHHA] 2011), but there are no seafood consumption advisories relating generally to microplastic contamination as it affects human health.

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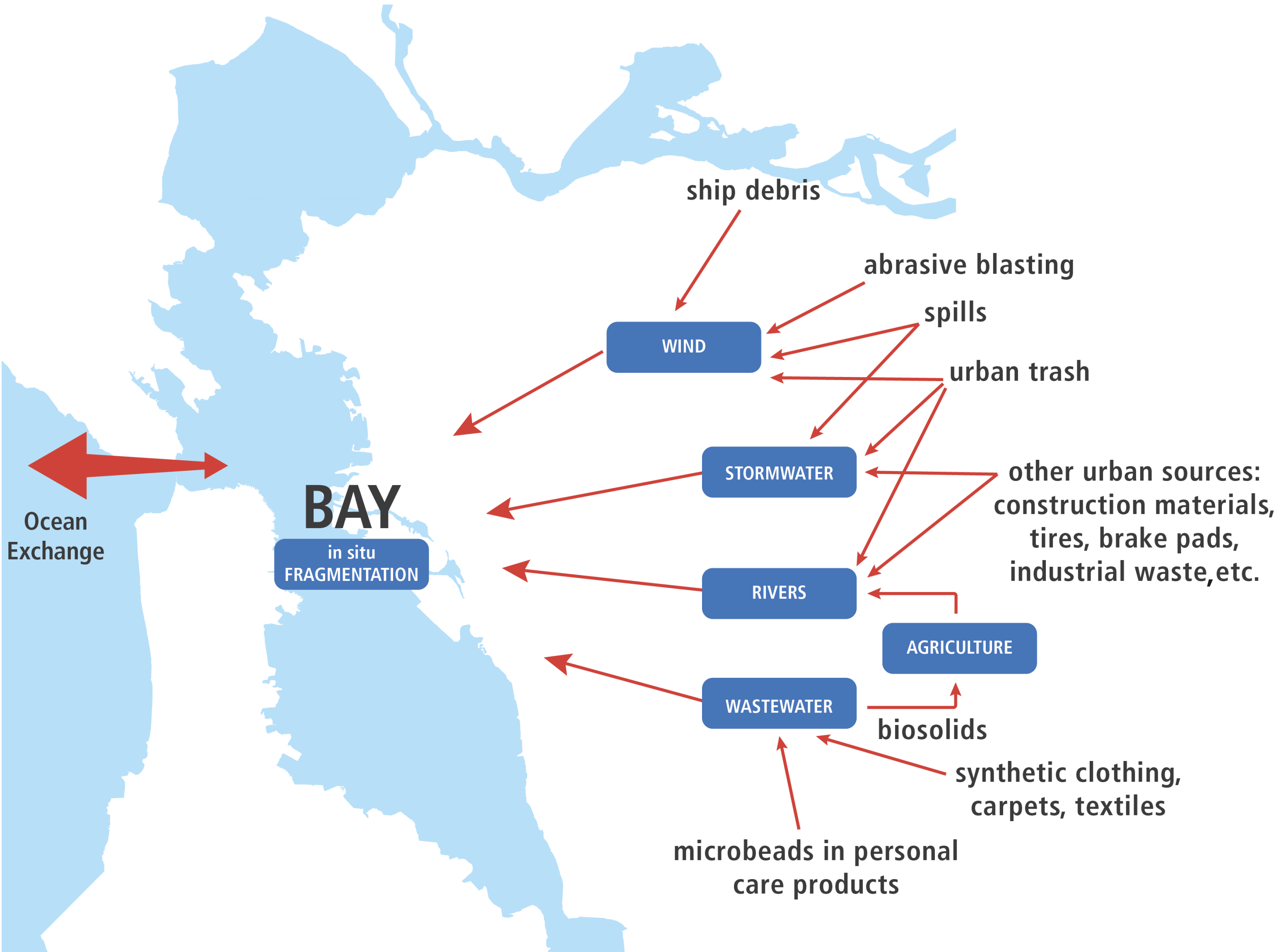
2.3 CONCEPTUAL MODEL OF MICROPLASTIC IN SAN FRANCISCO BAY: SOURCES, PATHWAYS, PROCESSES, AND FATE

Microplastic may be derived from primary or secondary sources (GESAMP 2015). Primary sources are manufactured as particles smaller than 5 mm, and include materials such as pelletized preproduction materials ("nurdles") that are molded into larger plastic items, or microbeads used as ingredients in consumer products (e.g., exfoliants or toothpastes). Secondary sources of microplastic are larger plastic items that disintegrate in the environment through physical fragmentation, photodegradation, chemical weathering, or microbial-mediated biodegradation (Yonkos et al. 2015; GESAMP 2015). Examples of materials that are derived from secondary sources include: foam particles from food packaging and cigarette butts, fibers derived from fishing lines or clothing and textiles made with synthetic material such as polyester or acrylic, plastic fragments from larger plastic items, and film from plastic bags and packaging. Spills may include preproduction materials or waste items that escape during the process of waste collection. Sources anticipated to be relevant to San Francisco Bay are listed in Figure 2.

The pathways by which macroplastic and microplastic can enter the aquatic environment are numerous and include wind advection, urban creeks and stormwater runoff, and illegal dumping of plastic materials

Figure 2. Conceptual model of microplastic sources and pathways to San Francisco Bay. Sources are listed in black; pathways (and the process of in situ fragmentation) are listed in blue boxes.



(Eriksen et al. 2013; Figure 2). Macroplastic breaks down into smaller, microplastic particles as it travels along pathways, or after it enters the Bay. Additionally, both microbeads from personal care products and fibers from synthetic clothing or carpeting can be washed down the drain and enter wastewater treatment plants. While the majority of particles are retained in sewage sludge (e.g., Murphy et al. 2016), the small size, buoyancy, and lack of reactivity of microplastic limits full removal, resulting in release via treated wastewater (Browne et al. 2011; NYS OAG 2015).

Wastewater-derived biosolids containing microplastic may be disposed of via land application (Rillig 2012), resulting in contamination of runoff and nearby waterways. Limited application of biosolids occurs on lands near the Bay; this pathway may be particularly important in Central Valley agricultural regions that drain to San Francisco Bay via the Sacramento-San Joaquin Delta. The Delta is also likely to be a conduit for microplastic particles derived from upstream stormwater and treated wastewater contributions.

What is the ultimate fate of microplastic in San Francisco Bay? While some plastic polymers are positively buoyant and tend to float when first released into the environment, many plastic particles are negatively buoyant, or become less buoyant over time due to growth of biofilm and/or adsorption of clay minerals (Anderson et al. 2016); these particles are likely to sink to the Bay floor, becoming incorporated into sediment. Some particles will be ingested by biota and incorporated into the food web; these particles may end up in sediment after excretion or when organisms die and sink to the Bay floor. Particles of all sizes will weather and fragment further in the environment; rates are likely to be relatively rapid at the shoreline, but generally several orders of magnitude slower elsewhere, decreasing in the following order: at the sea surface, within the water column, or within sediment (GESAMP 2015). As a persistent substance, plastic is expected to break into smaller particles of microplastic and, eventually, nanoplastic (Andrady 2011).

