San Diego Bay Debris Study

Special Study Plastic Debris Monitoring Report

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San Diego Bay Debris Study Workgroup

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**Surface Water Ambient Monitoring Program of the
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and

**Southern California Bight 2013 Regional Marine Monitoring Survey
Bight ’13 Debris Planning Committee**

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EXECUTIVE SUMMARY

Background

This study focused on San Diego Bay, a body of water bordered by the cities of San Diego to the north and east (1.4 million people), National City to the east (61,000 people), Chula Vista to the southeast (266,000 people), Imperial Beach to the south (27,000 people), and Coronado to the west (25,000 people) (U.S. Census Bureau 2015). The location of San Diego Bay is shown in Figure i.

Marine debris has become one of the most recognized pollution problems in the world's oceans and watersheds (Lippiatt et al. 2013). Approximately 60 to 90 percent (%) of the debris found in marine environments is generated from land-based sources (Derraik 2002; Sheavly 2010; Allsopp et al. 2006), suggesting that reducing watershed-based debris sources is an important management action for reducing marine debris. Of the debris found in watersheds, studies generally show that about 50 to 80 percent is composed of plastic-based items, which are also the most abundant type of material found in marine debris (Derraik 2002; Thompson et al. 2009). Debris in the environment also represents a substantial financial burden to cities and public agencies responsible for managing debris. It is estimated that the cities on the west coast of the United States spend $500 million per year on average to remove trash from streets and neighborhoods in an effort to prevent the trash from reaching coastal water bodies (Stickel et al. 2012). The perpetual cleanup required to prevent debris from entering the environment and the ongoing costs to the public suggest that debris represents a high-priority environmental issue for land and public agency managers.

Plastic debris can cause adverse impacts on aquatic and terrestrial wildlife, negatively affect human health, and reduce the aesthetics of freshwater and coastal environments. Debris that enters the environment has the potential to become ingested by animals such as fish and birds or to create entanglement problems for sea life (Thompson et al. 2009; Derraik 2002; Rummel et al. 2016; Allsopp et al. 2006; Browne et al. 2015). Persistent plastic pieces, which form the predominant type of marine debris found in the ocean and the type of material most often ingested by animals, can also function as a transport mechanism for persistent organic pollutants such as flame retardants, chlorinated organic compounds such as DDT, and chemicals created as byproducts of petroleum combustion and industrial processes (Rios 2007; Rios 2010; Teuten et al. 2009; Engler 2012).

The San Diego Bay Debris Study is a special study component under the Southern California Bight 2013 Regional Monitoring Program (Bight '13). The Southern California Bight Regional Monitoring Program (Bight Program) is a large-scale, multi-stakeholder monitoring program focused on assessing emerging or priority environmental concerns across the coastal area of the Southern California Bight. The Bight Program surveys, which are conducted once every five years between Point Conception and the US-Mexico Border, focus on assessing issues of common concern among the stakeholders. Previous Bight Program studies (1994, 1998, 2003, and 2008) have evaluated debris in the marine environment, but have never highlighted marine debris as a primary focus. In 2014, the Bight Program began the first-ever comprehensive marine debris survey, which included, for the first time, a coastal embayment special study to assess the connection between land-based sources of debris and transport to the coastal ocean. In southern California, and particularly along the San Diego County coastline, coastal wetlands and bays provide an important connection between upland rivers and the coastal ocean, and the coastal embayments may be a key environmental sink for upland land-based debris. The intent of this special study is to generate results that can be used as a baseline for future studies and for management of efforts to control trash, specifically plastic-based items. This report covers three of the four projects conducted in San Diego Bay and the contributing watersheds between fall 2014 and spring 2015. The fourth project focused on a wet-weather-based debris tracking study and the project findings are briefly described in this report, along with a reference citing the publication (Talley et al. 2016).

For the purpose of this report, the term "debris" is used for consistency with the Bight Program, but specifically refers to anthropogenic debris (trash). Plastic debris in particular was chosen as the focal point for this study because of its frequent use in urban society, its long residence time in the environment relative to other materials, the ability of plastics to absorb and potentially transport contaminants, and the persistence of plastics in overall marine pollution.

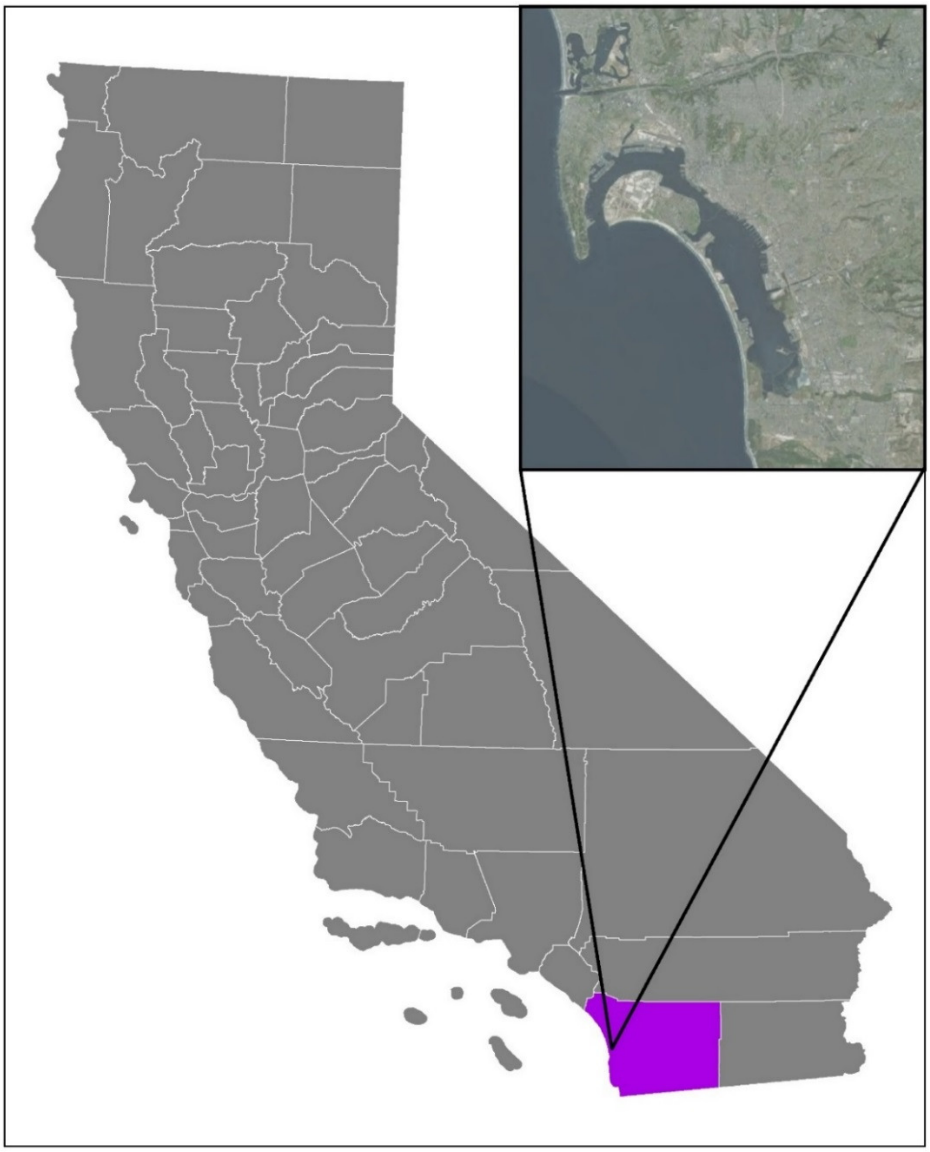

Figure i. Representation of California, the Location of San Diego County and San Diego Bay.

Study Goals

The overall goals of this study are to characterize the extent and magnitude of plastic debris in San Diego Bay in the various habitats and to evaluate the potential ecological impact of plastic debris on fish communities in the bay. Within this study, three core questions were developed to answer the study goals:

1) How do the quantities and types of debris in different habitats vary during dry and wet seasons?
    a) What are the quantities and types of debris found in San Diego Bay habitats?
    b) What are the quantities and types of debris found in watersheds flowing to San Diego Bay?
    c) How do the quantities and types of trash in different San Diego Bay habitats vary during summer and winter dry seasons?
    d) What types and quantities of trash are found in San Diego Bay following the first storms of the wet weather season?
2) What types of riverine debris do wet weather flows transport to San Diego Bay?
3) What species caught in the bay have ingested plastic pieces?

The first question evaluates the differences in the abundance and types of debris found in bay bottom sediments (benthic and epibenthic habitats), surface waters (open water habitats), salt marshes, beaches and mudflats (intertidal habitats), and upland watersheds (riverine habitats). The second question focuses on evaluating the types and quantities of debris in riverine habitats that are transported to San Diego Bay during storm events. The third question assesses demersal and pelagic fish communities in the bay by quantifying the abundance and types of debris ingested.

Study Design

The target population for the San Diego Bay Debris Study includes all bay or bay-influenced habitats, including high-tide zones as well as upland riverine areas. The sample frame includes three different strata, included sub-strata, assessed during this study:

1. Surface waters (trawls)
2. Intertidal areas, including:
    a. Mudflats and salt marshes
    b. Beaches
    c. Rip-rap
    d. marinas (marina skimmers)
3. Rivers

Sites within each of the study strata are shown in Figure ii.

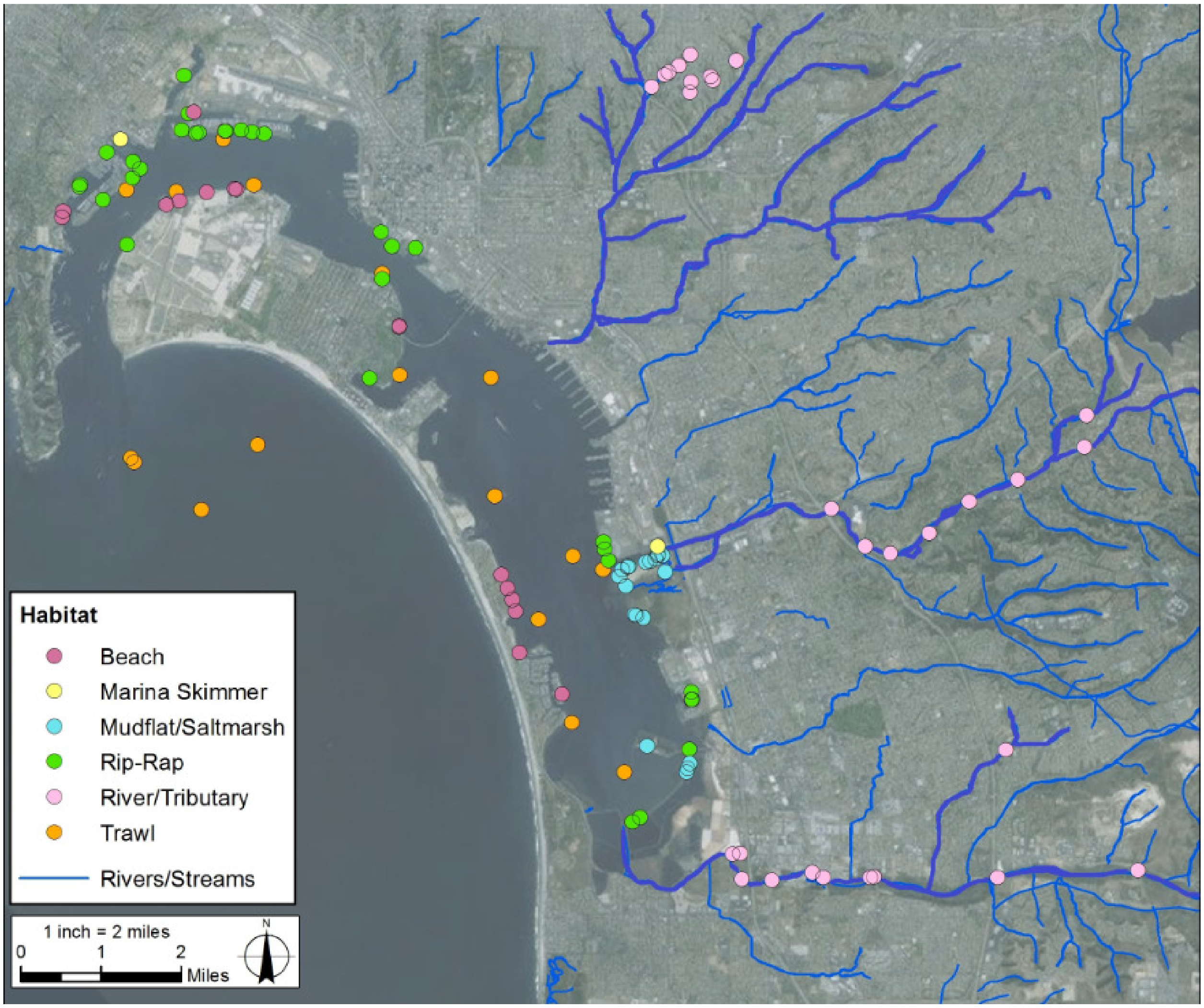

Figure ii. Strata and Sites Surveyed for the San Diego Bay Debris Study. Major drainages chosen as the focus for the River/Tributary portion of this study are shown in dark blue.

Sites within habitats were randomly selected to provide an unbiased sample among sites and to allow for inference into bay-wide conditions. Pre- and post-storm sampling was conducted in all habitats, and consisted of one survey conducted during dry weather in the summer and fall, and one survey conducted after a series of wet weather rain events that resulted in a cumulative rainfall total of greater than 1 inch. Continuous sampling in San Diego Bay was performed at two locations between the dry weather event and the post-storm weather event using marina trash skimmers (marina skimmers). The marina skimmers gathered continuous data throughout the study period to provide information on seasonal variations with regard to plastics. In addition to the habitat assessments listed above, this study investigated the impacts of small plastics and micro-debris ingestion by demersal and pelagic fish.

For this study, plastic items collected in each of the habitats were sorted, counted, and quantified by volume according to three different size categories. The classification and size ranges analyzed for this study follow the National Oceanic and Atmospheric Administrations (NOAA) Marine Debris Shoreline Survey definitions listed in Table i.

Table i. Debris Classification and Size Ranges for Analysis.

Category	Size
Macro-debris	> 25 cm
Meso-debris	4.75 mm – 25 cm
Micro-debris	2 mm – 4.75 mm
	1 mm – 2 mm
	0.71 mm – 1 mm
	0.5 mm – 0.71 mm
	0.355 mm – 0.5 mm

Key Findings

The key findings under the San Diego Bay Debris special study are as follows:

- **Plastic debris is present in approximately 88% of San Diego Bay intertidal zones.** In any intertidal habitat surveyed during this study, debris was present in more than 70% of the area surveyed. The intertidal habitat contains numerous pieces of plastics at various stages of degradation. It is estimated that the total abundance of plastic debris in San Diego Bay is greater than 20.4 million (±7.4 million) plastic pieces. Most of the plastic debris was concentrated in only a few sites; 16 of 71 sites surveyed made up the top 75th percentile of total plastic debris abundance (number of items).

- **Mudflats and saltmarsh habitats are key reservoirs for plastic debris in an enclosed bay environment.** A 100% of surveyed mudflat and saltmarsh habitats contained at least one plastic debris item. An estimated 3,004 (±1,900) macro and meso-sized plastic debris pieces were found per survey site in mudflats and saltmarsh habitats, a quantity that was five times greater than that at rip-rap sites and 27 times greater than that at beach sites. On a volume basis, the largest volume of plastic items was recorded in rip-rap habitats.

- **Polystyrene foam and persistent plastics were the most common types of plastic found in San Diego Bay watersheds and in bay habitats.** Polystyrene foam was consistently found in intertidal habitats, rivers, marina skimmers, and bay open-water trawls. Products made from polystyrene foam were found in intertidal area samples (47% of samples) and marina skimmer samples (32% of samples), while food wrappers, single-use plastic bags, and hard plastic pieces represented 45% of all plastic debris collected in rivers and tributaries drainages (Table ii). Fragmented plastics, including hard and soft plastic pieces, were also among the most common plastic debris types in all habitats, which may have reflected the breakup of larger, intact debris items.

Table ii. Top Plastic Debris Types Within River, Intertidal, and Marina Habitats.
Grey cells indicate the debris items representing the top 70% of total abundance for that habitat.

	Habitat		
Plastic Debris Type	**River**	**Intertidal**	**Marina**
Bags (single-use)	10%	2%	3%
Bottle Caps	2%	1%	2%
Cigarette Butts	4%	3%	19%
Fishing Line/Net	<1%	1%	<1%
Food Wrapper	25%	4%	6%
Hard Plastic Pieces	10%	18%	<1%
Lid	2%	<1%	3%
Other Wrappers	<1%	2%	7%
Polystyrene Foam Cup/Pieces	2%	<1%	11%
Polystyrene Foam Pellets	<1%	4%	9%
Polystyrene Foam Pieces	7%	43%	12%
Soft Plastic Pieces	6%	10%	9%
Synthetic Fabric	7%	<1%	<1%
Water Bottles	1%	<1%	2%

- **Stream monitoring efforts were effective in identifying hotspots and characterizing important pathways for trash to the bay.** Chollas Creek tributaries consistently contributed the largest amounts of plastic meso-debris in pre- and post-storm surveys. The absence of elevated debris quantities in the Sweetwater and Otay Rivers suggests that the upper watersheds (upstream of the intertidal zone in Sweetwater River) of these major river systems may not be important pathways for debris into San Diego Bay, and the other drainages not surveyed as part of this study potentially provided the necessary transport pathway to the bay. Most of the plastic debris found was recorded at only 5 of the 29 sites surveyed. This finding suggests that debris likely accumulates at only a few key areas within watersheds, and that the debris is transported to downstream areas during storm events.

- **Geomorphology plays an important role in determining the types and quantities of debris found in streams and influences the types of debris transported to San Diego Bay.** Not surprisingly, natural waterways consisting of earthen streambeds with emergent vegetation and riparian habitats accumulated the largest amount of debris from storm-based high flow events. The geomorphology results illustrate one of the key reasons that the most prevalent types of debris located in streams tend to be different from the most prevalent types of debris found in San Diego Bay. Streams with emergent vegetation and riparian foliage tend to accumulate plastic items such as food wrappers and plastic bags, whereas smaller (e.g., soft plastic pieces) or quickly degradable (e.g., polystyrene) items were preferentially transported to San Diego Bay.

- **Small plastic debris (0.5 millimeter [mm] to 1 centimeter [cm]) is abundant in surface waters and shallow water sands of San Diego Bay, and is being consumed by some fish species.** 100% of surface water trawls and 97% of shallow water sand samples contained small micro-debris sized plastics. Sand samples contained an average of 6,654 pieces of small plastic debris per cubic meter of sand. Most plastics found in sands were fiber material. Plastics made up of clear, white, black, and blue colors were especially common in both sand samples and surface water trawls. Recent studies have shown that plastic micro-debris affects biologic communities through ingestion, inhalation, and absorption. This study included dissection of a variety of benthic and pelagic fish species to look at accumulation of plastic micro-debris in fish guts. Approximately 18% of round stingray (*Urolophus halleri*) samples showed evidence of ingested plastic micro-debris, which was predominantly composed of hard plastic pieces and fibers. Plastics that were clear and white and consisted of hard and soft plastic materials were the most common items ingested by the one white seabass and 17 spotted sand bass analyzed during this study.

Recommendations

The following strategies for plastic debris mitigation, removal, and future monitoring are based on the findings of the San Diego Bay Debris Study monitoring results from 2014–2015:

1) **Focus cleanup efforts on hotspots to remove substantial amounts of debris from San Diego and schedule these cleanup events during the peak accumulation periods.**

   Debris management programs implementing debris cleanup strategies should prioritize the rivers and tributaries in the contributing watersheds during pre-storm dry periods (July through October) and mudflat and saltmarsh habitats after winter storm events (December through April).

2) **Implement targeted public outreach and source control programs to reduce polystyrene foam use and disposal.**

   In some locations studied, polystyrene foams and polystyrene pieces produced from degradation of food service containers were so abundant that they were impractical to count and nearly impossible to collect into a sample container. A targeted outreach effort supported by local initiatives to remove polystyrene products from food service practices would be environmentally beneficial. Elimination of this type of plastic from San Diego Bay would similarly translate into less effort needed for cleanup campaigns.

3) **Continue to implement plastic debris monitoring programs to track the progress of plastic debris reduction strategies.**

   The San Diego Bay Debris Study provided a baseline of bay conditions. The near-future implementation of trash reduction strategies, potentially by implementing the statewide Trash Amendments, is expected to reduce trash quantities in both the rivers and San Diego Bay. Maintaining a monitoring and assessment program would provide an opportunity to quantify trends over time. The explicit purpose of the detailed and labor-intensive monitoring effort for this study was to establish a robust baseline. Future receiving water monitoring efforts should improve upon current methods to develop a protocol for trash monitoring that requires minimal time and labor.

4) **Investigate the implications of plastic debris on sensitive habitats within an enclosed bay system.**

   Salt marsh and mudflat habitats provide important nesting and foraging lands for a variety of terrestrial birds and aquatic species. Fourteen of the 71 sites surveyed contributed more than 80% to total plastic debris and were located in or near the San Diego Bay National Wildlife Refuge, which protects critical saltmarsh and mudflat habitat and provides a buffer from surrounding urban development (U.S. Fish and Wildlife Service 2013). Additional research is needed to understand the effects of plastic debris specifically on critical habitats and its sensitive or endangered species.

5) **Further examine the food chain implications of fish caught in San Diego Bay that have ingested plastics.**

   The data generated in this study provided evidence that coastal embayments may have a higher rate of plastic ingestion in resident fish as compared to the fish that are caught in the open ocean. This study result found an elevated percentage of fish in the bay that are ingesting plastics, especially those fish caught in intertidal areas. These fish are prey for higher trophic species, creating a potential opportunity for transmission of plastic contaminants into predators such as larger fish and birds. Additional characterization of aquatic and terrestrial species in San Diego Bay that are ingesting plastic debris would further understanding of the long-term implications of plastic ingestion on food chain uptake pathways.

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I. Riverine Debris Across San Diego Bay Watersheds: An Assessment of Plastics in Otay River, Sweetwater River, and Chollas Creek Tributaries

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Abstract

Plastic debris accumulation in terrestrial and marine environments is a widespread economic and environmental health issue. California has recently enacted legislation to remove anthropogenic debris from storm drain system discharges to receiving waters. Rivers and streams are a key pathway for plastic debris transport from land to coastal embayments and the ocean, and the effects of land-based trash on the ocean are generally understood. However, river and stream trash monitoring is still a relatively new area of research. Receiving-water-based monitoring programs provide an opportunity to establish baselines for measuring the effectiveness of management decisions and provide a starting point for managers to begin prioritizing and focusing on specific locations for their trash reduction efforts.

San Diego Bay is a large embayment located in the southwestern portion of the greater San Diego metropolitan area that receives runoff from three major river systems—Otay River, Sweetwater River, and Chollas Creek—and a large number of smaller tributaries and storm drains. The trash impacts of major river systems on coastal embayments have not been well characterized in the highly populated coastal area of southern California. This report represents a special study conducted in the San Diego Bay watershed to study the inputs of trash from the major upland riverine habitats into a coastal embayment.

This study evaluates the magnitude and extent of plastic macro- and meso-debris in the upper watersheds of San Diego Bay, the recurrent types and sources, and the effect of seasonal variations and wet weather flows on debris distribution. Approximately 83% of sites contained plastic debris, with quantities ranging from less than one item per square meter (0.007 item/m^2) to 9 items per square meter. Food wrappers, single-use plastic bags, fragments of larger plastic debris (hard and soft plastic pieces), polystyrene foam, synthetic fabric, and cigarette butts constituted 68% of all plastic debris identified. Finally, plastic debris accumulated mostly throughout the rainy season at locations that had the highest debris densities during the initial pre-storm surveys, indicating that certain hotspot locations may be more prone to debris accumulation.

Introduction

With 311 million tons produced globally in 2014, plastics are one of the most commonly used materials worldwide (PlasticsEurope 2015). Plastics are consistently the most abundant debris type found during previous studies in southern California upper watersheds, generally making up 70% of total debris found in the upper watersheds and beaches (Moore et al. 2016; Moore et al. 2011; Golik and Gertner 1992). Plastics are used in a broad range of products because they are durable, inexpensive to produce, and easy for consumers to dispose of (Laist 1987). Although ingestion of micro-sized (< 5 mm) plastic debris has repeatedly been shown to have harmful effects on aquatic life through digestion and sorption (Brennecke et al. 2015; Cole and Galloway 2015; Rochman et al. 2013; Rochman 2015; Wu et al. 2016), the types and spatial distribution of macro-sized (>25 cm) and meso-sized (25 cm – 4.75 mm) debris that are the most damaging to the marine environment are not well understood. The fragmentation of macro- and meso-sized plastic debris contributes to the presence of micro-sized plastic debris in the marine environment (Barnes et al. 2009; Weinstein et al. 2016). Therefore, these size categories can provide important information about the potential impacts of plastic debris on the environment.

In the upper watersheds, factors such as densely populated urban areas, percent of paved roads (imperviousness), public accessibility, and the type of adjacent roadways have been associated with the greatest levels of plastics accumulation in the southern California region (Moore et al. 2016). The rivers and canyons in southern California flush debris during wet weather events from land-based sources in the upper watersheds to the lower reaches and eventually out into bays, estuaries, and the open ocean. Pathways of deposition include deliberate littering and dumping of unwanted debris and wind-blown loss from waste management areas (Ryan et al. 2009; Pruter 1987). Through the various sources and pathways, surface runoff eventually carries the deposited debris into receiving waters. Land-based sources contribute 60% to 90% of the debris found in the marine environment (Derraik 2002; Allsopp et al. 2006; Sheavly 2010). Recent California regulations require government agencies to eliminate all anthropogenic debris greater than 5 millimeters in size from the Municipal Separate Storm Sewer System (MS4) discharges in priority land use areas (California State Water Resources Control Board 2015). These regulations make it increasingly apparent that data on debris abundance (number of items), sources, and spatial distribution will be an important baseline on which municipalities can track conditions over time.

This study focused on identifying the magnitude, spatial distribution, and composition of plastic debris associated with the major rivers, and their tributaries, that feed into San Diego Bay: Chollas Creek, Sweetwater River, and Otay River. Chollas Creek is located within a sub-watershed of the Pueblo San Diego Watershed, on the northeastern end of San Diego Bay, within the San Diego Mesa Hydrologic Area. Of the San Diego Bay watersheds, Pueblo San Diego holds approximately 53% of the population. A total of 75% of the land area in the watershed is developed (Project Clean Water). The San Diego Mesa Hydrologic Area contains 40% residential, 29% transportation, and 6% open space land uses (San Diego Regional Water Quality Control Board 2016). Chollas Creek is currently on the Clean Water Act Section 303(d) list as impacted for trash (California State Water Resources Control Board 2015).

Sweetwater Watershed, located in the central-eastern portion of San Diego Bay, containing Sweetwater River, represents the largest area of the three watersheds (SANDAG 2015). Sweetwater River runs through three Hydrologic Areas—Upper, Middle, and Lower Sweetwater. The Sweetwater Reservoir serves as a physical barrier between the watershed above the reservoir, which is primarily undeveloped and protected lands, and the developed lower watershed. All surveys in this study were conducted within the Lower Sweetwater Hydrologic Area, below the Sweetwater Reservoir, where the land use is primarily residential (44%). .

Otay River lies within the Otay Watershed in the southeastern portion of San Diego Bay. Less than 50% of the watershed is developed, and the area is the least developed of the three watersheds.

Otay Watershed comprises three Hydrologic Areas, but only the areas below Lower Otay Lake were surveyed during this study because it represents the most developed portion of this watershed (primarily residential land use with some commercial properties). Similar to the Hydrologic Areas containing Sweetwater River, most of Otay Watershed above Lower Otay Lake consist of undeveloped land and open space (49%) (State Water Resources Control Board 2016).

The presence of plastic debris in Chollas Creek, Sweetwater River, and Otay River was evaluated by answering the following study questions:

1) What are the magnitude and extent of plastic debris in the upper watersheds?
2) What are the types and sizes of plastic debris in these San Diego Bay rivers and tributaries?
3) How do wet weather flows affect seasonal variances in the magnitude and spatial distribution of plastic debris in rivers and tributaries?

Materials and Methods

Study Design

A targeted site selection process was adopted to choose the monitoring locations within the watersheds and sub-watersheds of San Diego Bay. Sites along the Sweetwater and Otay Rivers were selected from the pool of sites generated by the Southern California Stormwater Monitoring Coalition (SMC) 2013 Regional Monitoring Program. The SMC sampling framework focused on all perennial, wadeable, second-order and higher streams (NHD Plus, US Geological Survey and US Environmental Protection Agency 2005). The numbers and locations of SMC sites needed for this study were not sufficient to collect representative samples in each stream, so additional sites were chosen in the Otay and Sweetwater watersheds using a randomized selection process. Sites were spatially distributed using predefined polygons representing evenly sized stream segments as the intended sampling areas and the final sites selected were determined using a random number generator. Sites located within the Sweetwater estuary west of the I-805 freeway were discarded due to inaccessibility and the intertidal characteristics of the river segment. The SMC's site selection process did not generate monitoring sites in the San Diego Mesa Hydrologic Area and an alternative process was used to locate representative sites. Four seasonal creeks within the San Diego Mesa Hydrologic Area sub-watershed were selected because they reticulate the mid-city region of San Diego and drain into Chollas Creek. These seasonal creeks were located in Swan, Manzanita, Hollywood, and Olivia canyons. Sites were evenly distributed longitudinally along each seasonal creek to capture the debris gradients from the input locations to the confluence with the Chollas Creek main stem. The selection process resulted in 29 sites located in three watersheds (Figure 1).

Sample Collection

Site surveys were conducted once during the dry season in the summer and early fall months (August through October) and then again after several major rain events (January through June). The data collection process followed the Rapid Trash Assessment (RTA) approach initially developed by the San Francisco Bay Regional Water Quality Control Board (2004). Each site consisted of a 30.5-meter-long (100-foot-long) transect parallel to the stream flow direction and spanned the streambed within the ordinary-high water mark, or bank-full width. Survey areas were established at each site prior to data collection. Survey lengths were measured using field transect tape which was positioned on the ground with the pre-determined site coordinates at center of the survey area. If obstructions such as heavy vegetation prevented teams from surveying the full 30.5-meter-long transect, the true transect length was recorded and accounted for during data analysis. Initial site characterization included an evaluation of storm drain inputs and the presence of homeless encampments within and upstream of the survey area, adjacent land uses, and stream geomorphology within the transect length. Land use classifications included on the field forms were residential, park, open space, commercial, and industrial. Multiple categories may have been selected if more than one land use type was observed. Plastic debris was collected within each survey area using the following steps (in order):

1) Collect all macro-debris (greater than 25 cm long).
2) Collect all meso-debris (between 25 cm and 4.75 mm long).

Plastic macro-debris was first collected and categorized as bags and packaging, household based items, toxic, food service, and miscellaneous, which covers items that do not fit any of these categorical descriptions. Each plastic debris item was then identified and counted by its specific debris type on the field data sheet. The same process was then performed for meso-debris inside the survey area. Finally, volumes of each debris size and category were measured using a 5-gallon volumetric container with 1-liter increments marked on the inside of the container.

Post-storm site visits were conducted after a period of substantial storm events (cumulative rainfall >1 inch) to observe changes in debris spatial distribution and re-accumulation amounts. From November 2014 to March 2015, the San Diego area received 6.5 inches of rainfall (Western Regional Climate Center 2016). Twenty-three sites were evaluated during the post-storm winter season. Flooding and temporary site restrictions imposed by local property owners prevented completion of the post-storm surveys at six sites.

Quality Assurance

Quality assurance protocols adopted for this study included protocol training, independent site audits, follow-up inspections, and data verification reviews. Surveys were performed by multi-agency members, which created an opportunity for error and personal bias to be introduced into results. To account for these potential errors, the survey protocol included several steps for quality assurance during sample collection, as well as quality control measures during post-sample processing. Agency-specific team leaders provided initial training for the designated field team captains and their field staff. Trainings focused on establishing consistency in data collection activities and identification of debris items using a standardized set of definitions. The agency team leaders also performed audits of their field team's data collection methodologies.

In the field audits, the team leader evaluated and scored each field team interviewed. Performance scores were based on completion, repeatability, and accuracy in location and item identifications.

Teams that did not receive a score of 100% on the performance audit received immediate feedback on areas of inconsistency.

In addition to the field-based quality assurance protocols, laboratory-based protocols were implemented for the study. Plastic debris collected at 10% of sites was retained for reanalysis, which included recounting the items and verifying the item debris category (bags and packing, household, food service, etc.). Macro- and meso-debris collected during initial surveys was later recounted to ensure accurate debris identification. The team recognized that quantities of debris could be skewed by the breakup of the items during transportation of the samples to the laboratory. Because data quality objectives have not yet been developed for debris surveys, variations of more than 30% in identified debris types were considered to be a sufficient basis for flagging the portion of the data quality in question.

All field forms were reviewed for completeness and consistency following initial data collection. A 100% check of all data entry against field forms was performed prior to data analysis.

Data Analysis

Debris density is defined in this study as the count (abundance) divided by the survey area. Plastic debris densities were calculated counting the number of plastic items found along the surveyed area and dividing the debris quantities by the area (site-specific length and bank-full width).

River and tributary comparison. Differences in the amount of debris (density and volume) found between rivers and tributaries before and after storms were tested using two-way Analysis of Variance (ANOVA) on log (x+1) transformed data to normalize data and homogenize variances. Differences in the composition of debris between rivers and tributaries were explored using Non-metric Multi-Dimensional Scaling (NMDS), Analysis of Similarity (ANOSIM), and Similarity Percentage (SIMPER) run on Primer Statistical Software (Clarke 1993). Debris densities pooled from pre- and post-storm periods were log(x+1) transformed to normalize distributions and homogenize variances. Bray-Curtis similarity indices of the log(x+1) transformed data were calculated to compare the debris type distribution between streams. Stress values resulting from up to 1,000 permutations were examined for stability to determine how accurately the NMDS diagrams represent the multidimensional distances between the rivers and tributaries. Clarke (1993) suggests that values <0.2 are useful; therefore, only the analyses with stress values <0.2 were used.

Factors contributing to differences in plastic debris density and volume between rivers and tributaries, such as channel substrate type and surrounding land uses, were evaluated using Kruskal-Wallis One-way Analysis of Variance (ANOVA) in JMP® 12.

Pre- and post-storm comparisons. Differences in amount of debris (density and volume) between pre- and post-storm periods were tested within each river and tributaries using a Matched Pairs t-test, and interactions between substrate type and debris accumulations or losses with rainy season were tested using two-Way ANOVAs. Both tests were run using JMP® 12 Statistical Software.

Results

Magnitude and Extent of Plastic Debris

Approximately 83% of sites surveyed pre- and post-storm contained at least one piece of plastic debris. A total of 2,681 pieces of plastic debris were identified and collected within 5,352 square meters of stream area. Survey transects covered 761.55 meters of stream length, representing 0.6% of the overall stream length of the four Chollas Creek tributaries, Sweetwater River, and Otay River. The mean density of plastic debris from the three rivers and tributaries was 0.83 (±0.37) items per square meter, with a mean volume of 0.21 (±0.15) liters per square meter (Table 1). Of the 29 sites sampled during pre-storm conditions, two sites did not have any plastic debris present; macro-debris items (debris size >25 cm) were observed at 62% of sites, and meso-debris items (debris size 5 mm – 25 cm) were found at 93% of sites. Five of the 29 sites represented 58% of the total macro- and meso-debris plastic density in the pre-storm period with site number and percentages as follows: SW106 (14.3%) and SW107 (8.5%) in Chollas Creek, SR-MLS (13.6%) in Sweetwater River, and ROR-12B (10.3%) and SMC04330 (11.4%) in Otay River (Figure 1).

Types of Plastic Debris

The most abundant plastic meso-debris types, composing approximately 70% of all meso-debris found, were food wrappers (25%), single-use plastic bags (10%), hard plastic pieces (10%), polystyrene foam (7%), synthetic fabric (7%), soft plastic pieces (6%), and cigarette butts (4%) (Figure 2, Table 2). The items identified as “Other” were most commonly identified within food service, household, and miscellaneous debris categories, and included car parts, commercial packaging, pieces of construction and painting supplies, mesh bags, Christmas decorations, public signs, and other uncommon items (Table 2).

Sizes of Plastic Debris

Across all rivers and tributaries, plastic meso-debris density was three times greater than macro-debris density (Table 3, Figures 3.a and 3.c), but three times less in volume than the macro-debris volume (Table 3, Figures 3.b and 3.d). Abundances of macro-debris were not consistent across rivers and tributaries, with no significant differences in density. Macro-debris volume was greatest in Otay River during the pre-storm period (Table 3, Figure 3.b).

Plastic Debris Composition Across Rivers and Tributaries

Chollas Creek had 43 to 58% higher mean plastic debris densities (more items per square meter), but lower mean volumes than the other two streams (Table 1). Composition of plastic meso-debris differed most between the Chollas Creek tributaries and the other two rivers (76 to 78% dissimilar; Table 4), in part because the composition between sites *within* Chollas Creek tributaries was more similar (63% dissimilarity) than that *within* the Sweetwater River and the Otay River (76 to 79% dissimilarity) (Figure 4; Table 4). Dissimilarities in plastic debris between Chollas Creek tributaries and both Otay and Sweetwater Rivers can also be attributed to debris types that are unique to each stream. About 75% of the dissimilarity between Chollas Creek tributaries and the other rivers was due to differences in just a few types of plastic items (SIMPER). Chollas Creek tributaries had the highest density of food wrappers and hard and soft plastic pieces, when compared with the two rivers (Figure 5). Sweetwater River had greater densities of single-use plastic bags, cigarette butts, and “other” items compared with the Chollas Creek tributaries (Figure

5). Otay River had higher densities of foam polystyrene pieces and cigarette butts than the Chollas Creek tributaries (Figure 5).

Trends in Land Use and Substrate with Plastic Debris

Observed surrounding land use and streambed substrate information collected during surveys was compared across sites to identify potential contributing factors to debris accumulation patterns. While there was no significant difference in macro-debris density between land uses, meso-debris volume was highest in locations identified within residential-commercial and commercial land uses (ANOVA, P=0.03).

Plastic debris accumulations throughout the rainy season were greatest at sites with earthen substrate (94% increase) and with both earthen and large rock substrate (65% increase), while the greatest losses of debris (83% reduction from pre-storm quantities) were experienced in sites with concrete and emergent vegetation (Table 5).

Impacts of Wet Weather Flows on Seasonal Variance of Debris Spatial Distribution

Plastic debris density and volume in Chollas Creek tributaries were significantly higher during post-storm surveys than during pre-storm surveys (Figure 3, $p = 0.02$), with a mean increase of 2.5 items, totaling 0.24 liter, per square meter. The greatest increase in debris densities occurred at sites MZ104, SW106, and SW107, where debris densities increased by an average of 6.4 items per square meter between pre- and post-storms.

Within the Otay and Sweetwater Rivers, macro- and meso-debris density decreased between pre- and post-storm surveys, but this decrease was not statistically significant (Figure 3). Notably, 54% of the sites along the Otay and Sweetwater Rivers did not have any trash present during post-storm surveys. Most of the post-storm debris recorded within the Otay and Sweetwater Rivers was observed at sites ROR-12B and SMC04330, which are located immediately downstream of an outfall. Site ROR-12B had the highest density of debris within these two streams during post-storm surveys. This site is the farthest downstream site and is directly adjacent to a major freeway. All sites with relatively high debris accumulation during post-storm surveys had earthen and/or large rocks in the streambed, and, with the exception of site SW107, all were located close to either a major roadway or a walking path.