There is also a question as to whether the Pacific Ocean is a sink or a source for microplastic to the Bay. Based on the decreasing concentration of microplastics from South Bay to Central Bay in the pilot RMP study of ambient surface waters of the Bay (see Section 2.4), it would appear that the Pacific Ocean is likely a sink for microplastic. However, further monitoring is necessary to confirm this.

2.4 MICROPLASTIC MONITORING OF SAN FRANCISCO BAY

While microplastic has been found to be a ubiquitous contaminant of aquatic environments, limited monitoring has been conducted in San Francisco Bay. In a 2015 RMP special study, nine Bay surface water samples were collected from the central and southern portions of the Bay during the wet season and examined for microplastic. In addition, treated effluent samples were collected from eight Bay Area wastewater treatment facilities during the dry season. Samples were processed using a method developed by the National Oceanic and Atmospheric Administration (NOAA) that was designed to measure microplastic in marine and freshwater samples (Masura et al. 2015). Detailed methods and findings are provided in Sutton et al. (2016).

With an average particle abundance of 700,000 particles/km^2, Bay surface water appeared to have higher microplastic levels than other urban water bodies sampled in North America, such as the Great Lakes and Chesapeake Bay (Eriksen et al. 2013; Yonkos et al. 2014; Sutton et al. 2016). Higher San Francisco Bay microplastic levels may be partially explained by the dense urban population surrounding a semi-enclosed body of water with limited interchange with the Pacific Ocean.

Microbeads derived from personal care products and tiny fibers, a portion of which were likely derived from synthetic clothing, were recovered from all nine Bay sites. South Bay levels of microplastic were generally higher than those of the central San Francisco Bay (Figure 3). Surface waters in the South Bay receive a large volume of treated wastewater and urban stormwater, have the highest hydraulic residence time relative to other portions of the Bay, and experience the least amount of dilution.

Tiny particles were also detected in treated effluent from Bay Area facilities (Sutton et al. 2016). Available studies indicate microplastic is ubiquitous in treated wastewater (e.g., Murphy et al. 2016), and suggest a portion of the particles detected in Bay Area effluent are likely to be plastic. However, because individual particles in both effluent and Bay surface water samples were not examined via infrared or Raman spectroscopy to permit polymer identification, a portion of the particles may not be plastic. In fact, the Bay Area Clean Water Agencies (BACWA) conducted a follow-up study that found fats, oils, and natural fibers like cotton could persist after sample processing using the NOAA method (Arsem 2016).

On average, Bay Area wastewater treatment facilities discharged 0.33 particles per gallon (Sutton et al. 2016); this was more than four times the average of 0.07 particles per gallon

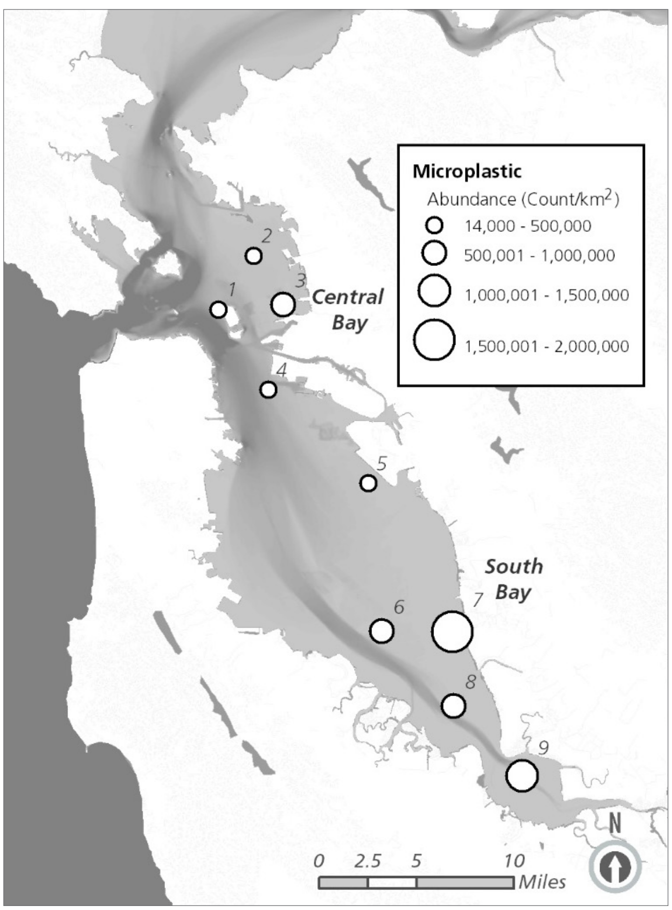


Figure 3. Estimated abundance of microplastic particles in surface water at nine sites in San Francisco Bay. Circles are located at trawl midpoints. See Sutton et al. (2016) for more information.

observed in the effluent of nine facilities located in the Midwest and Northeast and analyzed via identical methods (Mason et al. 2016). Higher particle levels in Bay Area wastewater may in part be a function of concentration due to water conservation efforts implemented as part of the extended drought.

Fibers made up 80% of the particles released into the Bay via treated wastewater (Figure 4); not all of these fibers are known to be plastic. In contrast, for Bay surface water samples, 55% of particles were classified as fragments, and 27% as fibers (Figure 4). This suggests a significant contribution from other sources such as stormwater (Sutton et al. 2016). Processes that occur within the Bay, such as the breakdown of larger plastic litter, settling of heavier particles onto the Bay floor, and ingestion by wildlife may also affect the array of particles found in Bay surface water.

While conducting the surface water trawls of San Francisco Bay (Sutton et al. 2016), nine small prey fish were inadvertently caught at one site. These fish were found to contain 52 particles. This average of nearly six particles per fish is higher than one to three particles typically found in Great Lakes fish (*personal communication,* Sherri A. Mason). 50% of the particles were classified as fragments, while 33% were classified as fibers (Sutton et al. 2016). In a study of California sport fish caught near Monterey Bay and sold for consumption at a local fish market, 25% of the fish were found to have particles in their digestive tracts, the majority of which were fibers (Rochman et al. 2015). Not all particles were definitively identified as plastic (Rochman et al. 2015).

In conclusion, the 2015 RMP special study found microplastic to be widespread in the Bay at levels greater than other urban U.S. water bodies (Sutton et al. 2016). As a dense urban metropolis surrounding a semi-enclosed water body, San Francisco Bay is an ideal laboratory for investigations of microplastic.

However, large data gaps remain regarding microplastic pollution, motivating focused attention from the RMP and others. In addition, limitations in the method used in the original 2015 study, specifically the lack of definitive polymer identification via spectroscopic means, limit the conclusions that can be supported by the results.

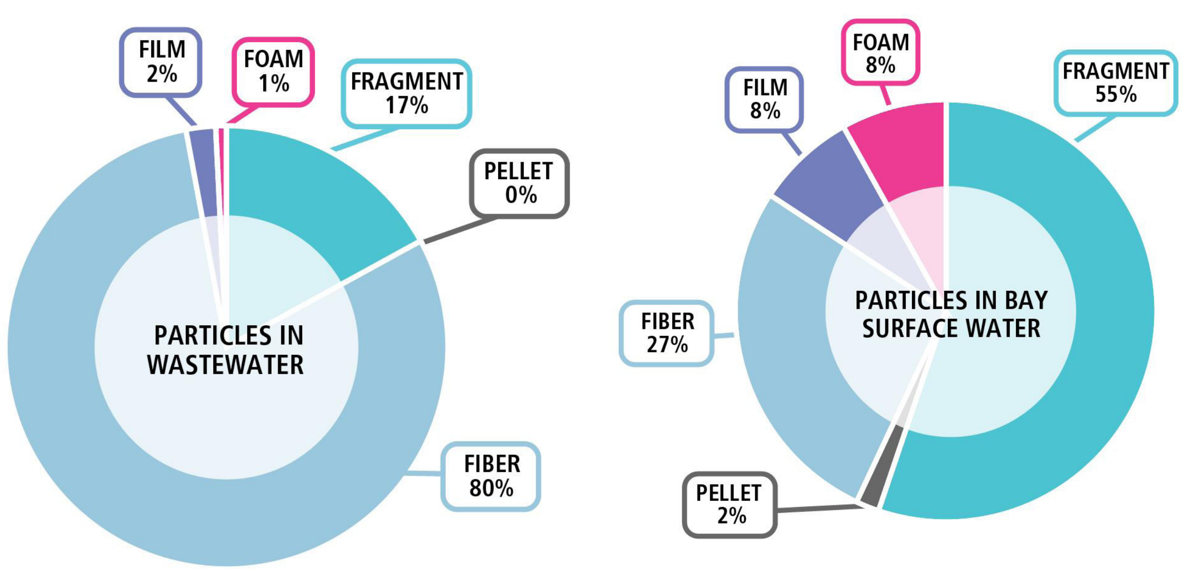


Figure 4. Percent contribution by particle type for wastewater and Bay surface water (Sutton et al. 2016).


NAIP imagery, 2012

3 Management Questions to Guide the Microplastic Strategy

The purpose of this document is to articulate the management questions for microplastic and to outline a workplan of studies needed to address these questions. Draft management questions were developed in the spring of 2016 in consultation with RMP stakeholders and external microplastic science advisors to the RMP. The management questions were further refined at an RMP microplastic workshop on June 29, 2016 that included RMP stakeholders, regulatory agencies, nongovernmental organizations, analytical laboratories, and invited microplastic experts. The final management questions are presented below, accompanied by text that gives a more detailed explanation of the intent of each question.

MQ1) How much microplastic pollution is there in the Bay?

This question encompasses two issues: a) selection or development of appropriate methods for characterizing microplastic pollution, and b) presence and abundance of microplastic within the abiotic and biotic Bay environment. As an emerging contaminant, microplastic sample collection and analytical methods for some matrices of interest are still in development. Selection or development of methods specifically validated for the matrix of interest is a key consideration for future monitoring studies. Also relevant is the fact that microplastic is a complex mixture of different polymers, particles types, and sizes. Through development of standardized methods, we will be able articulate a clear and consistent definition of microplastic, in terms of both size range and composition, which can be used across matrices.

Microplastic has been identified in Bay surface water as part of an initial screening study. Other matrices not yet monitored include the subsurface Bay water column, open Bay and margin sediment, and tissue from aquatic species making up different parts of the Bay food web (aside from a small sample of prey fish collected from a single Bay site in 2015). Evaluation of microplastic in different Bay matrices would provide information on the presence and fate of this contaminant in the Bay environment. Assessments may identify regional or seasonal variation in contamination. Levels of Bay contamination relative to other ecosystems studied using comparable methods can inform prioritization of further monitoring and management actions in the Bay.

MQ2) What are the health risks?

This question addresses risks to humans and wildlife from microplastic. Risks to wildlife include physical impacts such as blockages in the digestive tract, as well as impacts associated with chemical exposures from the constituents of plastic or from contaminants sorbed to the plastic. Risks will vary among species, and will also vary with plastic particle shape, size, and composition. The potential for trophic transfer of microplastic and associated contaminants in wildlife may exacerbate risk. Potential human risks may result from exposure to microplastic-associated contaminants via sport fish and shellfish consumption.

At this time, studies linking microplastic exposure to adverse impacts in wildlife via controlled laboratory settings have not resulted in development of specific aquatic or tissue-based toxicity thresholds. Evaluating the developing body of work on this subject can inform prioritization of monitoring and management actions.

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

This question evaluates the pathways by which microplastic ends up in the Bay. Different sources of plastic produce microplastic particles of characteristic composition and shape or type. Evaluation of potential sources of microplastic may aid in identifying management actions. An evaluation of pathways of microplastic pollution, such as wastewater and stormwater, necessarily involves selection or development of sample collection and analysis methods validated for the matrix, as noted for Bay matrices (MQ1). Loadings of microplastic via these pathways needs to be evaluated alongside other identified pathways, including spills and illegal dumping as well as wind transport, and with the in situ Bay process of fragmentation of larger plastic debris to form microplastic. It is also important to understand the fate of microplastic in the Bay, including assessing whether the ocean is a sink or source of microplastic.

MQ4) Have the concentrations of microplastic in the Bay increased or decreased?

This question addresses long-term temporal trends, with the specific goal of understanding the forces that lead to any identified trends, including changes in sources (e.g., urban/consumer use of plastic), implementation of management actions relating directly or indirectly to control of plastic or microplastic, and other, larger variables such as climate change and drought. For example, assessing the response of the Bay to the state ban on plastic bags or the federal ban on microbeads in rinse-off personal care products will provide an essential index of the effectiveness of these actions. Pollution trends may vary with particle size and shape, potentially reflecting different trends relative to sources or pathways.

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 is one example of microplastic-specific source control that will soon take effect. However, the sources of microplastic to the environment are diverse, and different sources or particle types may be more amenable to source control than others.

Current wastewater treatment technologies may be assessed for their performance in reducing microplastic loads to the Bay. Treatment technologies for both wastewater and stormwater that are likely to be implemented in the future for other reasons may also be assessed for the potential co-benefit of reducing microplastic pollution.

Management actions can be evaluated based on projected impacts and cost to help prioritize options for implementation. Measured impacts of current management actions may be assessed over time via MQ4.

4 Sampling and Analytical Methods

Methods for sampling and analyzing microplastics are relatively new. Although methods for sampling quiescent surface waters using trawls have been well-developed, methods for sampling turbulent stormwater events have not. Similarly, some matrices such as wastewater effluent are particularly challenging due to anthropogenic particulate content that is unique relative to natural waters. In these instances, further refinement of existing methods and potential development of new methods is needed. Finally, smaller-scale microplastics (<0.3 mm) are not always captured using existing methods, and may require improved collection techniques.

Given the complexities surrounding microplastic sampling and analysis methods, a general recommendation for any future monitoring is careful attention to study design that specifies the size fractions and metrics of interest, the method for sample collection, the method for polymer identification, quality assurance and quality control measures, and required documentation.

4.1 SAMPLING METHODS FOR MICROPLASTIC

Surface Water

Surface water microplastic samples are typically collected using a Manta Trawl (Eriksen et al. 2013; Free et al. 2014; Masura et al. 2015). The trawl consists of a winged, rectangular metal box open on the ends that funnels surface water debris into a net with a fine mesh (typically 0.355 mm), allowing for the characterization of microplastics greater than 0.355 mm (Figure 5). The trawl is towed behind a vessel for a set amount of time at a set speed to establish tow length; a flow meter may be used to improve the accuracy of this value. The length, multiplied by the width of the trawl, provides the surface area sampled, allowing for calculation of standardized values per square kilometer.