On average across all sites, four of the seven most abundant plastic meso-debris types increased during post-storm surveys. Food wrappers, single-use plastic bags, hard plastic pieces, and synthetic fabric clothing densities increased by over 100% from pre- to post-storm surveys; while densities of soft plastic pieces, cigarette butts, and polystyrene foam decreased by 24%, 50%, and 92% (respectively) during post-storm collection.

Discussion

A total of 61% of the 9,088 square meters surveyed in the Pueblo San Diego, Sweetwater, and Otay watersheds contained plastics debris. These are the three major watersheds discharging into San Diego Bay (San Diego Bay Watershed Copermittees 2013), indicating that urban plastics debris not only is a pollutant in these coastal watersheds, but also poses a threat to the health of the Bay (Hoellein et al. 2014).

Plastic Debris Spatial Distribution throughout San Diego Bay's Watersheds

Although plastic debris was present throughout most (83%) of sites surveyed during this study, the Chollas Creek tributaries had the highest average abundances of meso-debris items, contributing 43% of the total density and 30% of total debris volume found in this study. Chollas Creek tributaries had, however, 6 to 20 times fewer macro-debris items than the Otay and Sweetwater Rivers. Only the portions of Otay and Sweetwater Watersheds below the Sweetwater Resevoir and Lower Otay Lake were surveyed as a part of this study, which incorporates most of the developed areas within these two watersheds.

The amount of plastic debris observed at each location varied greatly and ranged from 0.007 plastic debris items per square meter to 9 items per square meter. While plastics were fairly evenly distributed throughout the Chollas Creek tributaries, the Otay River had the most highly varied distribution of plastics. Debris dispersion may be influenced by a variety of factors, including wind, stream substrate characteristics, proximity to inputs, rainfall patterns, surrounding population density, recreation, and land use (Ryan et al. 2009; Derraik 2002). Although the Pueblo Hydrologic Unit covers the smallest area of all three San Diego Bay watersheds, it is the most developed and densely populated (San Diego Regional Water Quality Control Board 2016; SANDAG 2015), which may account for the high and more even spatial distribution of trash throughout the areas studied.

Types of Plastics in San Diego Bay Watersheds

Food wrappers, plastic bags, plastic pieces, foam pieces, and cigarette butts were among the most abundant debris types found in this study and these results are consistent with those of other studies conducted in riverine habitats in Ohio and California (Moore et al. 2011; Lawrence 2016). Food wrappers and single-use plastic bags collectively accounted for 35% of the total pieces of debris counted within the 50 different plastic debris types identified during pre-storm surveys. Hard and soft plastic pieces, polystyrene foam, clothing, and cigarette butts made up the remaining 33% of the plastic debris items representing the majority of plastic debris density. The availability of the most common plastic types is likely a large contributing factor to their abundance in the environment. The packaging industry provided up to 34% of plastic materials produced during calendar year 2014 (American Chemistry Council 2015). Additionally, plastic bags are one of the most frequently used plastics used in urban areas (Adane et al. 2011). The City of San Diego recently became the 150th municipality in California to ban single-use plastic bags in local stores and retailers (San Diego Union Tribune 2016), but the statewide referendum included on the November 2016 ballot will determine whether the California State Plastic Bag Ban is upheld (CNN Money 2015).

Seasonal Accumulations

This study used additional post-storm surveys to examine how seasonal differences may affect plastic debris spatial distribution in the watersheds. Because debris was removed from the site during pre-storm surveys, post-storm densities represent the re-accumulation of debris during the wet season. Post-storm surveys revealed an overall increase in plastic debris density in Chollas Creek, where the highest amounts of meso-debris were recorded. Alternatively, no significant change in density or volume existed between pre- and post-storm periods in the Otay and Sweetwater Rivers. Debris densities decreased at all but one site in these two streams during post-storm surveys; consequently, it appears that while some re-accumulation does occur during storm events, most debris deposits in the Otay and Sweetwater Rivers occur during the dry summer months. Debris re-accumulation in these two streams occurred primarily at downstream locations.

Differences in substrate and plastic debris type found in-stream among the three rivers and tributaries may influence post-storm density results. During pre-storm surveys, there was high density of debris at sites with concrete and emergent vegetation substrates relative to sites characterized by rocky and earthen substrates. Debris densities at sites with concrete and emergent vegetation substrates decreased at these former group of sites during post-storm surveys, and increased at the latter group of sites associated with rocky and earthen streambeds. The differences in pre and post storm conditions is reasonably explained by the fact that buoyant debris tend to continue downstream during rain events in channels where there is less natural obstruction to block transport (such as concrete lined conveyances). Additionally, different types of debris may be transported into receiving water bodies at varied rates based on its structure or buoyancy. Debris types that are generally small and less dense, such as soft plastic pieces, cigarette butts, and polystyrene foam, decreased from pre- to post-storm surveys, while single-use plastic bags, hard plastic pieces, and clothing increased. These results were corroborated by a wet-weather tracking study conducted in coordination with this project.

The wet weather tracking study conducted in Chollas Creek watershed tracked plastic debris movement through the tributaries of the watershed after rain events to identify whether stream substrates and types of plastic material affected retention of the item downstream (Talley et al. 2016). The tracking study found that plastic bags were most likely to become entrapped in vegetation along the streambed, leading to longer retention times and an increased prevalence of plastic bags in the river channel. The tracking study research efforts and the results of this study suggest that natural obstructions could retain certain types of plastic debris in the watershed over time leading to a primary explanation as to why certain stream locations tend to accumulate trash. Moreover, the stream areas that accumulate trash provide a visual clue as to the upland watershed process and land areas that accumulate trash, and at the same time, the conditions of the stream substrate and the absence of trash can help to focus the geographic scale of trash reduction measures. . . .

Recommendations for Future Monitoring

A wide array of data were collected for this study, including site characteristics, outfall presence and size, debris identification, counts by debris type, and volume. Although this information was important for this study to establish a baseline of plastic debris in San Diego Bay watersheds, the time and number of personnel required to collect the data meant that teams were limited in the quantity of sites that could be surveyed within the period of this study. Future monitoring efforts could be improved by refining the survey methods and by focusing the study questions to collect information on either (1) overall magnitude of debris across the watershed, or (2) identification of debris types and potential sources. Conducting frequent monitoring to characterize the re-accumulation rates at known high-accumulation sites can provide valuable information on the success of mitigation efforts over a long-term period (Ryan et al. 2009). Many factors may influence contributions to overall debris amounts and should be considered for future studies. Future studies should expand on the range of potential explanatory variables that can affect debris amounts including median income of the surrounding area and volunteer clean-up programs.

Volunteer based clean-up programs provide process for reducing trash in riverine habitats. Similar to street sweeping reducing the net amount of trash on public roads, volunteer programs reduce a certain amount of trash in rivers. The recommendations for future monitoring programs should include an effort to characterize the relationship between baseline conditions in the river without clean up events and the conditions achieved following volunteer efforts. In turn, agency support for volunteer programs could help to establish performance standards and to refine the trash load reductions earned through these types of land based clean up events.

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Figures

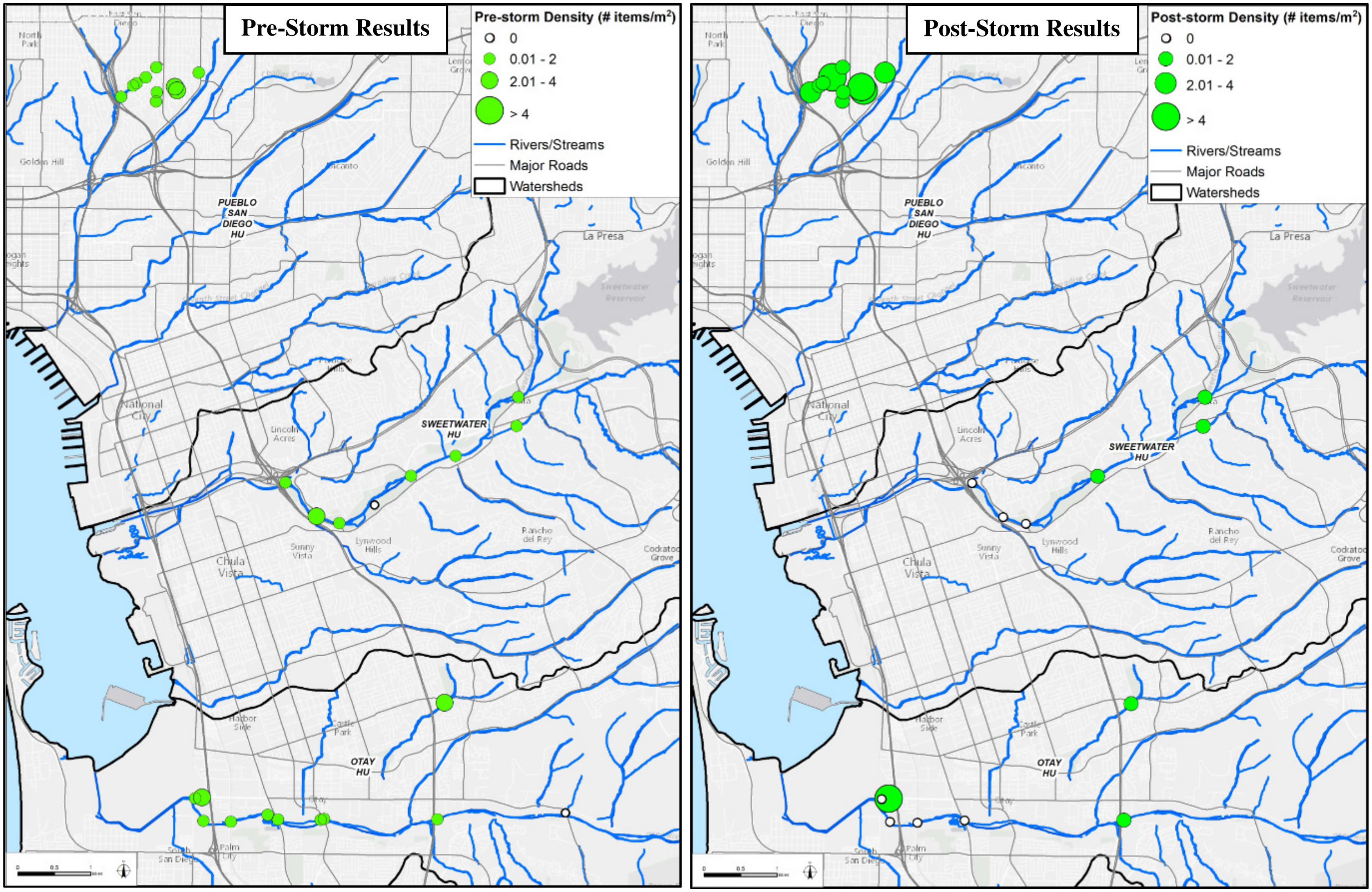


Figure 1. Map of San Diego Bay Watersheds (identified as Hydrologic Units (HU)) and Total Plastic Debris Counts from Pre-Storm and Post-Storm Surveys along Sweetwater River, Otay River, and Chollas Creek Tributaries. Surveys along Otay and Sweetwater Rivers included the main stem and tributaries where accessible. Four seasonal creeks were surveyed as tributaries of Chollas Creek.

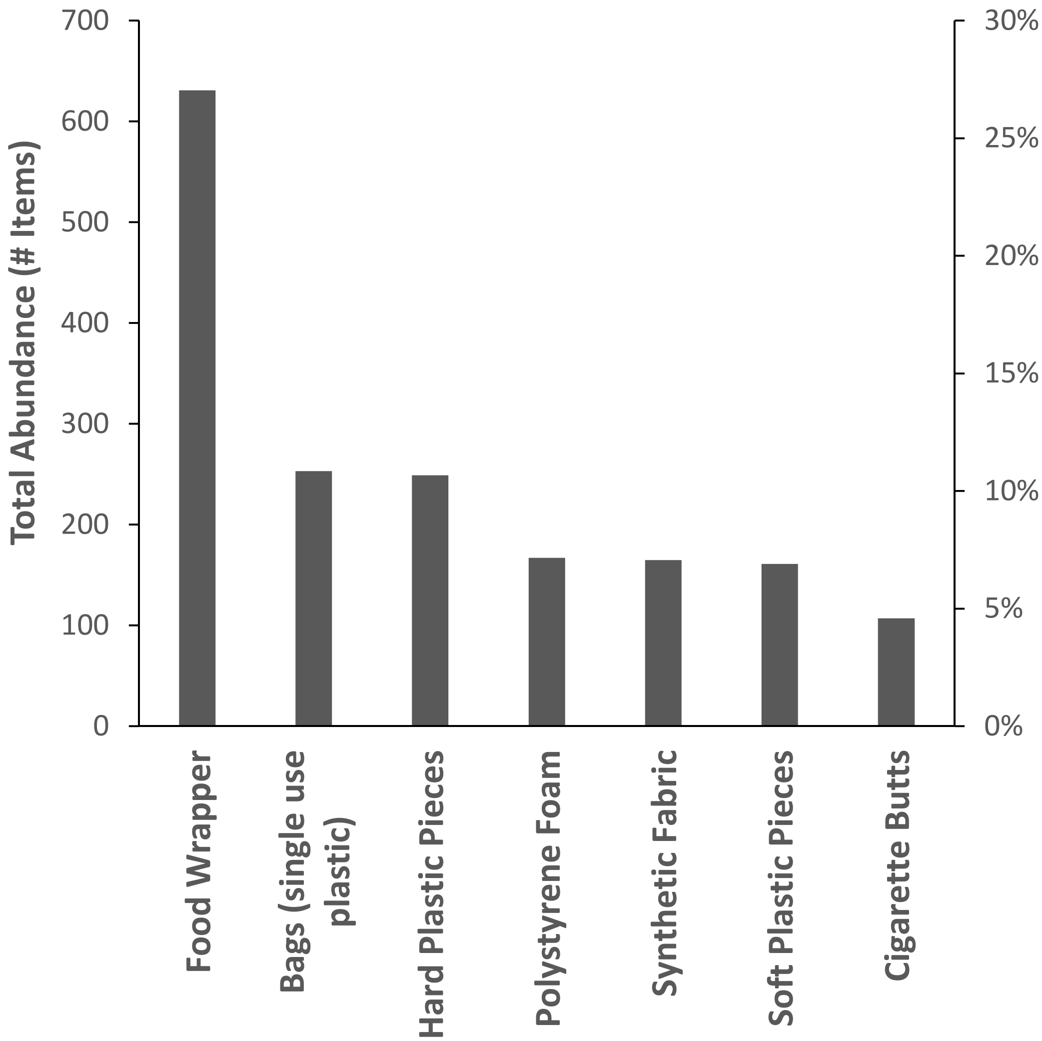


Figure 2. Total Abundance of Plastic Debris of Top Seven Plastic Debris Types from Pre-Storm Surveys. Second axis displays the contribution of each debris type as a percentage of total plastic debris count.

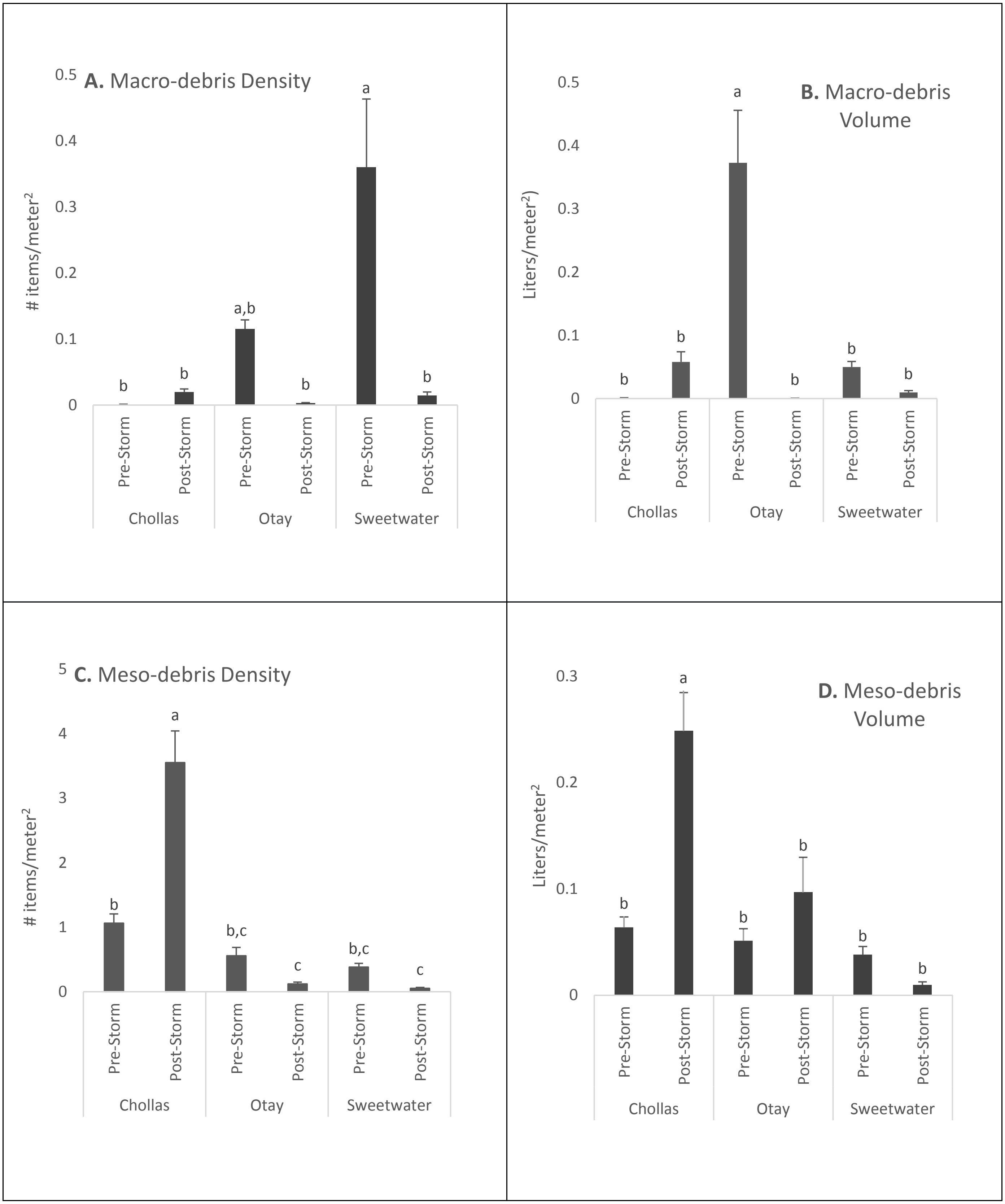
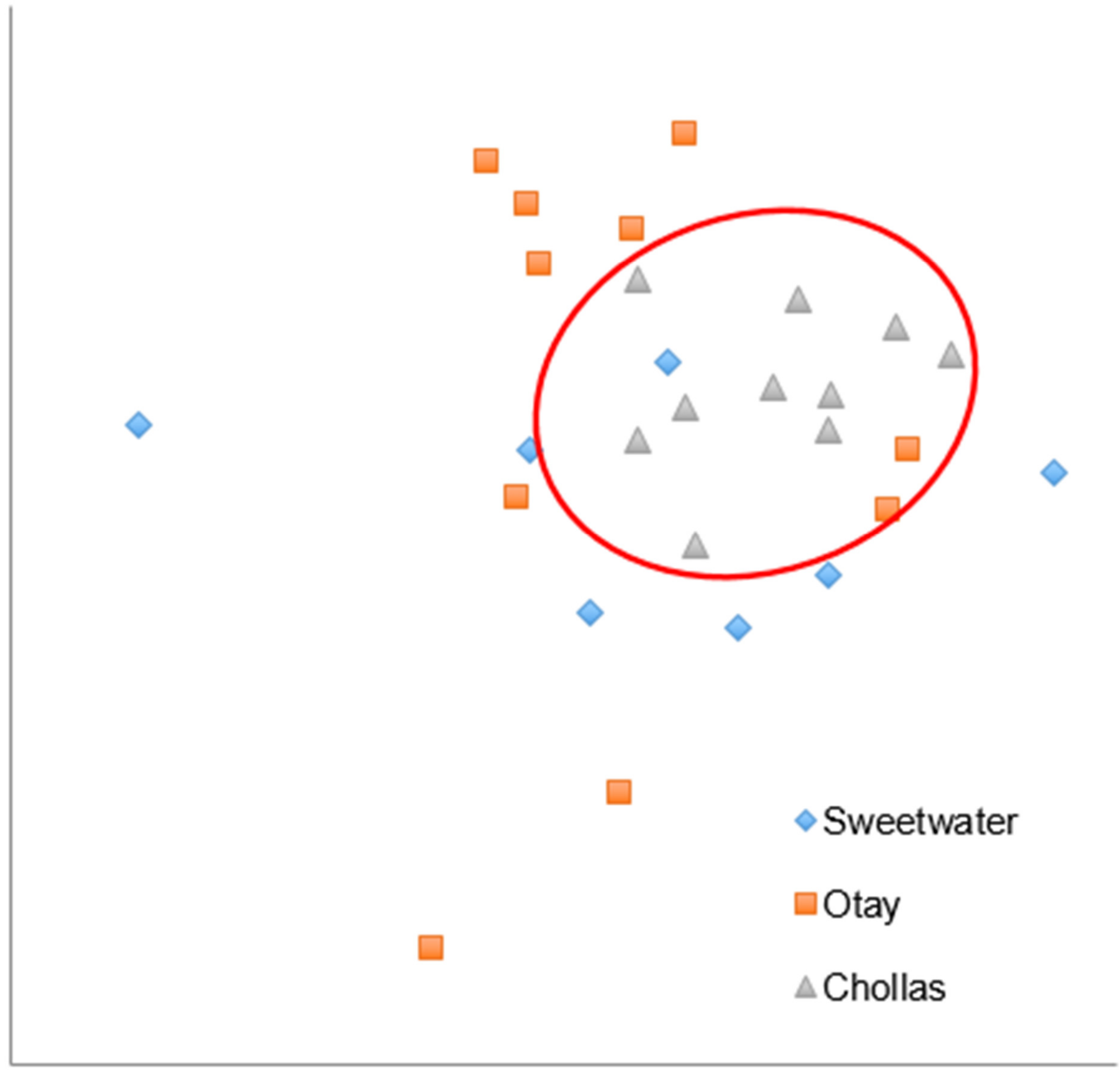


Figure 3. Total Plastic Debris Abundance (± SE) of Macro- and Meso-Debris Size Classes and Pre- and Post-Storm Periods for All Three Rivers. Bars labeled with the same letter are not considered significantly different.



NMDS Axis 1

Figure 4. Non-Metric Multidimensional Scaling of Differences in Debris Type and Abundance Among Samples Collected from the Three Study Watersheds. Circled points represent close similarities within Chollas Creek. Stress=0.13.

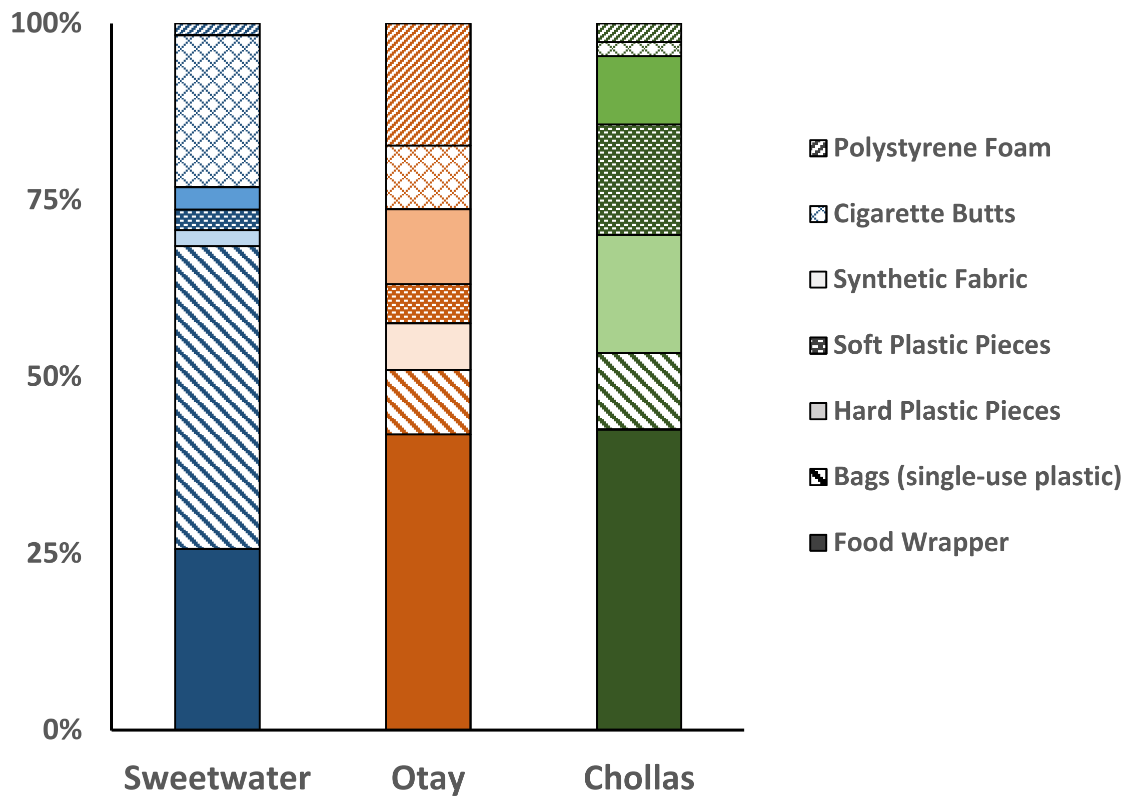


Figure 5. Relative Percent of Total Abundance for the Top Seven Plastic Debris Types within Each Stream. Data are from pre-storm surveys. Items identified as “Other” items are not included in this figure because of the ambiguity of this trash type.

Tables

Table 1. Summary of Mean Plastic Debris Counts and Volumes per Stream during Pre-Storm Surveys. Watershed area and stream length are approximate values.

Watershed	Monitored Stream	Watershed Area (km^2)	Total Stream Length (km)	Surveyed Stream Length (km)	Mean Density ($\#/m^2$)	CI 95%	Mean Volume (L/m^2)	CI 95%
Pueblo San Diego	Chollas Creek Tributaries	155,000	3.40	0.300	1.066	±0.636	0.065	±0.043
Sweetwater	Sweetwater River	596,000	88.51	0.174	0.743	±0.767	0.088	±0.076
Otay	Otay River	414,000	40.23	0.287	0.676	±0.573	0.424	±0.348
Combined		1,165,000	132.39	0.762	0.829	±0.366	0.208	±0.145

Table 2. Total Abundance of All Plastic Debris Types Collected During Pre-Storm Surveys. Debris items representing only the cumulative top 90% of each category total are included.

Plastic Debris Category	Plastic Debris Type	Total Abundance	% of All Plastic Debris	% Cumulative
Bags and Packaging	Food Wrapper	631	25%	25%
	Bags (single-use plastic)	253	10%	35%
	Hard Plastic Pieces	249	10%	45%
	Polystyrene Foam Pieces	167	7%	51%
	Soft Plastic Pieces	161	6%	58%
Food Service	Polystyrene Foam Cup/Pieces	62	2%	60%
	Lid	58	2%	62%
	Bottle Caps	52	2%	64%
	Polystyrene Foam Container	35	1%	66%
	Cups	34	1%	67%
	Water Bottles	30	1%	68%
	Other (condiment, bottle label, liquor bottle, food tray, etc.)	30	1%	69%
	Sports Drink Bottle	16	1%	70%
	Straws	15	1%	71%
Household	Synthetic Fabric	165	7%	77%
	Other (ice chest, sports bag, air freshener, rubber band, Christmas lights)	75	3%	80%
	Sports Balls	17	1%	81%
	Pipe (PVC)	10	<1%	81%
Miscellaneous	Other (car part, sign, mesh bag, safety flag, tubing)	82	3%	84%
	Rubber Pieces	21	1%	85%
	Cigarette Box/Wrapper	15	1%	85%
	Roping/Ties	9	<1%	85%
Toxic	Cigarette Butts	107	4%	90%
	E-waste	16	1%	90%
	Medical Devices (e.g., prescription bottles)[1]	13	1%	91%

[1] Medical Devices does not include syringes or medical pipettes as these were defined as a separate debris type.

Table 3. Comparison of Plastic Debris Abundance (density and volume) Between Storm Periods (pre- vs. post-storm) and Watersheds or Tributaries. Bold values represent significance at p≤0.05 using Student's t-test.

	All Data (*P*)	Storm Period (*P*)	Watershed (*P*)	Stream*Survey Period (*P*)
Meso-Debris Density	**<0.0001**	0.733	**<0.0001**	**0.012**
Meso-Debris Volume	**0.022**	0.161	**0.036**	0.118
Macro-Debris Density	**0.043**	**0.037**	0.166	0.137
Macro-Debris Volume	**0.012**	0.105	0.155	**0.031**

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Table 4. ANOSIM and SIMPER Results for Stream Comparison. ANOSIM p values are above the diagonal. SIMPER dissimilarity percentages on and below the diagonal. Bold values represent significant figures. Global ANOSIM p = 0.0008.

	Chollas	Otay	Sweetwater
Chollas	63%	**0.011**	**0.012**
Otay	**78%**	76%	0.135
Sweetwater	**76%**	79%	79%

Table 5. Mean Change in Plastic Meso-Debris Density and Volume Before and After the Rainy Season (post-storm minus pre-storm) for All Rivers and Tributaries Sampled.

Substrate (may include a mixture of geomorphologies)[2]	Change in Mean Density (# items/m^2)	Cl 95%	Change in Mean Volume (L/m^2)	CI 95%
Earthen	8.12	5.924	11.21	7.23
Earthen, Large Rocks	2.14	1.786	2.94	2.18
Concrete, Emergent Vegetation	-0.83	4.189	-0.001	5.11
Concrete, Earthen, Emergent Vegetation, Large Rocks	-0.83	5.924	-0.98	7.23
Concrete	-0.94	5.924	-0.96	7.23
Earthen, Emergent Vegetation, Large Rocks	-0.99	2.650	-0.99	3.24
Earthen, Emergent Vegetation	-1.00	4.189	-1.00	5.11

[2] Substrates were based on presence/absence and specific proportions were not determined during surveys.

II. Status of the Bay: Assessment of Plastic Debris in San Diego Bay

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Abstract

Coastal wetlands and bays are important intermediary waterbodies between the upland watersheds and the marine environment. As the primary connection between rivers and ocean, coastal embayments may be a key sink of land-based debris. The extended residence time within these embayments may also exacerbate the breakdown and deterioration of larger debris items into smaller pieces, which could potentially cause more harm to aquatic life. In addition, these small-sized fragments are difficult to remove from these tidal areas. San Diego Bay offers critical habitat for aquatic species, fosters recreation and tourism supporting the local economy, and serves as a major port for global shipping industries. A variety of ecological habitats make up San Diego Bay, including mudflats, saltmarshes, beaches, freshwater at river mouths, and open water. A series of manufactured protective barriers, commonly referred to as rip-rap, also make up portions of the bay shorelines. This study is the first of its kind to look at the quantities, types, and locations of accumulated plastic debris in San Diego Bay habitats. Results show that plastic debris is present in 88% (±5.1%) of assessed areas within San Diego Bay, with the greatest amounts of debris occurring in intertidal mudflat and saltmarsh habitats. Most plastic debris accumulated in the intertidal zone consisted of polystyrene foam pieces, hard and soft plastic pieces, and food wrappers. After a series of rain events, the abundance of plastic debris increased by an average of 257 items per site and debris became more spatially distributed across all areas of the bay. The results suggest that plastic debris accumulation in the intertidal environments is predominantly driven by wet weather flows from the upper watersheds rather than by generation from sources within the bay.

Introduction

Plastic debris is the focus of this research because of its frequent use in urban society, its long residence time in the environment relative to other materials, the ability of plastics to absorb and potentially transport contaminants, and the persistence of plastics in overall marine pollution. Plastic debris makes up 50 to 80% of waste found on coastal beaches, on the seafloor, and floating in the ocean (Derraik 2002; Thompson et al. 2009). Plastic debris in marine environments has been well documented as a threat to aquatic life through ingestion, physical damage to habitats, chemical uptake through bioaccumulation, entanglement, and spread of invasive species

(Thompson et al. 2009; Derraik 2002; Rummel et al. 2016; Allsopp et al. 2006; Browne et al 2015; Rochman et al. 2013).

Along the San Diego County coastline, San Diego Bay is particularly important because of its significance for southern California tourism, marine transportation, and preservation of critical habitat for both land-based and aquatic species. As the largest estuary in San Diego County, San Diego Bay consists of 10,532 acres of water and 4,419 acres of tidelands (Weston 2005). Representing the southernmost point of the Southern California Bight, San Diego Bay is part of a uniquely diverse ecosystem formed because of a severe marine temperature break at Point Conception, varied underwater topography, and mixed ocean currents (US Department of the Navy and San Diego Unified Port District 2007). San Diego Bay also contains two national wildlife refuges, the saltmarsh of Sweetwater Marsh and mudflats in the South San Diego Bay unit (U.S. Fish and Wildlife Service 2013), which are home to a variety of migratory birds, invertebrates, and fish species, including threatened and endangered species (US Department of the Navy and San Diego Unified Port District 2007). As economic and population expansion increases, the need for considerable action to eliminate plastic debris in the natural environment and long-term monitoring becomes increasingly important.

The intent of the San Diego Bay Debris Study was to better understand the types and quantities of debris, specifically for plastic debris, among the various habitats within a coastal embayment by answering the following study questions:

1) What are the magnitude and extent of plastic debris in San Diego Bay?
2) What are the types of plastic debris found in San Diego Bay habitats?
3) How do the quantities and types of debris in different San Diego Bay habitats vary by summer and winter dry season?
4) How does the quantity of plastics in the marinas change with seasonal wet weather flows?

This assessment of the status of plastic debris in San Diego Bay habitats forms a baseline against which to measure progress and guide future management actions, including prioritizing specific areas of the bay for efforts such as community clean-up events.

Materials and Methods

Study Design

Selection of intertidal habitats for this study was based on a stakeholder census of the priority habitat types present in San Diego Bay. The habitats of interest for the study included sandy beaches, mudflats, salt marshes, and engineered shoreline structures (rip-rap). These four habitat types extend across the entirety of the bay, except for shipyard piers and the river mouths which were indirectly evaluated in the riverine study. The riverine intertidal areas have also been the focus of previous efforts conducted during the Southern California Bight Regional Monitoring Program.

Sampling sites within the four study habitats were randomly selected to provide unbiased estimates of debris abundances (number of items) and volumes and to enable the study to make inferences across these habitats to the entire bay. These habitat strata were divided into evenly space grids covering the intertidal zone (mean lower low water [MLLW] to mean higher high water [MHHW]) and each grid was assigned a unique identifier number. The desired sample size (30 sites per habitat stratum), input feature class (delineated habitat layer), and identifier code were entered into a geographic information system (GIS)-based random feature selection tool. The output created a center point of randomly selected grid cells as the target coordinates for survey sites. Approximately 100 sites were initially chosen for each habitat, with the expectation that in a heavily populated bay with a large number of waterfront businesses, industries, military, and private property, such as San Diego Bay, accessibility to all sites would be difficult. From the selected 100 sites, 30 sites were targeted for each stratum and approximately seven sites per stratum were rejected for reasons such as restricted access, private property, or misidentified habitat type. Remaining sites were designated as over-draw pools to be used in cases where field visits determined that sites were inaccessible or the water level precluded access during low tide.

Marina trash skimmer programs in the Pier 32 and Point Loma Marinas were adopted into the study to provide a continuous data collection process between the pre- and post-storm synoptic survey events. The trash skimmers are located on the eastern bay in the Pier 32 marina and the western bay in Point Loma Bay (Figure 1). Technical issues with two additional trash skimmers located in the north-bay precluded the study from gaining additional spatial coverage.

Sample Collection

Survey methodology followed standardized protocols adopted for the NOAA shoreline survey method for intertidal zones along open ocean beaches (Lippiatt et al. 2013) and included a minor modification for the bay's saltmarsh and narrow intertidal areas (Viehman et al. 2009). Survey areas consisted of two 30.5-meter by 5-meter transects with one transect covering the intertidal zone and the second transect covering the wrackline. Only one transect was used within rip-rap habitats, which are 5 to 6 meters in width (MLLW to MHHW) at all locations in San Diego Bay. Survey times were schedule to occur within 1 to 3-hour time blocks around low tide stage to capture the maximum intertidal area.

Field Global Positioning System (GPS) coordinates were verified against a set of target coordinates representing the center of the survey area to ensure that teams arrived at the correct locations. The boundaries of the survey area were defined using pre-cut lengths of rope or a transect tape to create a consistent rectangular area for data collection. The debris collection process within each survey area consisted of three data collection steps (in order):

1) Collect all macro-debris.
2) Collect any meso-debris within five randomly placed 1.0-square-meter quadrats (NOAA Shoreline Survey Method).
3) Collect as much meso-debris as possible within a 10-minute period.

Within each survey area, teams first collected macro-debris (debris size greater than 25 cm), which was identified by type and material, and then counted and measured aggregate volume in 5-gallon buckets with 1-liter increments marked on the inside of the bucket. The second data collection procedure within each survey area focused on using a 1.0-square-meter quadrat to collect meso-debris quantities (Lippiatt et al. 2013). Plastic debris amounts within quadrats were later extrapolated during data analysis to estimate debris quantities throughout the entire transect. Quadrats were placed at 20% intervals along the 30.5-meter length of the survey area, alternating among side, center, and opposite side. The starting position was determined using a coin flip. Within each quadrat, meso-debris (debris size between 25 cm and 4.75 mm) was identified, counted, and split into debris categories and the volume was measured. The third step in the data collection process consisted of walking the survey area to collect any remaining meso-debris (or as much as possible) within a 10-minute time period. In some survey areas, primarily the salt marsh, mudflat, and rip-rap habitats, all of the meso-debris in the wrackline could not collected within the 10-minute time limit. The data collected represent the maximum amount collected, but may not be an accurate representation of the debris quantities in the wrackline. The 10-minute survey did not itemize or count debris types, but rather focused on collecting volumetric measurements.

All debris collected in the intertidal surveys was binned into specific categories of common types of trash. The categories classifications included bags and packaging, household, toxic, food service, and miscellaneous. Items that did not fit under any specific debris type identified on the field sheet were listed under the best-fitting debris category as "other," with a written description of the item.

Initial pre-storm surveys were conducted once during a dry period in the early fall (September through October 2014) and then were resurveyed after several major rain events (cumulative rainfall >1 inch) (January through May 2015).

This survey used marina trash skimmers (marina skimmers), which provided an opportunity to collect continuous debris data alongside the habitat surveys and trawl events. The marina skimmers, operated by the Point Loma and Pier 32 Marinas, are located in areas of the bay that have been previously documented to accumulate trash from tidal processes and daily surface winds (Port of San Diego 2011). The sample collection period occurred from October 2014 to August 2015 and has data overlap with intertidal pre-storm dry weather and post-storm wet weather surveys. The marina skimmer staff kept detailed logs of debris collected on a daily to monthly basis and recorded abundances for each type of debris collected.

Quality Assurance

Quality assurance protocols adopted for this study included protocol training, independent site audits, follow-up inspections, and data verification reviews. Surveys were performed by multi-agency members, which created an opportunity for error and personal bias to be introduced into results. To account for these potential errors, the survey protocol included several steps for quality assurance during sample collection, as well as quality control measures during post-sample processing. Agency-specific team leaders provided initial training for the designated field team captains and their field staff. Trainings focused on establishing consistency in data collection activities and identification of debris items using a standardized set of definitions. The agency team leaders also performed audits of their field team's data collection methodologies.

In the field audits, the team leader evaluated and scored each field team interviewed. Performance scores were based on completion, repeatability, and accuracy in location and item identifications. Teams that did not receive a score of 100% on the performance audit received immediate feedback on areas of inconsistency.