Characterizing microplastic pollution at lower depths in the water column requires different sampling equipment. However, research conducted in other regions suggests the majority of microplastic is found at the surface or within the sediment bed (e.g., Woodall et al. 2014; Enders et al. 2015). RMP microplastic experts suggested that only a small fraction of microplastic is likely to be found in the subsurface water column at any given time.

Sediment and Biota

Collection of sediment and biota is straightforward, assuming care is taken to avoid cross contaminating the samples through introduction of external microplastic such as airborne fibers from clothing (e.g., Klein et al. 2015; Rochman et al. 2015). Once collected, the samples are then transported to the laboratory for processing and analysis.

Stormwater

While some collection methods for capturing macroplastic and other litter in stormwater have been developed (EOA 2014), methods for collecting microplastic in stormwater have not. One potential approach to evaluating the contribution of stormwater to microplastic pollution in receiving waters would be to monitor microplastic at the mouth of stormwater discharges before and after storms. Alternatively, it may be possible to develop a system to pump stormwater from the surface layer.

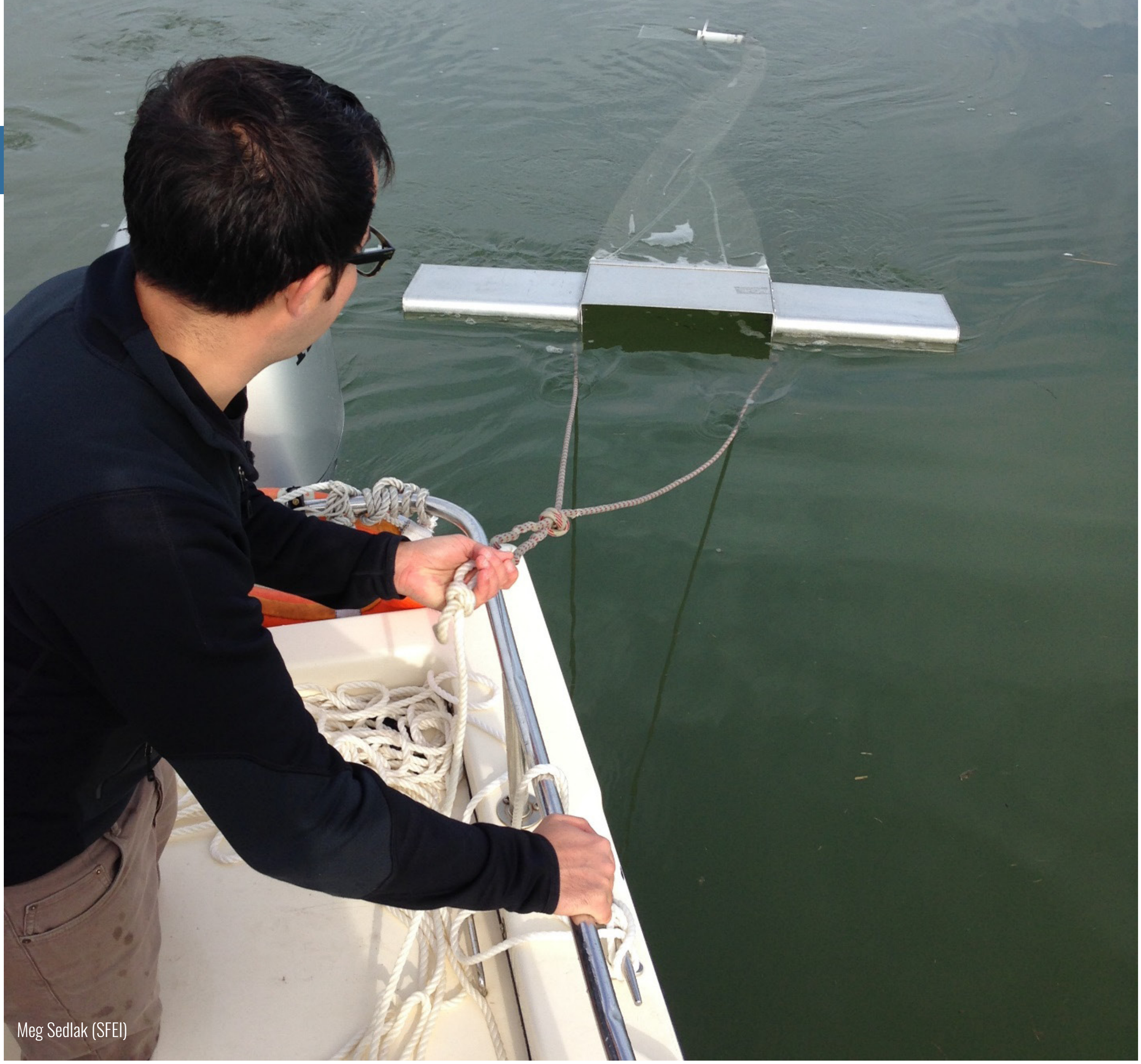


Figure 5. Ian Wren of San Francisco Baykeeper deploying the Manta Trawl.

Wastewater

Microplastic and other particles may be collected from wastewater samples by passing a steady flow of water through mesh screens for a defined length of time. This sample collection method can be used to collect smaller sized particles than possible with a surface water trawl; for example, stacked sieves with mesh sizes of 355 and 125 microns may be used. Once collected, the samples are then transported to the laboratory for processing and analysis. Particle counts can be converted to concentrations by calculating the total amount of water that passed through the screens using the flow rate and the length of time sampled.

Previous sampling of Bay Area wastewater treatment plants relied on samples collected over approximately two hours during peak flow (Sutton et al. 2016). However, a follow-up study by BACWA suggests it is possible to collect 24-hour samples, and these are likely to be more representative of a facility's discharge (Arsem 2016). Monitoring conducted at facilities in other parts of the U.S. indicates that facilities exhibit variability in terms of overall number of particles and distribution of particle types (Mason et al. 2016), suggesting a single monitoring event is insufficient to characterize a facility's potential discharge.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4.2 ANALYTICAL METHODS

Visual identification of particles above 1 mm is an accepted and robust method for positively identifying microplastic (Masura et al. 2015; Fuller and Gautam 2016). However, positive identification of plastic particles smaller than 0.5 to 1 mm requires the use of sophisticated analytical methods, all of which can be expensive and time-consuming.

NOAA has developed an analytical method for characterizing microplastic in water and sediment (Masura et al. 2015), which has been tested to ensure that the most common plastic materials survive. Briefly, samples are reacted with an oxidizing agent (30% hydrogen peroxide solution in the presence of an iron (II) catalyst), which breaks down natural organic material, leaving synthetic plastic material behind. Density differences are used to separate the microplastic from the remaining material; after oxidation, the residual material is placed in a solution of sodium chloride, which causes the microplastic to float to the top. The floating material is collected via filtration, air dried, weighed, and then visually sorted and characterized.