In addition to the field-based quality assurance protocols, laboratory-based protocols were implemented for the study. Plastic debris collected at 10% of sites was retained for reanalysis, which included recounting the items and verifying the item debris category (bags and packing, household, food service, etc.). Macro- and meso-debris collected during initial surveys was later recounted to ensure accurate debris identification. The team recognized that quantities of debris could be skewed by the breakup of the items during transportation of the samples to the laboratory. Because data quality objectives have not yet been developed for debris surveys, variations of more than 30% in identified debris types were considered to be a sufficient basis for flagging the portion of the data quality in question.

All field forms were reviewed for completeness and consistency following initial data collection. A 100% check of all data entry against field forms was performed prior to data analysis.

Data Analysis

Total meso-debris abundance and volume within the entire transect area was estimated by multiplying debris amounts by the area that was not accounted for using the quadrat method. Area-weighted totals, means, and percent cover were analyzed using R version 3.1.3 and complementary user interface: R Studio, version 0.99.441 (R Core Team 2015). Debris count data were skewed and so nonparametric methods were used. Differences in plastic debris types were tested with Kruskal-Wallis one-way analyses of variance (ANOVA). Debris data collected from marina skimmers were counted following each maintenance event. Pier 32 Marina collected debris daily from November through January and weekly from February through August. Point Loma Marina collected debris data twice per week from October through December and February through March. Monthly mean values and maximums were calculated to compare variations in plastic debris throughout the storm season.

Results

Adjustments in the Survey Design

The first round of pre-storm surveys revealed little-to-no visible trash in the intertidal zone (MLLW to wrackline), which is subject to diurnal tidal exchanges. A summary of the intertidal zone and wrackline debris abundances is provided in Table 1, illustrating the differences observed during the initial surveys.

The finding that the debris in San Diego Bay is concentrated along the wrackline is consistent with other studies. Similar studies conducted in intertidal zones have found that most debris is concentrated in the high-tide wrack line (Viehman et al. 2011; Thornton and Jackson 1998).

The intended study design of 60 samples per strata with 30 pre-storm and 30 post-storm samples also required adjustment in response to several factors including access restrictions after the initial site verification, physical challenges to crossing habitats, withdrawal from sites in response to rising tides, and early season storm events. The resulting site count, as shown in Table 2, indicates the final number of surveys per habitat for each of the beach, rip-rap, and mudflat and saltmarsh habitats. To maintain the statistical significance of the results, mudflat and saltmarsh strata were combined to provide estimates of magnitude (area-weighted mean abundance and volume) and spatial extent (percent of bay area) of plastic debris.

The second adjustment to the study design included comparing only the pre- and post-storm wrackline surveys based on the findings from the initial surveys during the pre-storm monitoring period. The datasets analyzed for the intertidal portion of this study focus on the wrackline datasets, given that the post-storm surveys did not include the intertidal zone between the low water line and the wrackline.

Magnitude and Extent of Plastic Debris in San Diego Bay

Debris quantities collected from the four habitats were analyzed to provide an estimate of the magnitude and extent of coverage across San Diego Bay. The results of this study indicate that plastic debris is present in an estimated 88% (±5.1%) of the bay intertidal area (Table 3.a). Total abundance of plastic debris in San Diego Bay throughout the entire study period (September 2014 through May 2015) is estimated to exceed 20.4 million (±7.4 million) items, with the greatest abundance in mudflat and saltmarsh habitats. Total volume is estimated to exceed 1.09 million (±332,700) liters of plastic debris.

Mudflats and saltmarsh habitats had the greatest extent, as plastic debris was present in 100% of the habitat area. The mean abundance of trash was highest in this habitat type with 3,004 (±1,900) items per site. The mudflats and salt marsh areas represent the least publicly accessible portions of San Diego Bay. The mean abundance within the rip-rap habitat was five times less (Table 3.a), while beach sites had the lowest mean abundance and extent of the study habitats. Beach sites tend to be the most accessible locations in the bay and many of the beaches have active trash removal programs.

Debris was heterogeneously distributed throughout San Diego Bay, with isolated pockets in the bay accumulating large quantities. Sixteen sites made up the top 75th percentile of plastic debris abundance during pre-storm surveys (>92 debris items per survey) (Figure 2). Fourteen of the 71 sites surveyed were located within the mudflat, saltmarsh, and rip-rap wrackline areas, and were concentrated in a region where Sweetwater River discharges into San Diego Bay. These 14 sites contributed more than 80% to total plastic debris. These locations have extensive mudflat and saltmarsh habitat along the shoreline relative to other areas of the bay.

The intertidal surveys focused on implementation of standardized methods or methods previously adapted for salt marsh habitats (Lippiatt et al. 2013; Viehman et al. 2009). As a pilot project to evaluate survey methods for meso-debris in intertidal habitats, a rapid survey technique was performed in each survey area to compare the quantities of debris obtained by quadrats with the amount of debris that could be obtained during a 10-minute collection period. The paired analysis was performed for 120 of 154 surveys. The quadrat method produced a total meso-debris volume of 307.1 liters. The 10-minute survey method produced a total meso-debris volume of 1,143 liters, or 3.72 times more debris than produced by the quadrat method.

Types of Plastic Debris

This study itemized and categorized trash types to determine the most abundant types of debris present in San Diego Bay. Results indicate that polystyrene foam pieces, hard and soft persistent types of plastic pieces, and food wrappers are significantly more abundant than the other plastic debris types found in San Diego Bay (Kruskal-Wallis, $P<0.001$). These types of debris were observed in more than 45% of the entire bay (polystyrene present in 57% [±6.1%] of habitat areas, hard plastic 54% [±6.1%], soft persistent plastic 45% [±6.1%], and food wrappers 46% [±6.3%]). Relative to each of the study habitats, polystyrene foam pieces and hard and soft plastic pieces were found in highest abundance in mudflat and saltmarsh habitats, while food wrappers were primarily observed in rip-rap habitats (Figure 3). Polystyrene foam was the most abundant debris type across all three study habitats (Figure 4), with an estimated total abundance of 9.1 million (±3.4 million) pieces in the bay. Area-weighted mean abundances for the top 10 plastic debris items representing approximately 90% of all debris found within the study area are shown in Table 4.

Debris was sorted according to size to determine quantities present in San Diego Bay on a size basis. Overall, meso-debris abundance was 286 times greater than macro-debris abundance, while the total volume of meso-debris was only five times greater than the macro-debris volume (Figure 5), which indicates that debris quantities evaluated solely on the basis of volume could be misleading if the abundance were not taken into consideration. Meso-debris (25 cm to 4.75 mm) was present across the bay at 79% (±8.1%) of sites in comparison with macro-debris (greater than 25 cm), which was present at 52% (±8.8%) of sites. The mean abundance of meso-debris was highest in mudflats and saltmarsh habitats, while the mean volume of meso-debris was highest in rip-rap habitats (Figure 5). All habitats had a small number of very large items, as indicated by the low abundance and high relative volume of macro-debris collected in each habitat.

Impacts of Seasonal Variance and Wet Weather Flows

The results discussed above apply to data collected during the pre-storm dry period from September through November 2014. Post-storm site visits were conducted from January 2014 through March 2015 after a period of substantial storm events (cumulative rainfall >1 inch) to observe changes in debris spatial distribution and re-accumulation. The extent of plastic debris across San Diego Bay increased after wet season rain events. The surveys conducted during the winter wet season indicated that an estimated 95% (±2.4%) of San Diego Bay contained plastic debris. Mean debris abundances across the entire bay increased by 257 items per site during post-storm surveys. The mean debris abundance in mudflat and saltmarsh habitats remained relatively constant at 3,277 (±1,984) items (10% increase) following storm events (Table 3.b). Beach habitats showed the greatest increase in mean debris abundances following storm events (373% increase).

Post-storm sampling also showed that the volume of macro-debris decreased across all habitats, excluding beach habitats. The overall increase between pre- and post-storm surveys is attributable to an increase in number of meso-debris items. It is estimated that the percent cover of meso-debris increased across rip-rap and beach habitats by 12 to 38% while the percent cover of macro-debris decreased across the entire bay by 15% after wet season rain events (Table 3).

During post-storm surveys, 15 sites were within the top 75th percentile of plastic debris abundance. These sites consisted of four rip-rap sites, five beach sites, and six mudflat and saltmarsh sites. The post-storm bay debris quantities showed more dispersal following the storm events, as compared with pre-storm debris, which tended to accumulate in isolated pockets. Figure 6 exhibits the uniform increase in debris abundance throughout the entire bay.

Quantity and Type of Plastic Debris in Marina Trash Skimmers

Two marinas skimmers were included in the study to capture continuous measurements of debris quantities between the two synoptic surveys. The skimmers provided the opportunity to characterize debris quantities generated by storm events and to measure the dry weather conditions over the storm season.

Two marina skimmers collected 1,237 plastic debris items from October 2014 through August 2015. The 10 debris types representing the top 80% of all debris found are shown in Table 5. The most abundant debris items collected by marina skimmers include cigarette butts (19%), followed by polystyrene foam (pieces, pellets, and cups at 32%, cumulatively). The Point Loma Marina skimmer collected a maximum of 433 items in any sample, which was substantially more plastic debris than collected by the Pier 32 marine skimmer (maximum of 21 items). The Point Loma Marina collected samples only from October through December 2014 and February through March 2015; therefore, the period of sampling for the Point Loma Marina was markedly shorter than that for Pier 32.

The mean abundance of plastic debris collected by marina skimmers was highest from December 2014 through February 2015 (Figure 7). A maximum of 433 items were captured in the December 2014 survey time period, while the lowest debris amounts were recorded in April through August 2014 (maximum of five items per survey). The flux of plastic debris throughout the survey period corresponds with monthly precipitation totals for water year 2015 (Figure 7). Cumulative monthly rainfall of 4.5 inches was recorded in December 2014, which was 42% of the annual precipitation and the highest total monthly rainfall recorded throughout the 2014–2015 season. Cumulative rainfall for the three months prior to the December 2014 storm events was 0.37 inch.

Discussion

Extent of Plastic Debris in San Diego Bay

Plastic debris is present in an estimated 88% (±5.1%) of San Diego Bay, which increases to 95% (±2.4%) after rain events. The results of this study indicate that plastic debris is prevalent throughout San Diego Bay, but tends to be present in the highest quantities in the locations that are the least accessible to the public suggesting that volunteer clean up events could provide an ecological benefit to San Diego Bay.

Distribution in San Diego Bay Habitats

While all types of habitats included in this study appear to be saturated with plastic debris, mudflat and saltmarsh habitats contained the highest mean abundance of plastic debris in the two survey periods of this study. In the 31 surveys conducted within mudflat and saltmarsh habitats throughout the study period, 100% of the surveys found at least one plastic debris item. This finding is consistent with those of similar studies conducted in other saltmarsh habitats (Viehman et al. 2011). The thick vegetated bottom substrates commonly associated with mudflats and saltmarshes likely trap and retain debris during high tides or large storm events (Thornton and Jackson 1998), and therefore could be a focus area for future debris cleanup efforts.

Persistent Types of Plastic Debris

Fragmented plastics were in high abundance compared with other debris types, including pieces of polystyrene foam and indistinguishable hard and soft persistent plastic pieces. Polystyrene foam products and pieces have been shown to be a persistent marine pollutant along the west and east coasts of the United States (Viehman et al. 2011; Thornton and Jackson 1998) and international coastlines (Lee et al. 2013; Ocean Conservancy 2015; Browne et al. 2010). The presence of polystyrene packaging and food service products suggests that deposition sources include urban areas in localized upstream watersheds or transport from other near shore areas (Lee et al. 2013). Household use and commercial production of packaging materials are recognized as the most common uses of plastic materials (Adane and Muleta 2011; Andrady and Neal 2009; American Chemistry Council 2014). Local recreation and land use activities in upper watersheds are likely the key contributors of the debris found in enclosed bays and estuaries (Thornton and Jackson 1998; Viehman et al. 2011; Hoellein et al. 2014). In addition, the riverine portion of this study identified the same debris items (food wrappers, hard and soft plastic pieces, and polystyrene foam pieces) as some of the most persistent debris items in the upper watersheds.

Accumulation After Seasonal Wet Weather Flows

Less plastic debris was found in intertidal habitats and marina skimmers during the dry summer months, a time when outdoor recreation increases through San Diego Bay (San Diego Tourism Authority 2015). This finding suggests that activities in San Diego Bay tend to be less important or insignificant sources of debris to the bay, in contrast with transport mechanisms of debris during high flow events discharging from the upper watersheds during rain events.

The riverine portion of this study showed that the concrete portions of the channels and drainages had little to no debris after a rain event, in comparison with the earthen and natural drainages, which tended to accumulate debris. While these surveys were conducted during a dry year relative to expected precipitation for this region, San Diego received a total of 6.5 inches of rainfall between pre and post-storm surveys (Western Regional Climate Center 2016) meaning that the amount of debris in the Bay could varying substantially as the amount of rainfall changes in response to atmospheric influences. Rainfall intensity, rainfall duration, number of rain events, and antecedent dry period have been shown to be factors that can influence debris transport (Bel et al. 2016). Research into local factors that trigger debris flow, such as rainfall intensity, antecedent dry period, and soil saturation as identified by Bel et al. (2016), may provide further characterization of ideal time periods for debris removal. Continuous data from marina skimmers support the results that San Diego Bay experiences an influx of debris after rain events. The types of plastic debris collected by the marina skimmers were similar to those collected manually during intertidal surveys. Along with polystyrene foam and soft plastics, the marina skimmer data highlight cigarette butts as one of the key plastic pollutants in San Diego Bay and past studies suggests that cigarette butts can be toxic to both saltwater and freshwater fish species (Slaughter et al. 2011).

Recommendations for Future Monitoring

This study provided a baseline of plastic debris in San Diego Bay and the results of this effort create an opportunity to measure the effectiveness of future trash control strategies and outreach efforts. This study also identified key locations that tend to accumulate debris. These areas, through coordination with the stakeholders, could be the focus of future community-based cleanup events. While the broad scope of the study provided baseline information on debris magnitude and extent, and the impacts of wet weather flows, this broad scope also limited the number of surveys and the amount of detail on potential sources that could be collected.

Secondly, the intertidal habitat survey methods should be optimized and standardized so that a rapid technique, such as the 10-minute survey, can be implemented for future receiving water monitoring programs. The 10-minute survey proved to be a time-efficient, labor-efficient technique to obtain debris quantities quickly. The current limitation of this method is the unknown relationship between the debris quantities found using the 10-minute survey technique and the total abundance/volume of debris in San Diego Bay.

This study found that saltmarsh and mudflat habitats are key sinks for plastic debris. Debris in mudflat and saltmarsh areas are also less likely to be collected by clean-up groups. These habitats support a variety of threatened and endangered species which rely on these areas for nesting and foraging. Additional research is needed to examine the impacts of plastic debris on sensitive species residing in the saltmarsh and mudflats of coastal estuaries and bays. Furthering our understanding of the impact of plastic debris on these most critical habitats may determine if considerable remediation is needed for species protection.

Finally, the residence time for some of the plastics may be a contributing factor for the abundances observed in locations such as mudflat/saltmarsh habitats. The constant exposure to solar irradiance, saltwater, and consistent wet/dry cycles with the tides provides a reasonable explanation for the small, often brittle, degraded polystyrene and hard plastic pieces observed. Future monitoring efforts could benefit from additional research into methods for dating or tracking debris from the time of disposal to transport into the bay. An effort to establish a residence time would help to clarify whether a debris item was deposited recently or historically. Field observations in this study suggested that the wrackline continuously moved and changed composition with the tides and prevailing winds, and that a strong possibility exists that some of the debris may be remaining in the bay over multiple years (as evidenced by observations of antiquated logos and product labels).

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Figures

Figure 1. Map showing locations and photos of the Point Loma Marina and Pier 32 Marina trash skimmers used for plastic debris collection.

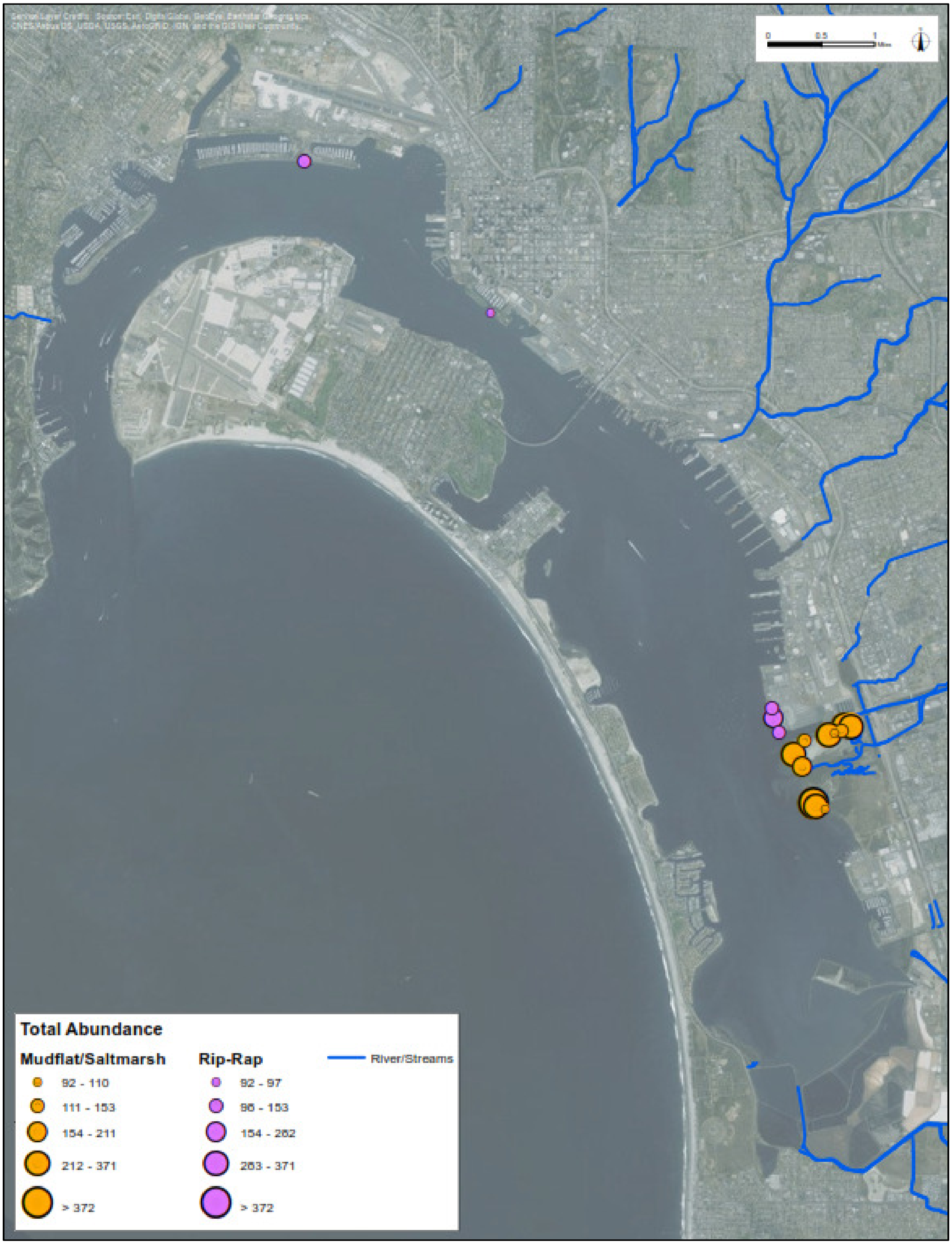

Figure 2. Total abundance of the sites representing the top 75th percentile of plastic debris abundance from pre-storm surveys. Only sites with plastic debris abundance within the top 75th percentile are shown. Plastic debris abundance at sites located in beach habitats was not within the top 75th percentile and therefore this habitat is not shown. Pre-storm surveys were conducted from September through November 2014.

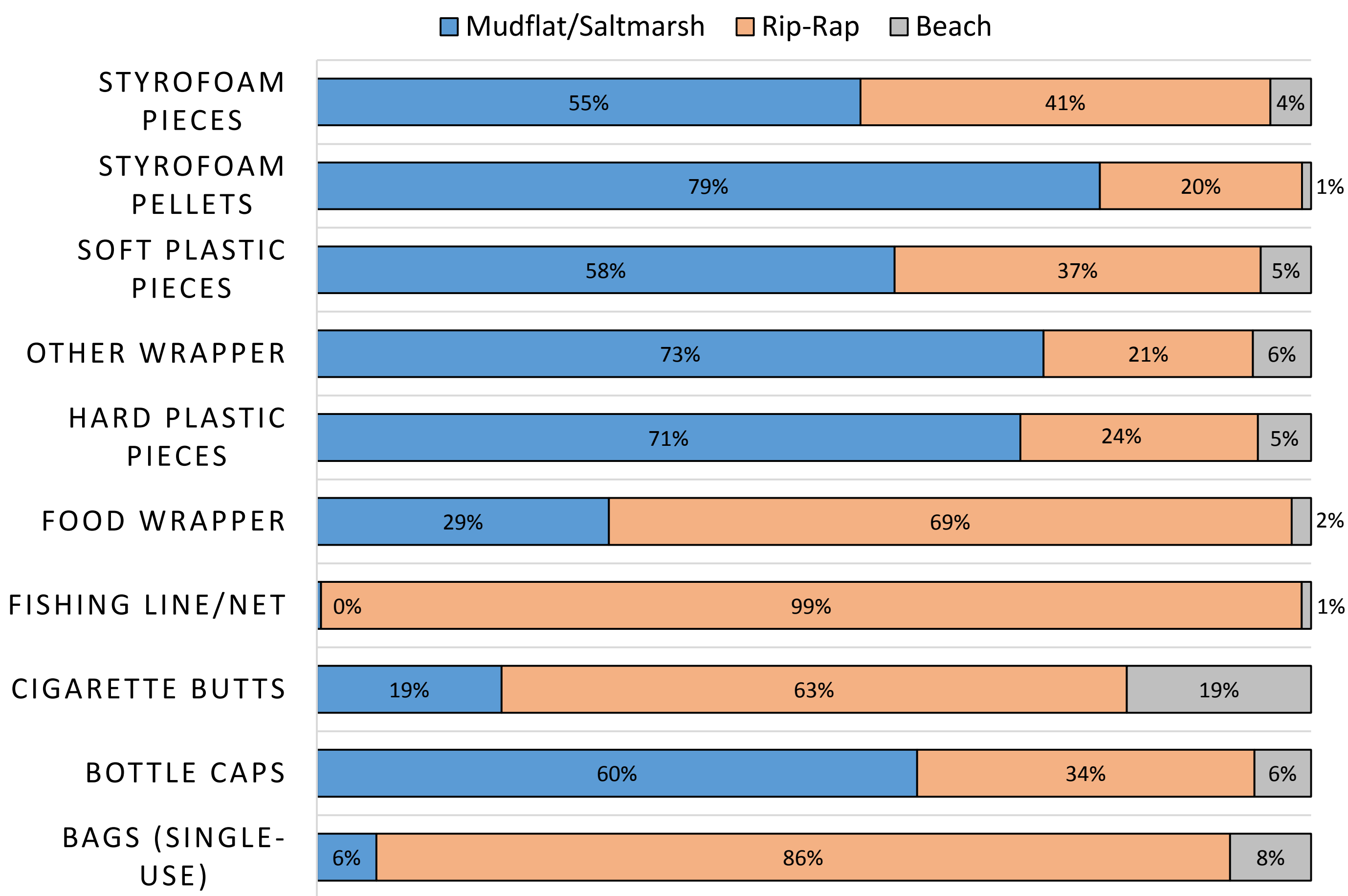

Figure 3. Total Abundance of Debris Per Debris Type Shown as a Proportion of the Study Habitats Where the Debris Type Was Identified.

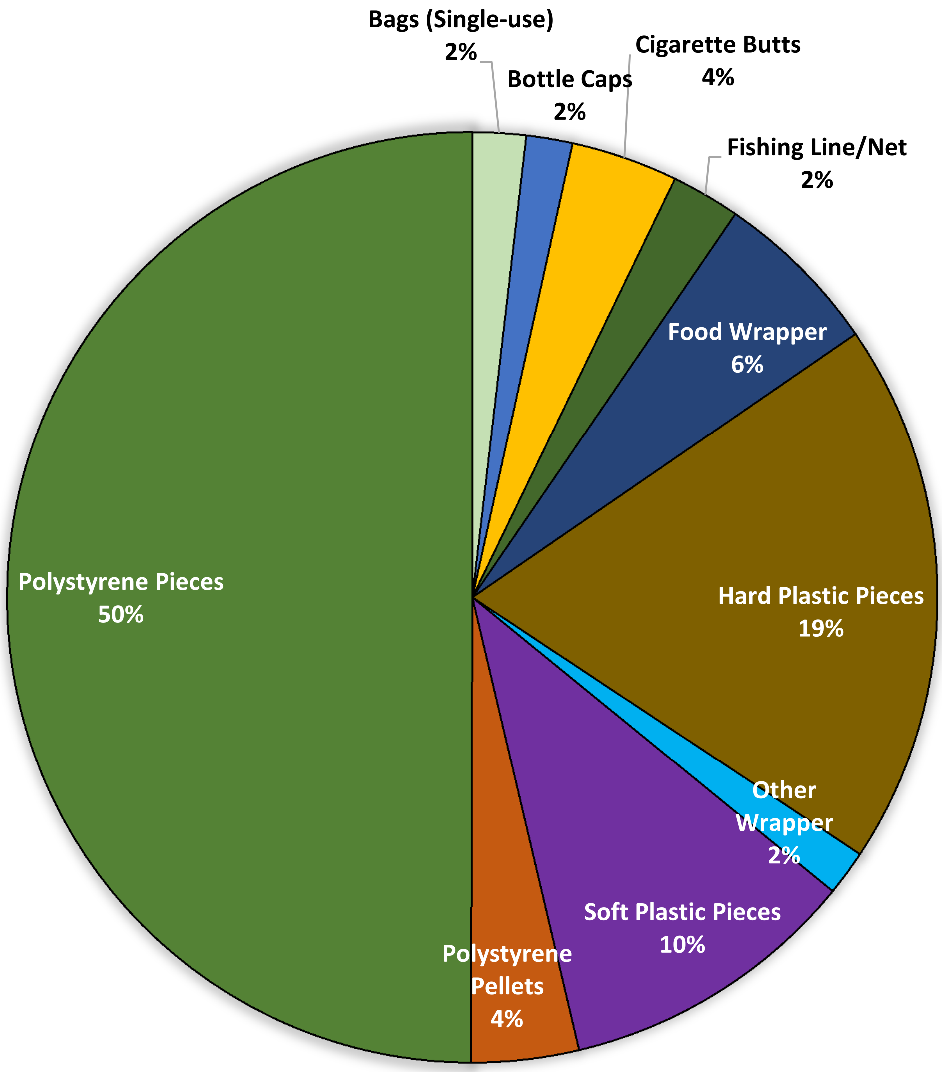

Figure 4. Percentage of Total Abundance of the Top 10 Plastic Debris Types Representing Approximately 90% of Plastic Debris Collected During the Study Period.

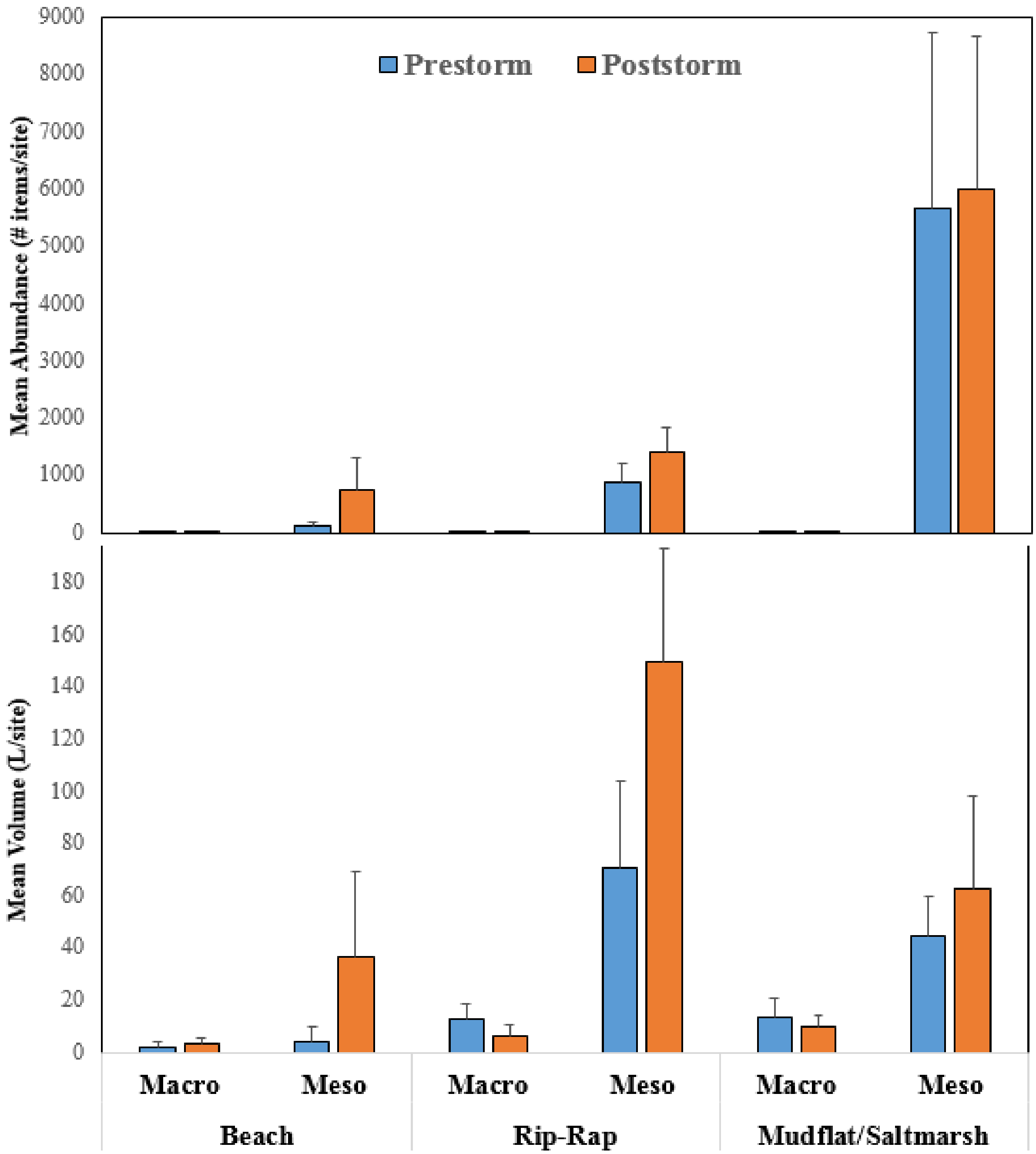

Figure 5. Mean Abundance (number of items per site) and Volume (liters per site) of Plastic Debris for Each Study Habitat, Size Class, and Storm Period. Pre-storm data were collected from September through November 2014. Post-storm data were collected from January through May 2015.

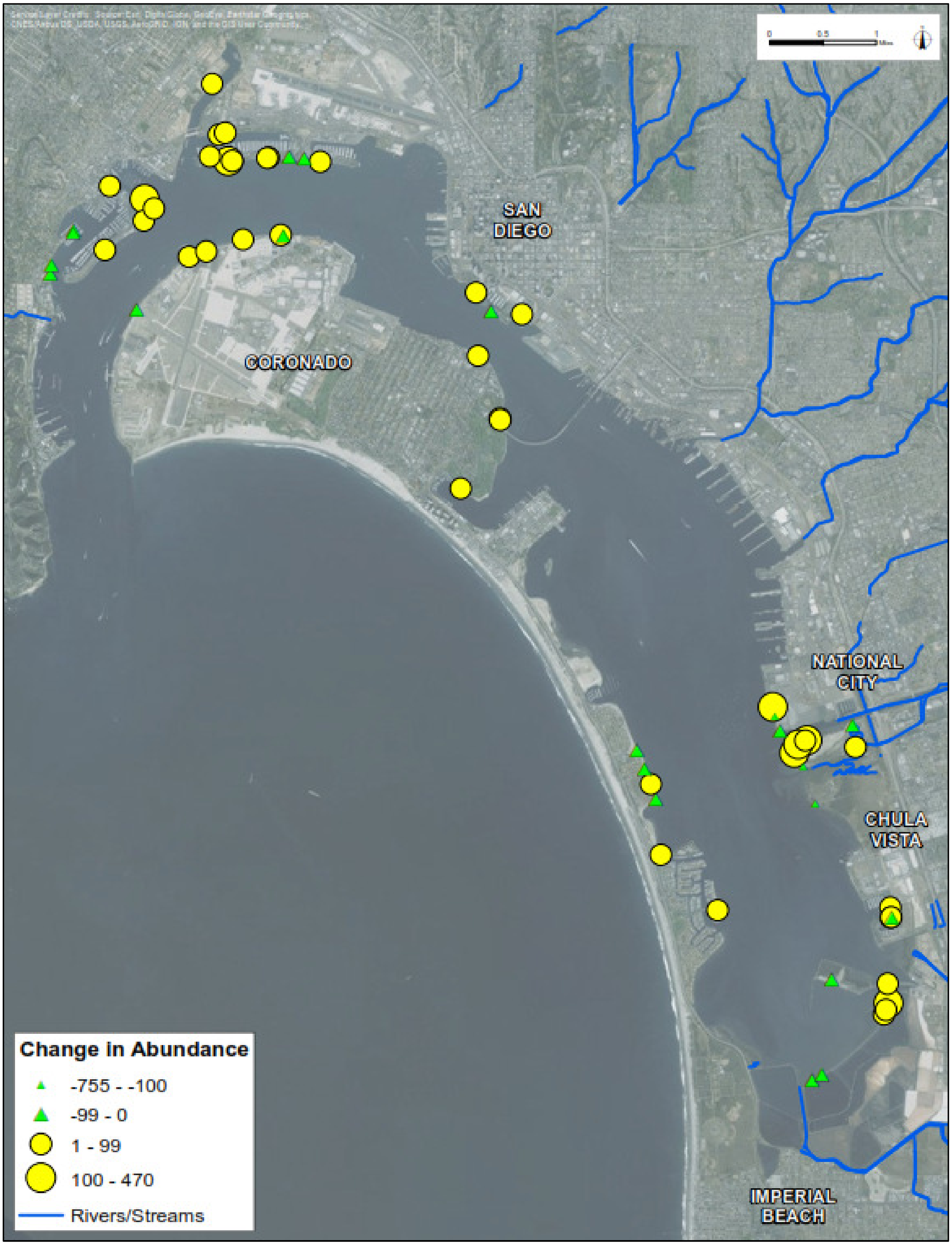

Figure 6. Change in Total Abundance of Plastic Debris from Pre to Post-Storm Periods at Each Site Surveyed.

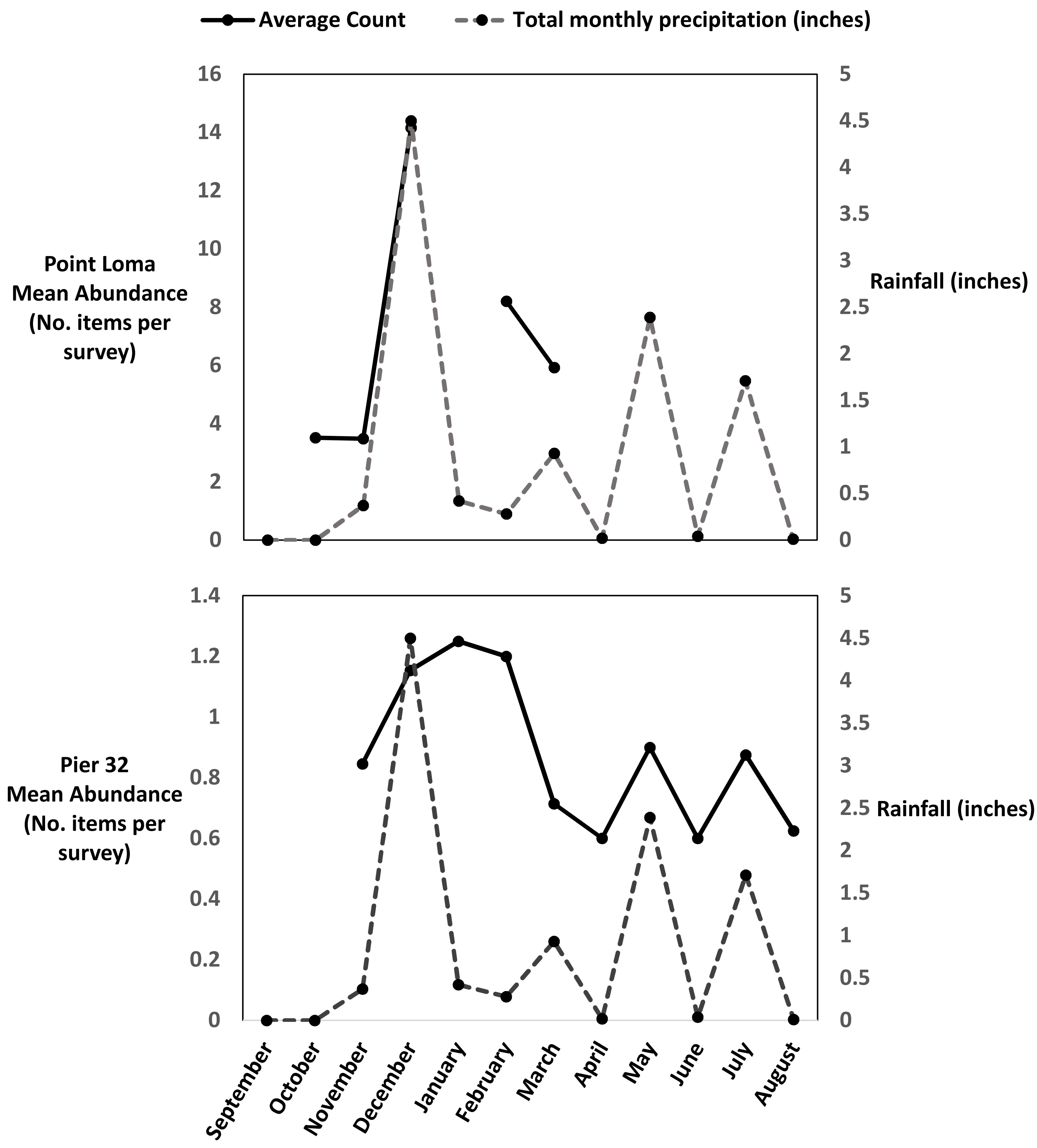

Figure 7. Mean Abundance (number of plastic debris items per collected sample) and Rainfall Totals for Pier 32 Marina and Point Loma Marina Skimmers. Data collection occurred from October 2014 through August 2015. Rainfall data is from the Western Regional Climate Center.

Tables

Table 1. Comparison of Total Debris Abundances in the Intertidal zone and the High Tide Wrackline. Data in the intertidal zone were collected only during the pre-storm period from September through November 2014 because of the absence of plastic debris in the intertidal zone. Values for total abundance and volume include only sites where both intertidal and the wrackline surveys were conducted.

Stratum	Total Abundance	Total Volume (L)
Intertidal	16	5.13
Wrackline	237	147.3

Table 2. Number of Samples by Habitat and Marina within San Diego Bay from September 2014 through July 2015.

Stratum	Sample Sizes		
Habitat	Pre-storm	Post-Storm	Total
Beach	19	19	38
Rip-rap	33	33	66
Mudflats/Saltmarsh	19	12	31
Marina Skimmers			
Pier 32	---	---	118
Point Loma	---	---	30
All San Diego Bay	71	70	283

Table 3. Summary Statistics of Plastic Debris in All Study Habitats in San Diego Bay during Pre- and Post-Storm Sampling Periods.