To evaluate whole organisms such as shellfish, the entire tissue sample may be similarly oxidized or digested to separate the microplastic from the tissue (Rochman et al. 2015). Hydrogen peroxide or potassium hydroxide may be used to eliminate labile tissue. Once the natural organic material is removed, the remaining material is sieved into fractions and then characterized. In contrast, for larger organisms such as fish, the digestive tract may be removed and subjected to oxidation/digestion to isolate microplastic particles (Rochman et al. 2015).

Once the particles have been separated, the most reliable method for identification of microplastic is by Fourier Transform Infrared (FTIR) spectroscopy, although Raman spectroscopy is also frequently used (Hidalgo-Ruz et al. 2012). FTIR and Raman spectroscopies use slightly different chemical/physical properties to confirm the sample identity; however, in both cases the spectrum of the sample is compared to a known library of spectra. Possible new methods include flow cytometry (Sgier et al. 2016), pyrolysis followed by gas chromatography/mass spectrometry (Fries et al. 2013), and field flow fractionation (*personal communication,* Anna-Marie Cook).

Spectroscopic polymer identification has been shown to be particularly important for wastewater samples. BACWA recently sponsored a study to develop methods to characterize microplastic in effluent. Researchers found that some microparticles present in effluent that survived the NOAA oxidation process and might originally have been identified as microplastic were shown not to be plastic via FTIR spectroscopy, and instead were identified as grease, cotton, and other non-plastic materials.

Likewise, comparisons of spectroscopic and visual-only characterization of particles extracted from environmental samples indicate the need for robust polymer identification via FTIR or Raman spectroscopy. A study of particles in surface water samples found that 68% of visually counted "microplastic particles" were later confirmed as plastic via Raman spectroscopy; particles below 100 μm had a significantly lower confirmation percentage than larger ones (Lenz et al. 2015). In a study of fibers identified in the guts of invertebrates along the Mediterranean coast, many of the fibers present were not plastic but instead were confirmed as a synthetic, cellulose-based polymer (viscose/rayon) using Raman spectroscopy (Remy et al. 2015). While these non-plastic particles cannot be assumed to be free of risk, they are beyond the scope of this strategy document.

USEPA is currently working with partners to develop new collection, extraction, and analytical methods for microplastic by October 2017.

5 Identifying Data Gaps

5.1 CHARACTERIZING MICROPLASTIC SOURCES TO SAN FRANCISCO BAY

The conceptual model developed for San Francisco Bay identified a myriad of possible sources of microplastic (Figure 2). A few of these sources have been evaluated in terms of their potential to contribute to plastic pollution.

- ***Microbeads*** – Consumer products such as toothpaste, facial cleansers, shampoos, shaving creams, moisturizers, and cosmetics can have a surprisingly high concentration of microbeads and have been identified as a significant source of microplastics to the marine environment (Napper et al. 2015). In a study of facial scrubs, researchers found that 4,594 to 94,500 microbeads are released in a single use (Napper et al. 2015).

  It is important to note that round, bead-like, brightly-colored particles classified as pellets typically make up less than 10% of the microbead content of personal care products *(personal communication,* Sherri A. Mason). The rest of the microbeads are rough, plain particles classified as fragments. While the detection of small pellets can be considered a tell-tale sign of microbead contamination, these particles are only a small part of the plastic pollution from personal care products. To detect a temporal trend in microbead levels in response to the federal ban, it may be necessary to evaluate fragments as well as pellets derived from these products.

- ***Synthetic clothing*** – Studies evaluating the release of fibers from synthetic clothing also suggest that it may be a significant source as well (Hartline et al. 2016). A single garment can release 1,900 fibers per wash (Browne et al. 2011). Other textile-based sources, such as carpeting, have not been characterized.

- ***Urban litter*** – Bay Area monitoring studies conducted on behalf of the Bay Area Stormwater Management Agencies Association (BASMAA) have characterized urban litter, including macroplastic items that will break down into microplastic in the environment. Over 150 storm drain trash capture devices were monitored between 2010 and 2011 (EOA 2014). Overall, plastic items made up 2.2-15.1% of the trash captured by volume during the four storm events characterized, but just 0.3-3.0% by mass, a reflection of its lightweight properties. Median household income was identified as the most consistent predictor of trash generation in a region. Local municipalities were predicted to generate an estimated total of 3.2 million gallons of trash each year. Bay Area trash generation was comparable to that of the Los Angeles region.

  While the BASMAA studies do not directly explore the connection between macroplastic and microplastic pollution, they provide useful information regarding the mass and volume of urban litter, a potential source of microplastic.

Many other potential sources have not been characterized, such as particles derived from abrasive blasting, urban sources such as brake pads and construction materials, or releases via spills or from ships. The relative importance of these sources to the Bay is unknown. Improved information regarding the relative contributions of sources of microplastic would be particularly useful to regional stakeholders attempting to identify policy solutions to address this contaminant.

5.2 CHARACTERIZING MICROPLASTIC PATHWAYS TO SAN FRANCISCO BAY

Four primary pathways channel plastic pollution to the Bay (Figure 2): stormwater discharges; effluent from wastewater treatment plants; wind or airborne particles; and riverine inputs, which can aggregate stormwater, effluent and wind inputs from the greater watershed. In addition, exchange with the Pacific Ocean may introduce some plastic particles to the Bay, though the ocean is likely to be a net sink for this pollution.

To date, limited work has been conducted to evaluate pathways for microplastic into the Bay. Based on a review of the literature, it is likely that the two most significant local pathways for microplastic to the Bay are effluent from wastewater treatment facilities discharging to the Bay and stormwater runoff to the Bay (Anderson et al. 2016). The Sacramento-San Joaquin River Delta, which aggregates wastewater and stormwater inputs from a much larger portion of the watershed, is likely to be a major pollution pathway as well.

Wastewater treatment facilities are not designed to remove microplastic. Nevertheless, significant removal can occur. For example, a recent mass balance of a European wastewater treatment facility employing secondary treatment indicated that the plant successfully removed approximately 98% of the microplastic entering the facility, with a significant portion of the reduction occurring during the grease removal stage (Murphy et al. 2016). Despite the high removal efficiency, it was estimated that the facility released 65 million microplastic particles per day via treated effluent to the environment (Murphy et al. 2016).

As discussed in Section 2.4, an initial evaluation of Bay Area wastewater treatment plants indicated that microparticles are being discharged in concentrations higher than those observed from similar facilities in the midwest and northeastern U.S. (Mason et al. 2015). Follow-up study using spectroscopic polymer identification is needed to better understand the potential loadings from this pathway.

At present, there is no information regarding the contribution of microplastic from stormwater to the Bay, although trash monitoring studies have been conducted in local storm drains and demonstrate the ubiquity of larger plastic items within urban litter (e.g., EOA 2014). Storm events likely play a major role in mobilizing macro- and microplastic derived from litter. A southern California study evaluating inputs from the Los Angeles River drainage to the coastal ocean near Long Beach found that concentrations of microplastic increased 7-fold following a storm, from 8 pieces per cubic meter to 56 pieces per cubic meter (Moore et al. 2005).