3.a Pre-Storm Results

Habitat	% of Habitat Covered	95% CI	Area Weighted Mean Abundance (# items/site)	Standard Error	95% CI	Area Weighted Mean Volume (L/site)	Standard Error	95% CI
Beach	73.68	17.45	110	36.09	70.75	5.01	2.50	4.89
Rip-rap	87.50	7.26	613	144.60	283.40	57.28	14.55	28.53
Mudflats/ Saltmarsh	100	0	3,004	969.64	1900.45	31.82	31.82	9.54
Entire Bay	88.40	5.14	1,096	242.19	474.69	43.85	8.40	16.46

3.b Post-Storm Results

Habitat	% of Habitat Covered	95% CI	Area Weighted Mean Abundance (# items/site)	Standard Error	95% CI	Area Weighted Mean Volume (L/site)	Standard Error	95% CI
Beach	91.30	7.37	521	205.37	402.52	28.16	12.00	23.51
Rip-rap	95.23	4.31	1,119	188.83	370.11	123.14	19.81	38.82
Mudflats/ Saltmarsh	100	0	3,277	1,012.26	1,983.99	39.81	10.86	21.28
Entire Bay	95.22	2.37	1,353	210.49	412.55	90.05	12.19	23.89

Table 4. Top 10 Plastic Debris Types Representing 89% of Plastic Debris Collected in Intertidal Habitats of San Diego Bay during the Study Period.

Debris Item	Area Weighted Mean Abundance (# items/site)	Standard Error	95% CI	Maximum	Cumulative % of Total Abundance represented by Debris Item
Polystyrene Foam Pieces	534	101.80	199.53	968	43.1
Hard Plastic Pieces	202	31.61	61.95	178	61.3
Soft Plastic Pieces	111	16.06	31.49	94	70.8
Food Wrapper	62	8.74	17.12	51	75.2
Polystyrene Foam Pellets	40	12.60	24.70	128	78.9
Cigarette Butts	40	9.87	19.34	45	81.5
Fishing Line/Net	26	4.21	8.23	17	85.0
Bags (single-use)	20	3.12	6.12	12	83.6
Other Wrapper	17	3.46	6.79	30	87.0
Bottle Caps	17	2.71	5.32	12	88.5

Table 5. Top 10 Plastic Debris Types Representing 80% of Plastic Debris Collected in Marina Skimmers during the Study Period.

Debris Item	Total Abundance	Mean Abundance (# items/sample)	Standard Error	95% CI	Cumulative % of Total Abundance represented by Debris Item
Cigarette Butts	231	10	1.57	2.77	18.7
Polystyrene Foam Pieces	147	10	6.34	7.60	30.6
Polystyrene Foam Cup/Pieces	131	16	11.24	19.84	41.2
Polystyrene Foam Pellets	115	58	30.05	45.34	50.4
Soft Plastic Pieces	106	35	26.42	51.78	59.0
Other Wrapper	85	4	0.98	1.33	65.9
Food Wrapper	72	2	0.41	0.49	71.7
Bags (single-use)	39	2	0.25	0.33	74.9
Lid	31	1	0.11	0.15	77.4
Water Bottles	27	2	0.14	0.18	79.6

III. Micro-plastics in San Diego Bay Surface Waters, Intertidal Sands, and Bay Fish

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Abstract

There is increasing awareness of the prevalence of plastic debris in our oceans, yet the extent to which plastics are accumulating in urban coastal waters and being ingested by aquatic species in coastal embayments is only starting to be realized. This study determined the extent, abundance, and types of plastic debris (0.5 mm to 1 cm in size) floating on or below surface waters, present in intertidal sands, and entrained in the guts of fish residing in the shallow water habitats of San Diego Bay. Teams performed fish gut dissections, sorted through beach sands, and performed open water trawls to characterize plastic micro-debris throughout San Diego Bay. The open water trawls were all inclusive of any debris captured; the trawl nets captured an abundance of 4.7% meso-debris (debris size between 4.75 mm and 25 cm) and 0.03% macro-debris (greater than 25 cm). The majority of debris items captured by trawls were micro-debris, which represented 95% of the total items counted. Our findings show that 100% of trawls and 97% of shallow water sands contained small plastics or micro-debris. The wrackline of beach sands contained an average of 6,654 pieces of plastic micro-debris per cubic meter (m^3) of sand and about half of those were fibers, with remaining items consisting of polystyrene, hard plastic pieces, and soft plastic pieces. Clear, white, black, and blue colored plastics were consistently the more abundant than plastic debris of other colors found among trawls and sand samples.

Four different fish species were analyzed as part of this study and small plastic debris was found in the guts of three of the four species evaluated. Nearly one-fifth of round stingrays (*Urolophus halleri*) caught had consumed plastic debris, which consisted mostly of hard pieces and fibers. The stingray had higher proportions of red, white, and blue hard pieces and fibers in its gut than were found in the sand, suggesting some sort of intentional or unintentional preferential ingestion. We also found that females were more likely than males to have ingested micro-

plastics. While 12% of spotted sand bass (*Paralabrax maculatofasciatus*) and the only white seabass (*Atractoscion nobilis*) examined contained plastics, none of the California halibut (*Paralichthys californicus*) did. This study corroborates the findings of other recent studies about plastics ingestion in game fish, and supports ongoing investigations of plastic ingestion.

Introduction

Small plastics and micro-debris, less than 1 cm in size, are accumulating along our coastlines (Browne et al. 2011) and becoming a topic of great importance for studies of ecosystem health (Rochman et al. 2014; Rochman et al. 2013; Browne et al. 2013). Small plastic debris may enter a system as primary plastics (manufactured as tiny pieces, such as microbeads), or as secondary plastics (broken down from larger pieces of plastic, such as packaging or bottles) (Barnes et al. 2009; Cole et al. 2011). Coastal urban embayments, such as San Diego Bay, and the organisms within them may be at particular risk because of the high intensity of plastic inputs from the land, and restricted flow patterns that may trap debris within embayments (Moore et al. 2016).

The effects of plastic debris accumulation on organisms and ecosystems in coastal embayments are not yet fully understood. Recent studies have shown that plastic micro-debris adsorb and transfer suites of contaminants to fish and other marine species through ingestion, inhalation, or absorption through the skin (Teuten et al. 2009; Rochman et al. 2013; Browne et al. 2013; Chua et al. 2014), including many species of interest to the commercial, subsistence, and recreational fishing industries (Rochman et al. 2015). These findings have implications for coastal cities such as the greater San Diego metropolitan area, which has a small but vibrant coastal commercial fishing industry and high incidence of recreational and subsistence fishing along coasts and in bays (Environmental Health Coalition 2005).

This project, therefore, characterized small plastics and plastic micro-debris quantities in the bay and investigated the presence of ingestion of plastics by fish in the surface waters and shallow water sediments of San Diego Bay. This study addressed the following objectives:

1) Document the types and abundances (number of items) of small plastic debris in shallow, sandy intertidal habitats around the bay.
2) Identify types and abundances of small plastic debris floating on or below the water surface of the bay.
3) Determine the types and abundances of small plastics and plastic micro-debris ingested by fish living in the bay’s shallow waters.

Materials and Methods

Sample Collection

Sand samples were taken from 13 sites around the coast of San Diego Bay (see Figure 1). At each site, a 30.5-meter transect was established parallel to the shore from the low tide mark up to the wrackline. Five cores (625 cm^2 by 3 cm depth) were collected at 0, 6, 12, 18, and 24 meters along each transect. All five cores from each transect were composited in watertight bags until analysis. Sand samples were collected at each of the 13 sites during a pre-storm period (September through November 2014) and a post-storm period (March 2015) for a total of 26 sand samples used for analyses.

Trawls were conducted in October of 2014 to capture the early fall dry weather period and only a limited amount of rainfall coincided with the trawls (<0.01 inch), which did not produce runoff into the bay (these samples represent the pre-storm time period). The same trawl locations were resurveyed in April 2015 following a series of winter rain events (post-storm time period). Surveys were conducted in four regions consisting of (1) outside the mouth of the bay (open ocean) and (2) within the north, (3) central, and (4) south areas of the bay. The intent of the trawl design is to account for differences in tidal flows, circulation patterns, habitat types, watershed inputs, and vessel traffic (Largier 1995; Largier et al. 1997; Komoroske et al. 2012). Trawl stations were randomly selected within the above mentioned strata and conducted along fixed transect lines in each region. A total of 17 trawls were conducted per time period with four trawls performed in the north, south, and mouth regions and five trawls performed in the central region. Trawl field methods were consistent with monitoring approaches adopted for the Southern California Bight 2013 Regional Monitoring Program (Bight '13 Field Sampling & Logistics Committee 2013). . Trawls were conducted using an aluminum framed manta trawl with 0.335-mm net mesh and cod-end. Timed 30-minute trawls were towed along fixed bay transects at roughly 1 to 3 knots over a target distance of 1,000 meters. A flow-meter was attached to the manta trawl to calculate volumetric trawl data. At the end of the prescribed trawl time, the net was retrieved and brought onboard the vessel. Any debris caught on the cable was noted, but not included in the final item tally. The net was rinsed from the outside using site water to move sample into the cod-end. Large items were manually removed from the net when necessary. The catch was deposited into a tub, holding tank, or pre-cleaned 1-liter glass jar, depending upon sample size. The criteria used to evaluate the success of any trawl included making sure that proper depth, scope, speed, and distance (or duration) were maintained, determining whether the net was fouled (e.g. tangled), and determining whether the catch showed evidence that the opening was fouled in any way (e.g., kelp, large plastic bags, etc.). Samples were placed on ice in the field and were immediately frozen for preservation before laboratory analysis. Plastic debris items were counted and measured later at the laboratory.

Fish were sampled using semi-balloon otter trawls throughout the shallow water habitats of San Diego Bay from April 21 through 23, 2015 (Figure 1). Three trawls each were performed at the north, central, and south end of the bay, by passing the trawl for 10 minutes at a speed-over-ground of 1.0 meter per second (1.5 – 2 knots). The course of the trawl passed within the 100-meter radius area surrounding each of the nine fish site coordinates. Once each trawl was complete, the net was brought onboard the boat, and the fish were transferred to precleaned containers on deck for sorting, identification, and length measurements. A total of 79 fish from four different species (two demersal, and two not demersal) from these collections were used in this study: 16 California halibut (*Paralichthys californicus*), 45 round stingray (*Urolophus halleri*), 17 spotted sand bass (*Paralabrax maculatofasciatus*), and 1 white seabass (*Atractoscion nobilis*).

Sample Analysis

A 1-liter subsample was taken from each of the 26 sand samples, all of which had been previously weighed and mixed. The weight of each subsample was recorded. A magnifying lamp, which reliably revealed plastics down to 0.5 mm in size, was used to sort small plastic debris from the samples. All plastic pieces were collected using tweezers, and stored in glass vials labeled with the collection site ID and collection date. Non-plastic debris, such as shell, glass, or algae, and plastics larger than 10 mm were excluded from analyses.

Dissecting microscopes were used to confirm whether the items collected using the magnifying lamps were plastic, and to identify the color, size (maximum length), and type of plastic (e.g., polystyrene, soft piece, hard piece, or fiber). The total volume of plastic debris per subsample was measured and recorded. A control experiment was performed to examine potential environmental contamination of fibers and other debris. Particles that settled into three clean (sterile) dishes over 30 minutes, the maximum time taken to sort a dish of sand, were identified and counted. The mean number of each item was subtracted from each sand sample unless the difference resulted in a negative value, in which case a zero was assigned. An average of 1 (±1 SE) fibers per dish were associated with background contamination; this included an average of 1 ±1 each of clear/white and blue fibers, 0.7 ±0.7 each of black and pink fibers, and 0.3 ±0.3 red fibers. During fish gut analysis, researchers were positioned to minimize hovering above the samples. Gut contents were systematically picked from the newly opened segments to minimize potential contamination.

The fish were thawed, measured, weighed, sexed, and gutted in the lab. All gut contents were identified (or described) and enumerated, when feasible, using dissecting microscopes. For items not feasibly enumerated (e.g., sand grains, organic debris, filamentous algae), presence in the gut was noted. Ten of the 79 fish sampled had empty guts and were therefore excluded from further analyses. Plastic debris was categorized by color and type of plastic, and maximum lengths were measured. All plastics were kept in vials labeled with the fish ID.

Trawl samples were thawed and sorted by debris material type (plastics, paper, feathers, etc.) prior to filtering and analysis. Large items were rinsed with deionized water in the laboratory to remove smaller debris that adhered to the surface. A dissecting scope was then used to remove and sort remaining debris in categories. Filtering was conducted using six pre-cleaned Newark type sieves, sized 4.75, 2.0, 1.0, 0.710, 0.500, and 0.355 mm. Teams recorded the specific types of material observed when feasible. Following sorting and identification, each size class was dried in a lab oven (65°C) for a minimum of eight hours. Volume and mass were then measured and recorded for each size class. Debris items within each of the size class categories was also sorted according to color (i.e., white, red, black, etc.) based on previous studies, indicating a feeding preference by fish based on the color of plastic micro-debris (Boerger 2010). Notes included additional descriptive information regarding the debris such as brand names and item color(s) in the comments section for that item. In cases where very small volumes for each size class could not be measured, a total volume was recorded.

Data Analyses

Abundance of plastics across the various fish species and the San Diego Bay sand samples were examined using descriptive statistics. Manly's Alpha (Chipps and Garvey 2007) was used to examine fish prey preference by comparing the abundance of the types of plastics found in the sand samples with the abundance of the types of plastics consumed by the fish. Differences in plastics ingestion between fish size and sex were explored using chi-square analysis and t-tests, respectively. Plastic debris counts from trawl surveys were weighted against the amount of water volume filtered during the trawl to get the density of plastic debris per cubic meter. Prior to statistical analysis, data was log (x+1) transformed to achieve a normal distribution. Subsequently, one-way ANOVA was performed in conjunction with Tukey and Scheffe post-hoc tests to determine differences between plastic abundances in size and color classifications, respectively.

Results

Plastic Debris in Surface Waters

A total of 100% of trawl surveys conducted during the study period contained plastic debris. Plastic micro-debris represented 95% of all debris collected in trawls, while macro- and meso-debris represented less than 1% and 5%, respectively. Mean density of white, clear, blue, and black colors was significantly higher than that of other colors identified during pre- and post-storm sand surveys (ANOVA, $p = <0.001$), making up 88% of total plastic debris density. Micro-debris mean density in the 2-mm to 1-mm size range was highest among all micro-debris size classes during pre-storm surveys, and was significantly higher than mean debris density of meso-debris (25 cm – 4.75 mm) (ANOVA, $p = 0.04$). Within the various micro-debris size classes, the total number of micro-debris items identified during pre-storm surveys ranged from 359 to 931 (±57.86) plastic items, showing no significant difference between means. The debris collected in the south bay represented 45% of plastic debris obtained during pre-storm trawls (Figure 2).

Plastic debris density among all size classes decreased from pre- to post-storm surveys, except for the smallest micro-debris size class (0.5 mm – 0.355 mm). There was a significant increase in the mean density of the 0.5-mm to 0.355-mm micro-debris during post-storm surveys (ANOVA, $p = 0.02$). During post-storm surveys, the abundance of plastic debris shifted from the south bay to north-bay (Figure 2), as 54% of plastic debris was found in the north bay during post-storm trawls.

Small Plastic Debris in Sand

The shallow-water sands around San Diego Bay (see Table 1) contained 21 types of small plastic debris, all of which fell into four categories: polystyrene, soft pieces, hard pieces, and fibers. An average of 6,654 ± 1,232 (± 1 SE) plastic debris pieces per cubic meter was found across all sand samples (Table 1), with only one sample lacking any plastic debris. Synthetic fibers were the most common (50%) plastic debris found in San Diego Bay sands, followed by hard pieces, polystyrene, and soft pieces (Figure 3).

Small Plastic Debris in Fish Guts

Of the 79 fish caught for this study 11 of the fish analyzed had ingested plastics micro-debris. Polystyrene was not present in the guts of any of the species, despite being present in the sand. Eight of the 45 round stingrays (~18%) had plastic debris in their guts (Table 1). Plastics in the guts of the round stingray most resembled the composition in the sand, with a predominance of hard pieces and fibers (over 90%) being present in the gut (Figure 3). Of the eight different types of plastics consumed by the round stingray, five, including white, red, and blue hard pieces, and white and blue fibers, were preferentially consumed over what was available in the sand (Table 1). The one white seabass sampled had only clear/white hard plastic pieces in its gut, while ~12% (2 of 17) spotted sand bass individuals contained only clear/white soft plastics (see Figure 3). None of the 16 California halibut contained plastics in their gut.

Plastics Consumption Based on Fish Size or Sex

In all of the fish species caught, plastics were found in the gut of male white seabass, spotted sand bass and round stingray, but only found in the gut of female round stingrays. Round stingray females were 4.5 times more likely to have plastics in their stomachs than expected by chance (see Table 2.b). The sizes of spotted sand bass or round stingray that consumed plastics were no different from the sizes of the same species that did not consume plastics (see Table 2.b). Note that only one white seabass was captured, none of the California halibut contained plastics, and only two spotted sand bass males contained plastics. Thus, all three species were excluded from one or more of these analyses.

Fish Diets

The round stingray had the highest diversity of prey items of any of the fish sampled, including mostly shells and unknown digested organics (see Table 3). Spotted sand bass contained a diverse number of prey items, including fish, crustacean, and mollusk parts (see Table 3). The one white seabass had no prey items found in the gut (only sand and silt) (see Table 3). The California halibut contained no plastics but did contain diverse prey items (see Table 3).

Discussion

Presence of Small Plastic Debris in San Diego Bay

The results of this study indicate that small plastic debris (0.5 mm – 1 cm in size) is widely distributed throughout San Diego Bay. Small plastics or plastic micro-debris was found in 100% of trawl surveys and 97% of sand samples. Enclosed or semi-enclosed bays, estuaries, and seas such as San Diego Bay appear to serve as key sinks of small plastics (Barnes 2009; Duis 2016) and therefore could provide insight into long-term trends for plastics management.

Fish Consumption of Plastics

Plastics consumption rates varied with species, and may also be a factor of small sample sizes of some of the species, life cycle stage (e.g., sub adult vs adults), sex, and/or sampling chance. The round stingray had relatively high levels of susceptibility to plastic debris consumption, as approximately 18% of the round stingray surveyed contained plastics in their guts. The round stingray had the highest diversity of prey items and the most diverse suite of plastics among all the species surveyed. Round stingrays typically feed by using their pectoral fins to burrow into soft substrate (Babel 1966; Bester n.d.). They primarily consume bivalves, polychaetes, and crustaceans, and use scent, sight (including ultraviolet [UV] vision), and electroreception to detect their prey (Babel 1966; Bester n.d.; Bedore 2013a; Bedore et al. 2013b). Although uncertain, it is possible that the round stingray's preference for white, red, and blue hard pieces, and white and blue fibers, was due to the plastics' resemblance to its prey items. The hard pieces may have resembled the shells and appendages of bivalves or crustaceans, and the fibers may have resembled polychaetes. Given the magnitude and abundance of plastic pieces within San Diego Bay, it is also possible that observed plastic pieces are a product of incidental ingestion while consuming regular prey items, but the incidental ingestion concept does not fully explain why female round stingrays were more likely, and males less likely, to have ingested plastics.

The two spotted sand bass containing plastics had only white or clear soft plastic pieces in their guts. Overall, the spotted sand bass surveyed displayed relatively diverse prey items. While this species is not demersal, it lives near the sandy substrate in semi-protected reefs that often contain eelgrass or surfgrass (Smith-Vaniz et al. 2010; Allen et al. 1995). Benthic invertebrates, including Brachyuran crabs and bivalve mollusks, make up the majority of the spotted sand bass's diet, which also includes bony fishes and amphipods (Allen et al. 1995). It is unclear why the spotted sand bass selectively consumed white and clear soft plastics, but it may be due to the plastic's resemblance to prey attributes, such as scales or shells.

Conclusions are difficult to draw from the small sample size of one white seabass, but at the very least, this study shows that plastics ingestion is possible for this pelagic species. Sand and/or silt were the only items in the white seabass's gut, and this intake of sand could explain the presence of white or clear colored hard plastics. Future studies could investigate whether plastic debris bioaccumulates, and whether it would be possible for white seabass to have plastic in its gut from ingesting prey species (such as northern anchovy or Pacific sardine [Antes et al. 2011]) with plastic in their guts.