Discharge of microplastic to the Bay via the Sacramento-San Joaquin River Delta has not yet been evaluated. However, studies of tributaries to the Chesapeake Bay and the Great Lakes suggest that they can be a significant pathway for microplastic pollution (Yonkos et al. 2015; Baldwin et al. 2016). Surface waters of four tributaries to Chesapeake Bay were monitored for microplastic monthly between July and December to assess relative loads and the influence of storms on the loads (Yonkos et al. 2015). All but one of the samples collected contained microplastic, ranging in concentration from < 1 to >560 g/km^2. Highest concentrations were associated with heavily urbanized areas and with storm events (Yonkos et al. 2015). A study of 29 Great Lakes tributaries, each sampled three or four times, found 98% of plastic particles were small enough to be considered microplastic (Baldwin et al. 2016). Fragments, films, foams, and pellets were found at higher levels in tributaries draining urban watersheds, and during conditions leading to runoff, such as rainfall or snowmelt. Interestingly, fibers, the most frequently detected particle type, were not associated with urban areas, wastewater discharges, or runoff (Baldwin et al. 2016).

Air deposition is not expected to be a major pathway for microplastic pollution for the Bay. Airborne microplastic was recently characterized in a case study in Paris, France (Dris et al. 2015). Researchers measured atmospheric deposition of microplastic particles (100-5000 microns), mostly fibers, at 29-280 particles/m^2*day.

5.3 CHARACTERIZING MICROPLASTIC WITHIN SAN FRANCISCO BAY

While the RMP's 2015 special study provided an initial indication of levels of surface water contamination, information is lacking on levels of contamination in other Bay matrices such as sediment and biota. Further characterization of spatial and temporal distribution of microplastics within San Francisco Bay is needed to assess trends, to identify hot spots, to evaluate the potential for bioaccumulation, and to identify possible mitigation measures.

Hydrological differences may play a role in levels of microplastic contamination in different parts of the Bay. The North and Central Bays experience frequent tidal flushing and receive freshwater inflows from the Sacramento-San Joaquin River Delta, which likely contain microplastic from upstream watersheds. In contrast, the South Bay receives much lower levels of freshwater inputs and oceanic flushing. Additional studies of surface water, sediment and biota are described in more detail in the next section.

Comprehensive characterization of Bay matrices is strongly recommended to occur in the near future, to provide baseline data that may then be compared to targeted studies in later years designed to evaluate the impacts of policy actions such as the federal microbead ban. Without baseline data, we would be unable to determine whether specific management actions are having the desired effects.

Shira Bezalel (SFEI)

6 Monitoring Strategy: Multi-Year Plan for Microplastic in San Francisco Bay

Table 1 shows a multi-year plan for microplastic science in San Francisco Bay. The studies in the multi-year plan are needed to address the management questions presented in Section 3, and were prioritized based on input from the June 2016 microplastic workshop and additional discussions with RMP microplastic experts and stakeholders.

There was consensus at the June meeting that microplastic pollution is a complex, global issue that extends well beyond the Bay and the RMP. As such, additional resources external to the RMP will be needed to fully address all management questions (see Section 8 for a description of additional partners/funding strategies). Table 1 indicates efforts that could be undertaken by the RMP, external partners, or a collaboration of the two.

This section presents a brief description of potential studies, including the entity best suited to undertake the study, how the study addresses the management questions, and the priority and ideal timing of the work.

6.1 DEVELOPING ROBUST METHODS

A high priority for microplastic workshop participants was accurate measurement of levels of microplastic in the Bay, addressing MQ1: How much microplastic is there in the Bay? In addition, development of methods suitable for measuring microplastic in pathways such as effluent and stormwater, is an element of MQ3: What are the sources, pathways, loadings, and processes leading to microplastic pollution in the Bay? In order to answer these questions, reliable and robust analytical techniques are needed.

As discussed in Section 4, a major concern with the currently available analytical techniques is the need for spectroscopic confirmation to assure particles recovered are plastic. Spectroscopic characterization of individual particles adds considerably to the time and resources needed to conduct a study; this step was not always included in earlier microplastic monitoring studies, including the RMP's 2015 special study. A growing body of work now indicates spectroscopic polymer identification is an essential part of any study on microplastic, which is likely to increase analytical costs.

As shown in Table 1, USEPA is developing new methods for the collection, extraction and analysis of microplastic. Based on discussions with agency staff, USEPA intends to develop methods suitable for fish, sediment, wastewater, and other matrices. This project is scheduled to be completed by October 2017. During the same time period, NOAA is conducting a laboratory intercomparison exercise to evaluate the precision of current methods among different laboratories. Depending on the outcomes of these two studies, the RMP may consider proposing follow up studies or coordinating additional intercomparison exercises using the new methods. A placeholder for a possible follow up study in 2018 is presented on Table 1.

Depending on the results of additional microplastic studies of abiotic and biotic Bay matrices, it may be desirable to better understand the composition of the microplastic particles that are being detected in the Bay. It is well-known that microplastic can adsorb pollutants; more importantly, the plastic itself may be composed of monomers or additives that have the potential to impact ecological or human health (GESAMP 2015). A placeholder for additional characterization of microplastic is listed for 2020 and beyond, based on the recommendation from participants in the microplastic workshop that this study was a low priority.

Table 1. Multi-Year Plan for microplastic studies.

			Data Gathering and Synthesis			*Long-term Monitoring and Management*		
Task	**Funder**	**Management Questions addressed**	**2016**	**2017**	**2018**	**2019**	**2020**	**Beyond**
Method development [HIGH PRIORITY]	RMP & partner	1 & 3			Additional method development/ pilot testing ($150K)			
	USEPA	1 & 3	New methods for collection, extraction, analysis			Lab inter-comparison ($100K)		
	NOAA	1 & 3	Laboratory intercomparison study					
Monitoring biota [fish HIGH PRIORITY]	RMP	1, 2, 4			Bivalves ($50K)	Sport fish ($190K)	Bivalves ($50K)	Benthic organisms ($50K)
	Moore Fdn with RMP	1, 2, 4		Prey fish ($130K)				
Monitoring water and sediment [surface sediment HIGH PRIORITY]	Moore Fdn with RMP	1, 3, 4		Archived ambient & margin sediment ($100K)				
	Moore Fdn with RMP	1, 3, 4		Surface water ($100K)				
	Moore Fdn with RMP	1, 3, 4		Surface water of adjacent ocean ($120K)				
	RMP	1, 3, 4						Sediment cores ($50K)
Characterizing sources, pathways, loadings, processes	RMP	1 & 3				Refine conceptual model ($50K)		
	Moore Fdn with RMP	1 & 3			Stormwater & effluent ($90K)			
	Moore Fdn with RMP	1 & 3			Model transport in Bay and ocean ($80K)			
Evaluating control options	Moore Fdn with RMP	5				Evaluating policy options ($40K)		
	RMP & partner	5					Options for fiber control ($40K)	
	external	5						Characterize microplastic composition to identify management actions ($60K)
Synthesis	Moore Fdn with RMP	1 & 3				Synthesize findings, hold symposium ($220K)		

6.2 CHARACTERIZING THE BAY

Fish and other biota

Microplastic workshop participants placed a high priority on monitoring studies that characterize the concentration of microplastic in biota, particularly fish. This information will help to answer the following management questions: MQ1 How much microplastic is there in the Bay?; MQ2 What are the health risks?; and MQ4 Have the concentrations increased or decreased? (assuming that future studies are undertaken to evaluate trends). Microplastic has been identified in nine prey fish in the Bay (Sutton et al. 2016); in addition, microplastic has been identified in coastal California fish caught for human consumption (Rochman et al. 2015).

A key aspect of this study will be assessing the risk to human health and wildlife, addressing the question of whether microplastic is accumulating in fish and has an adverse impact on human or wildlife health. To characterize these risks, microplastic will be evaluated in prey fish to assess wildlife exposure, and in sport fish to assess potential human exposure.

Studies to assess concentrations of microplastic in prey and sport fish are included in the multi-year plan. In 2017, a study of prey fish is proposed. Prey fish will be collected from a larger number of locations around the Bay and analyzed for microplastic. The locations of these sites will be determined based on proximity to stormwater, effluent discharges, and other potential sources. Prey fish are more widely distributed throughout the Bay, and provide a valuable index for monitoring spatial patterns and temporal trends. The prey fish monitoring will provide valuable information addressing MQs 1-4: characterizing exposure and risk to aquatic life, determining spatial patterns in relation to sources and pathways, identifying areas of particular concern (high exposure) at a regional and local scale, and providing a foundation for tracking interannual trends. In 2019, a study will evaluate sport fish from up to five popular fishing locations. The sport fish sampling will provide information on potential risk to human health.

In addition to the fish analyses, it could be helpful to conduct additional assessments of microplastic in the food web, particularly lower trophic organisms. A special study to evaluate microplastics in bivalves is planned in 2018 to augment the existing RMP bivalve collection effort. A placeholder for future food web accumulation studies is included in 2020 and beyond. At present, it is assumed that the RMP would fund these studies; however, it possible that external funds may be identified.

Management Questions (addressed in Table 1):

- MQ1: How much microplastic is there in the Bay?
- MQ2: What are the health risks?
- MQ3: What are the sources, pathways, loadings and processes that lead 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?

Bay surface water and sediment

To better characterize ambient Bay conditions, both Bay surface water and sediment samples will be collected and analyzed for microplastic in 2017. Microplastic workshop participants placed a high priority on collection of sediment samples; a medium priority was placed on collection of surface water samples. These rankings in part reflect the absence of data for sediment and the small amount of preliminary data for surface water. This information will help to answer the following management questions: MQ1 How much microplastic is there in the Bay?; and MQ4 Have the concentrations increased or decreased? (assuming that future studies are undertaken to evaluate trends).

Several studies are described in the Multi-Year Plan. As shown in the table, considerable external funds have been secured for this work. In 2017, archived RMP margin and Bay sediment samples will be analyzed. The same year, surface water samples will be collected from four regions (e.g., South Bay; Lower South Bay; Central Bay and San Pablo Bay) during both wet and dry seasons. The purpose of this sampling will be to better understand spatial variability in the Bay as well as the impact of wet weather events. In addition to the archived samples, approximately 40 sediment samples could be collected during the dry season, with a focus on the margins of the Bay. Seasonality is not expected to have a large effect on sediment concentration and therefore will not be addressed.

In addition to the Bay, in 2017, surface water samples from each of the three Marine Sanctuaries located just outside of the Golden Gate (i.e., Greater Farallones, Cordell Bank and Monterey Bay) will be analyzed for microplastic during both wet and dry seasons. Because the Bay may act as a source for Pacific Ocean microplastic, this work will address MQ3 What are the sources, pathways, loadings, and processes leading to microplastic pollution in the Bay? This aspect of surface water monitoring was not directly discussed at the Microplastic workshop, although a moderate priority was placed on understanding ocean exchange.

Inclusion into Status and Trends

If microplastic is determined to present a significant risk, then it is likely that elements of this baseline characterization will be included in status and trends monitoring to assess trends in microplastic concentrations particularly with regard to management actions.

6.3 CHARACTERIZING PATHWAYS

As described in Section 5, two important pathways for microplastic to enter the Bay are discharges from wastewater treatment facilities and stormwater. The RMP has limited data on effluent and no data on stormwater. To address this data gap, stormwater and effluent surveys are proposed for 2018. Characterizing pathways to the Bay was given a medium priority by the microplastic participants in June. Information from this work can be used to answer MQ3, What are the sources, pathways, loadings, and processes that lead to microplastic pollution in the Bay?

Methods for sampling microplastic in stormwater are still in development. It is likely to be difficult to sub-sample stormwater directly for microplastic during storm events given the fine mesh of the trawls used to sample water and the turbid nature of flow during storm events. To overcome this sampling challenge, surface water trawls can be performed at the mouth of the creeks discharging into San Francisco Bay after major storm events. Alternatively, methods to sample directly from these surface waters using pumps will be developed.

Shira Bezalel (SFEI)

In 2018, effluent will be sampled from wastewater treatment facilities during the dry season and during one wet weather event. Ideally, one of the facilities will have a combined stormwater and sanitary sewer, which will allow assessment of some of the impacts of stormwater to the Bay. The latter was a specific suggestion raised during the June meeting.

The data collected on pathways will improve understanding of the relative loads discharged by each pathway. This understanding may be further refined via the modeling exercise discussed below.

6.4 MODELING MICROPLASTIC TRANSPORT

To better understand the fate and transport of microplastic within the Bay and the exchange with the adjacent Pacific Ocean, it will be important to develop a model of microplastic transport. This modeling exercise will help us better understand whether the conceptual model for microplastic is representative and will also assist in identifying the relative loads and pathways of microplastic pollution. It will also enable assessment of the impact of policy decisions. This element addresses the following management questions: MQ3 What are sources, pathways, loadings and processes that lead to microplastic pollution in the Bay (including relative impacts)? and MQ5 Which management actions may be effective in reducing microplastic pollution?

Microplastic transport modeling will be carried out with particle tracking models, predicting trajectories of virtual microplastic particles as they are transported within the Bay and out into the coastal ocean. The particle tracking will draw on multiple sources for currents using an estuarine hydrodynamic model within the Bay such as SUNTANS or Delft Flexible Mesh, and a combination of a coastal hydrodynamic model such as Regional Ocean Modeling System (ROMS) and observed surface currents outside the Bay.

SFEI has an in-house hydrodynamic model calibrated for the estuarine portions of the Bay, which is actively being used in nutrient studies. The first step of the microplastic modeling will be to inject microparticles into the modeled currents at the relevant surface water and wastewater inputs. Information from studies described in Sections 6.2 and 6.3 on sources and pathways will be used to calibrate and validate the model. The particles will be advected throughout the Bay based on predicted surface currents extracted from the estuarine hydrodynamic model. In addition to creating spatial maps of microparticle distribution within the Bay, these results will also be used to estimate microparticle loading out the Golden Gate to the coastal ocean. This loading then serves as an input to a second particle tracking model for coastal waters based on surface currents from UCSC ROMS and coastal radar observations.

Loss of microparticles from surface water due to settling and other processes may be formulated as a half-life or similar relationship. Initial studies would be limited to tracking microparticles at the surface, under the assumption that the highest concentrations and most mobile fraction of microplastics are found near the surface. However, particle tracking within the Bay could be extended to a three-dimensional, full water column approach if observations suggest that depth-varying transport is important. SFEI modelers will work in collaboration with other microplastic modelers to verify assumptions; funds for up to two honoraria may be appropriate to compensate external research groups for their involvement on model calibration and review.

This work is proposed for 2018 after the first year of data is available from the surface water and sediment monitoring. The outcomes from this exercise will be a functional model that is able to provide coarse estimates of microplastic transport within the Bay and exchange with the Pacific Ocean.

6.5 EVALUATING CONTROL OPTIONS

An important element of the Strategy will be evaluating whether there are management actions that can mitigate the impacts of microplastics (i.e., MQ5 Which management actions may be effective in reducing microplastic pollution?). Evaluation of source control options can only be completed after monitoring of the Bay and Bay biota and characterization of sources and pathways has occurred, because understanding the composition of microplastic detected in the environment may help us to better understand sources and possible control options. As a result, this element is largely scheduled for 2018 and beyond.

In general, pollution control that is designed to eliminate or reduce the source of the pollution is considered more effective and less expensive than pathway control options. In this case, the source of pollution is plastic, and current source control measures that are in effect or soon to be implemented in all or part of the Bay Area include bans on plastic bags, polystyrene foam, and microbeads. An evaluation of the impacts of these measures is suggested for the future, once a sufficient body of monitoring work exists to evaluate temporal trends. Such a study may require additional external funding.

A notable deficiency in the source control measures listed above is the lack of attention to reducing discharge of microfibers to the Bay. Microfibers are likely derived from synthetic textiles, including clothing and carpets, and are likely discharged primarily via treated wastewater. Changes to residential or commercial laundering practices may be an effective means of controlling this source of pollution. The RMP may choose to explore additional options specific to microfibers in collaboration with an external partner.

6.6 SYNTHESIS AND INFORMATION DISSEMINATION

Upon completion of the initial microplastic special studies, a synthesis report will be prepared in late 2018. Results will be presented at a national science meeting and the RMP Annual Meeting. In addition, a symposium will be organized to disseminate these results to a wider audience.

7 Current and Potential Future Management Actions

As the magnitude of plastic pollution becomes increasingly apparent, many local, regional, and national agencies have implemented a number of restrictions and management actions on plastic, and in some instances on microplastic. Regulatory actions have been supplemented by educational campaigns organized by agencies, industries, and NGOs, which promote voluntary actions on the part of consumers and businesses to limit plastic pollution.

7.1 SOURCE CONTROL

A number of government agencies have implemented bans on specific plastic items. Plastic bag bans have been a popular and effective solution to reducing the millions of plastic bags that ultimately end up in San Francisco Bay (http://www.savesfbay.org/plastic-bags-banned). Alameda, San Francisco, San Mateo, Santa Clara, Sonoma and Marin counties and many of the cities surrounding San Francisco Bay including San Jose, Richmond, Walnut Creek, Sunnyvale, Corte Madera, Larkspur, Cupertino and Millbrae have all banned the use of single-use plastic carryout bags. In November 2016, California banned single-use plastic bags from grocery and convenience stores. Several cities around the Bay including Berkeley, Palo Alto, and San Jose have approved bans of polystyrene foam for use in food packaging in an effort to reduce foam pollution. In July 2016, San Francisco enacted one of the most comprehensive bans of polystyrene foam, prohibiting its use in food-packaging materials, coolers, dock floats, and packing peanuts among other items; the bill goes into effect in 2017. Lastly, a national ban on the use of microbeads in rinse-off bath and beauty products was passed in 2015; this law bans production by July 2017 and sale of these products by July 2018.

There are many other options for source control of microplastics, including better management of larger plastic trash items that ultimately fragment into microplastic, the management of industrial microplastic materials that may be blown or wash off surfaces into creeks and stormdrains that discharge to the Bay (e.g., nurdles, abrasive-blasting materials), and changes in laundering practices such as implementation of microplastic filters on laundry machines to reduce the release of fibers to wastewater. Meanwhile, educational campaigns promote voluntary measures that consumers, businesses, and government agencies can take to reduce use of plastic, particularly single-use plastic items. For example, Clean Water Action's ReThink Disposable campaign is active in the Bay Area. CalRecycle is also leading efforts to reduce packaging waste.

7.2 PATHWAY CONTROL

Removal of plastic and microplastic from contaminated waters traveling to the Bay is likely to be more challenging and expensive than source control measures like those outlined above. However, current wastewater treatment is already considered likely to remove a significant portion of plastic in wastewater, retaining most microplastic particles within sewage sludge. Existing wastewater treatment technologies may be assessed for their ability to reduce microplastic loads to the Bay.

In addition, treatment technologies for both wastewater and stormwater that are likely to be implemented in the future for other reasons may also be assessed for the potential co-benefit of reducing microplastic pollution. For example, the City of San Jose and the Santa Clara Valley Water District have constructed an advanced water treatment system that can provide up to eight million gallons a day of highly treated water suitable for reuse. Advanced treatment technologies are expected to play a larger role in California's water systems in the future as drought and other impacts of climate change affect the state. Evaluation of the potential effects of advanced treatment on microplastic levels in treated water and waste products may be of interest.

Local municipalities have also made strides in controlling discharge of urban trash to the Bay via stormwater. The Bay Area's Municipal Regional Stormwater Permit requires permittees to conduct receiving water trash monitoring to assure current and future trash reduction measures are effective. Because the macroplastic component of urban trash is a source of microplastic particles, it is expected that these efforts will lead to a reduction in microplastic pollution.

8 External Partners and Funding Strategy

Plastic is a ubiquitous part of modern society, resulting in widespread macro- and microplastic pollution even in the most pristine areas. The issue of microplastic pollution extends far beyond the Bay and the RMP and will require substantial resources to answer the management questions articulated in this document. The microplastic workshop in June brought to the table many new participants such as clothing manufacturers, federal agencies (NOAA Marine Debris Program, USEPA Marine Debris Program), state agencies (CalRecycle), and nongovernmental organizations (San Francisco Baykeeper, Clean Water Action, The 5 Gyres Institute, Environmental Working Group). SFEI has initiated discussions with many potential partners regarding possible collaboration and funding for some of the study ideas discussed in this Strategy document, as well as to ensure that efforts are not duplicative. In addition, SFEI staff are pursuing foundation funding and other external grant opportunities.

A major outcome of this outreach, SFEI and the 5 Gyres Institute have been awarded a 2-year grant for $880,000 from the Gordon and Betty Moore Foundation to complete many of the initial studies outlined in the multi-year plan (Table 1), including: a) baseline characterization of microplastic levels in Bay surface water, sediment, and prey fish; b) baseline characterization of microplastic in adjacent ocean surface water; c) characterization of Bay wastewater and stormwater; d) development of a microplastic transport model for the Bay and surrounding ocean; e) symposium to communicate a synthesis of the findings. The RMP has allocated matching funds of $75,000 to support this effort. In addition, 5 Gyres will lead work to investigate potential control options to address microplastic.

Shira Bezalel (SFEI)

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Appendix

Microplastic Workgroup Science Advisors

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- Chelsea Rochman, University of Toronto

The meeting summary for the RMP's June 2016 Microplastic Monitoring and Science Strategy Workshop may be found at:

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