All 16 California halibut individuals surveyed contained no ingested plastics. The California halibut is a visual "sit and wait" predator, hunting as the prey swims by (Haugen 1990). It may be that by hunting prey selectively, this species avoids most oral contact with the substrate and therefore reduces its risk of plastic debris consumption. Thus, despite being a demersal species, the California halibut seems to avoid the plastic present in the San Diego Bay substrate.

Implications for Health of Fish and Food Webs

The effects of plastic debris within organisms, once ingested, are still largely uncertain. The plastics themselves may accumulate in the gut or gills of organisms (Murray and Cowie 2011; Watts et al. 2014; Browne et al. 2008), and/or do physical or chemical damage to organisms' internal organs and cellular function (Rochman et al. 2013; Browne et al. 2013). It is unclear whether small plastic debris is transferred between trophic levels, but some of the metals and other contaminants they carry with them could be transmitte (Rochman et al. 2014). Thus, the presence of these plastics in the environment has potential impacts on food webs and ecosystems.

This study corroborates the findings of other recent studies (Rochman et al. 2015; Van Cauwenberghe and Janssen 2014) that plastics occur in species consumed by humans. All four of the species surveyed in this study are labeled as game fish (fishbase.org). California halibut has significant commercial value, and round stingray and white seabass have minor commercial value (fishbase.org). Humans, too, may be impacted by small plastic debris and the contaminants they adsorb (Rochman et al. 2015).

Recommendations for Future Monitoring

The goal of this study was to document the types and abundances of small plastic debris present in San Diego Bay surface waters, sediments, and shallow-water fish. The results of preliminary survey of intertidal juvenile fish indicated a much higher rate of plastic ingestion than the shallow water fish caught in the Bay. Likewise, the fish survey results from this study indicate a much higher rate of plastic ingestions for the fish residing in coastal embayments than the fish caught in open ocean surveys during the 2013 Southern California Bight Regional Monitoring Program (Moore, 2016) Needed next are the investigations into the plastic ingestion rates for pelagic and demersal fish in other coastal embayment including an assessment of the impacts from plastic debris on sediments, fish, food webs, and ecosystem health. Future research could include studies that test the relative risk of pelagic and demersal species to plastic debris ingestion and contamination by adsorbed toxins. Studies that test whether plastic debris bioaccumulates within San Diego Bay marine food webs, and studies that test the damage done by plastic debris to the biological or behavioral functioning would be the recommended next steps needed to ensure that humans are not being unnecessarily exposed to potential transference of contaminants through the food chain.

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Figures

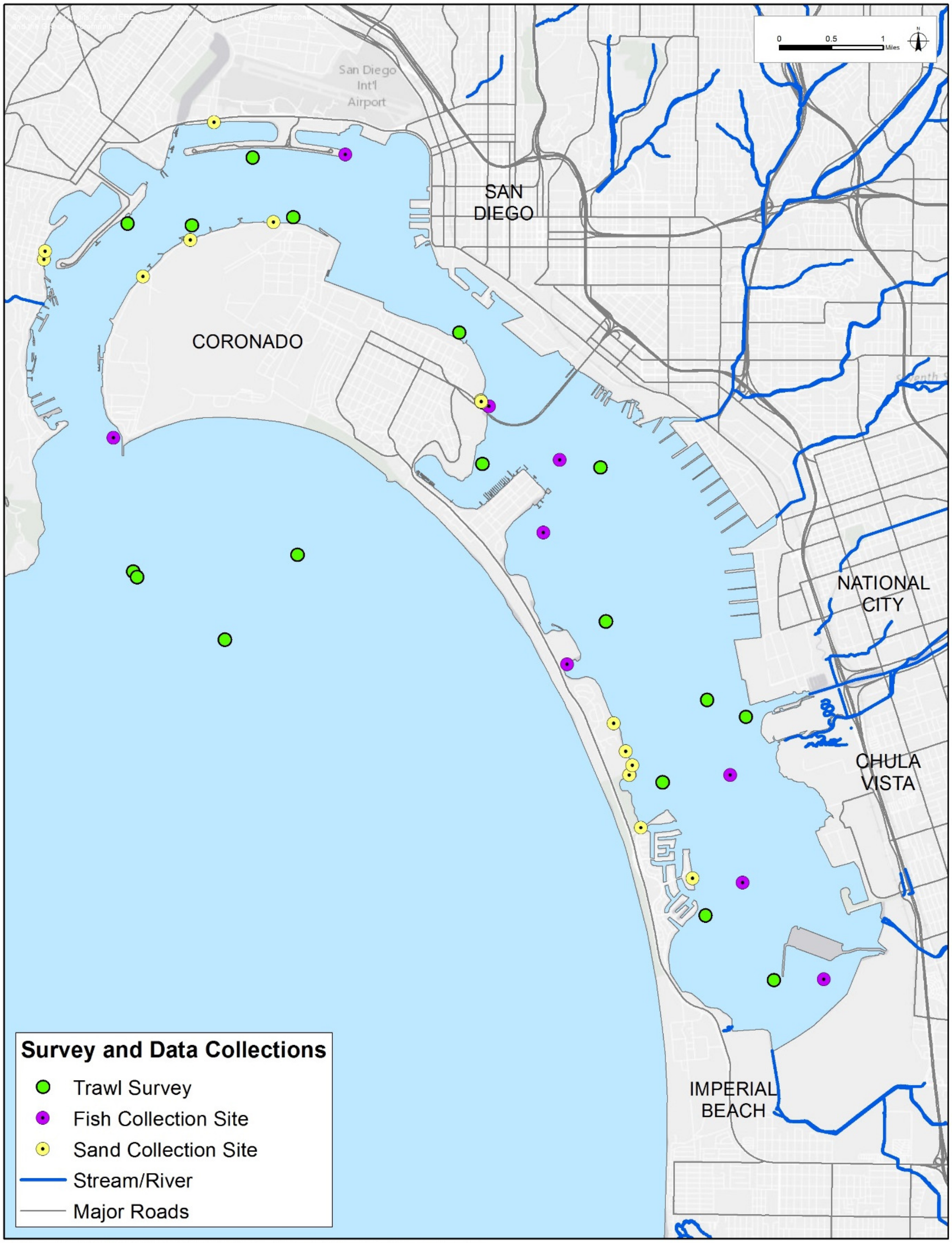

Figure 1. Sand, Fish, and Trawl Data Collection and Survey Locations in San Diego Bay, San Diego, California.

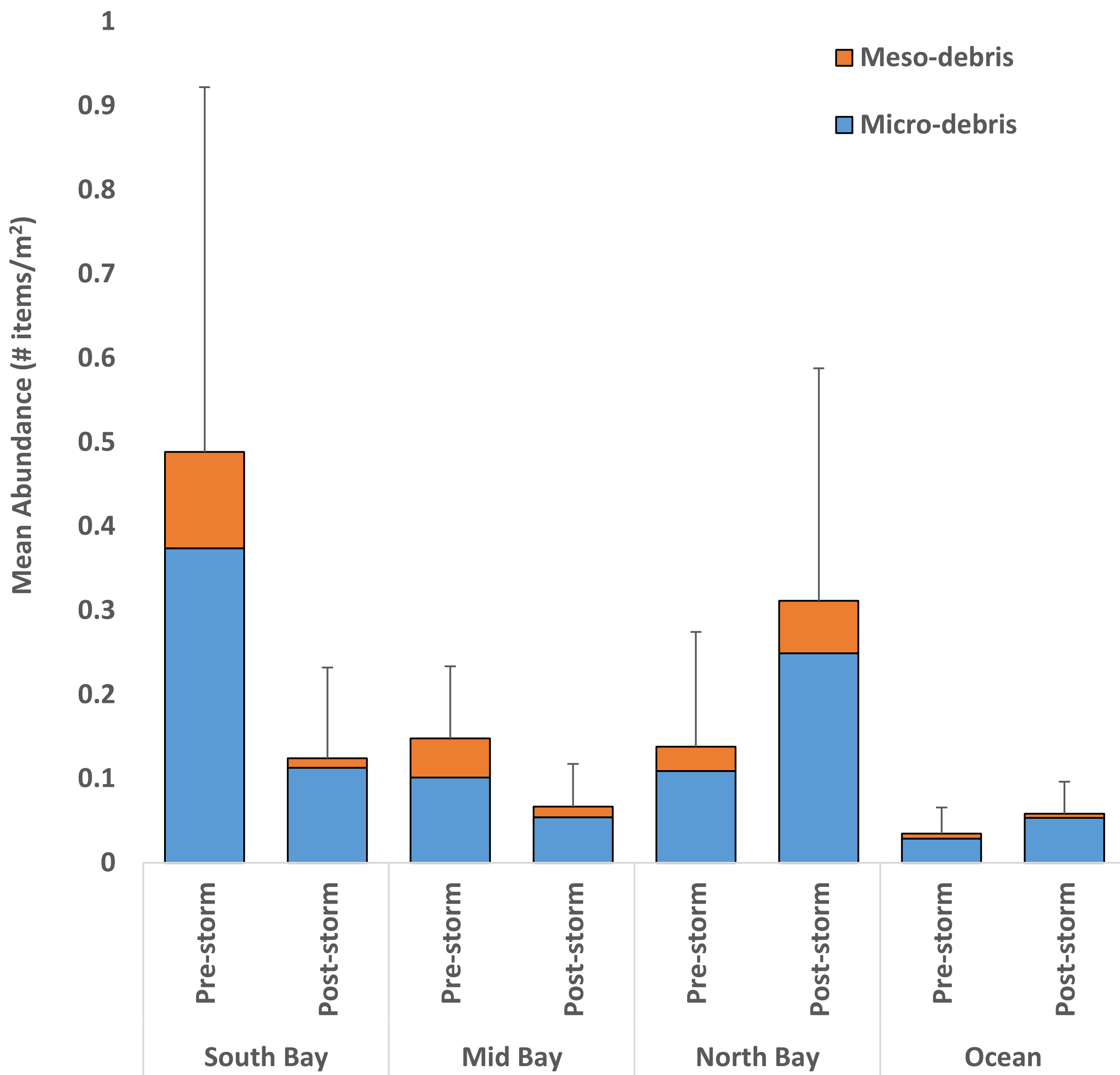

Figure 2. Mean Density (number of items per square meter) of Plastic Micro-Debris Found in Manta Trawls Conducted Throughout San Diego Bay. Data were collected in October 2014 (pre-storm) and April 2015 (post-storm). Macro-debris was less than 0.01 items per square meter and was found in the north-bay during post-storm surveys. Macro-debris is not shown in this figure because of the miniscule relative abundance.

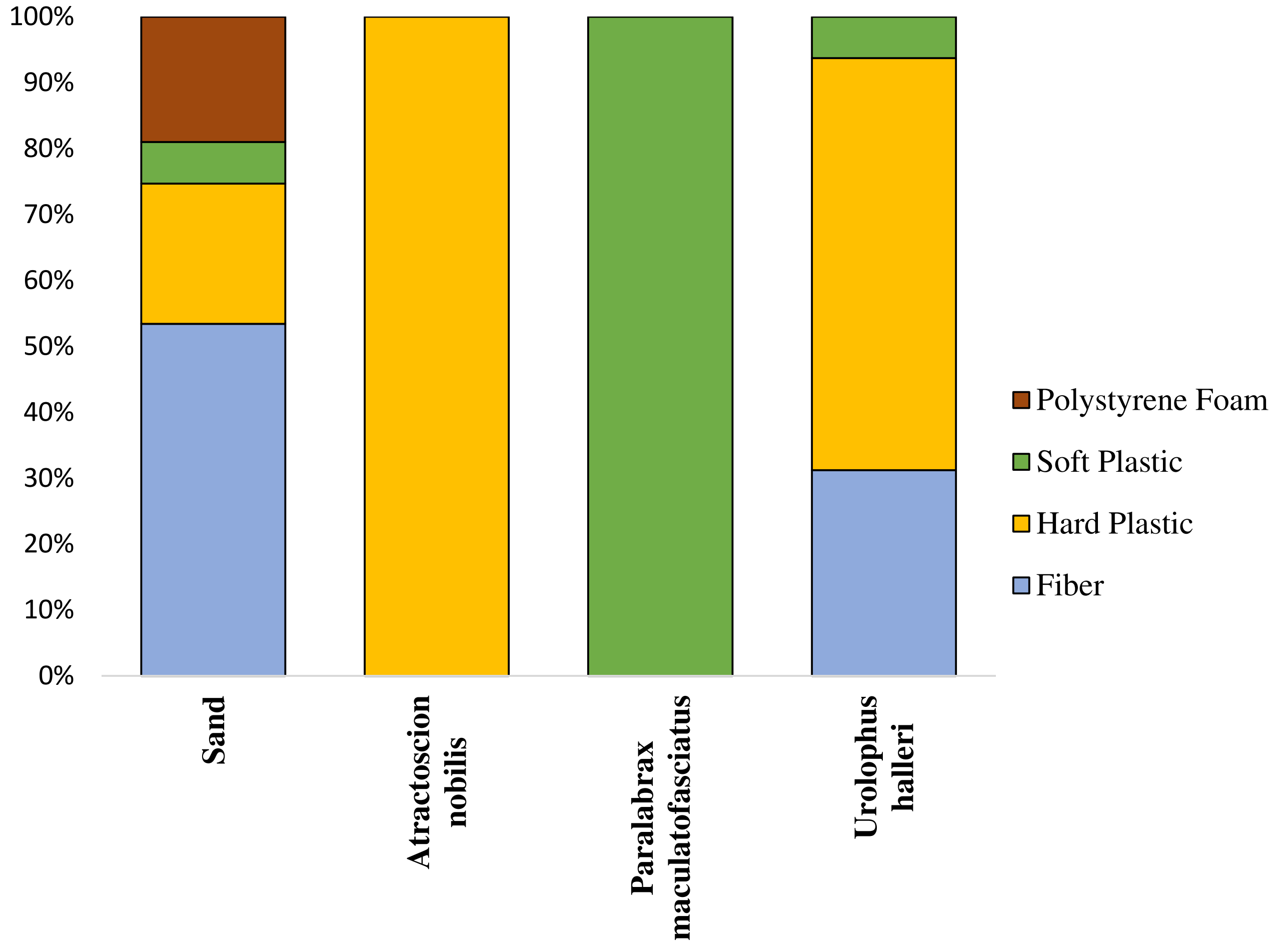

Figure 3. Relative Abundance and Composition of Plastic Debris Found in Sand and Guts of Three Local Species of Fish in San Diego Bay (n = 26 sand samples, 1 white seabass, 2 spotted sand bass, and 8 round stingray). Data were collected September through November 2014 and March 2015 (sand samples) and April 2015 (fish samples).

Tables

Table 1. Abundance of Plastic Debris in Sand and Guts of Local Bay Fish. Manly's alpha a ≥ 0.091 (shown in bold). Cells are grey highlighted for presentation purposes to highlight micro-debris found in the fish gut.

Type of plastic debris	**Sand**	**white seabass**	**spotted sand bass**	**round stingray**	**white seabass**	**spotted sand bass**	**round stingray**
Sample size (n)	26	1	2	8	1	2	8
	Abundance (number per m^3) Mean ± 1 SE	Abundance (number per gut)			Manly's alpha ($\alpha \geq 0.091$)		
Polystyrene Foam	1269.23 ± 524.94	0	0	0	0	0	0
Soft plastic pieces							
Clear/White	192.31 ± 96.38	0	4	1	0	**1**	0.06 ± 0.06
Green	0	0	0	0	0	0	0
Blue	38.46 ± 38.46	0	0	0	0	0	0
Red	0	0	0	0	0	0	0
Yellow	0	0	0	0	0	0	0
Orange	0	0	0	0	0	0	0
Purple	0	0	0	0	0	0	0
Grey	115.38 ± 63.90	0	0	0	0	0	0
Black	76.92 ± 53.29	0	0	0	0	0	0
Total	423.08 ± 185.41	0	4	1	-	-	-
Hard plastic pieces							
Clear/White	500 ± 177.59	1	0	5	**1**	0	**0.26 ± 0.16**
Green	0	0	0	0	0	0	0
Pink	192.31 ± 78.82	0	0	0	0	0	0
Blue	269.23 ± 118.42	0	0	2	0	0	**0.15 ± 0.12**
Red	76.92 ± 53.29	0	0	2	0	0	**0.17± 0.11**
Yellow	153.85 ± 91.02	0	0	1	0	0	0.04 ± 0.04
Purple	0	0	0	0	0	0	0
Grey	38.46 ± 38.46	0	0	0	0	0	0
Black	115.38 ± 63.90	0	0	0	0	0	0
Gold	0	0	0	0	0	0	0
Silver	0	0	0	0	0	0	0
Orange	76.92 ± 53.29	0	0	0	0	0	0
Total	1423.08 ± 267.02	1	0	10	-	-	-

Table 1 (cont.). Abundance of Plastic Debris in Sand and Guts of Local Bay Fish

Type of plastic debris	**Sand**	**white seabass**	**spotted sand bass**	**round stingray**	**white seabass**	**spotted sand bass**	**round stingray**
Fibers							
Clear/White	2000 ± 526.23	0	0	2	0	0	**0.14 ± 0.14**
Black	307.69 ± 164.26	0	0	2	0	0	0.08 ± 0.08
Blue	653.85 ± 207.12	0	0	1	0	0	**0.14 ± 0.14**
Yellow	0	0	0	0	0	0	0
Green	38.46 ± 38.46	0	0	0	0	0	0
Pink	346.15 ± 123.32	0	0	0	0	0	0
Red	76.92 ± 53.29	0	0	0	0	0	0
Grey	38.46 ± 38.46	0	0	0	0	0	0
Orange	0	0	0	0	0	0	0
Tan	38.46 ± 38.46	0	0	0	0	0	0
Purple	0	0	0	0	0	0	0
Total	3500 ± 810.03	0	0	5	-	-	-
Total – All Debris Types	6653.85 ± 1231.56	1	4	11	-	-	-

Table 2. Comparison of Sizes and Sex of All Fish with Sizes and Sex of Fish That Had Plastic Debris in Their Guts. Shown are results of t-tests for morphological variables, and Chi square tests for sex ratios; white seabass and California halibut did not have enough fish to run analyses.

2.a White Seabass and California Halibut

Species	White Seabass						California Halibut					
	All fish			Fish with plastics			All fish			Fish with plastics		
n =	1			1			16			0		
Variable	**Avg**	±	**1 SE**	**Avg**	±	**1 SE**	**Avg**	±	**1 SE**	**Avg**	±	**1 SE**
standard length (cm)	19.50	±	0	19.50	±	0	16.19	±	1.46	0	±	0
total length (cm)	23.00	±	0	23.00	±	0	19.16	±	1.61	0	±	0
weight (g)	111.20	±	0	111.20	±	0	88.72	±	24.94	0	±	0
sex: female/ male/ unknown	0/1/0			0/1/0			2/0/14			0/0/0		

2.b Spotted Sand Bass and Round Stingray

Species	Spotted Sand Bass									Round Stingray								
	All fish			Fish with plastics			t-test/Chi square results			All fish			Fish with plastics			t-test/Chi square results		
n =	17			2			-	-	-	45			8			-	-	-
Variable	**Avg**	±	**1 SE**	**Avg**	±	**1 SE**	**P**	**t/ Chi sq**	**df**	**Avg**	±	**1 SE**	**Avg**	±	**1 SE**	**P**	**t/ Chi sq**	**df**
standard length (cm)	18.97	±	0.84	20.25	±	0.25	0.62	0.51	17	4.47	±	0.15	5.50	±	0.32	0.78	0.28	51
total length (cm)	22.82	±	0.99	25.00	±	0.50	0.47	0.73	17	5.27	±	0.17	6.40	±	0.40	0.92	0.11	51
weight (g)	166.06	±	17.60	191.70	±	10.00	0.63	0.49	17	2.57	±	0.27	4.20	±	0.94	0.95	0.06	51
sex: female/ male/ unknown	11/2/4			0/2/0			0.03	7.33	2	27/18/0			6/2/0			**0.002**	**9.38**	**1**

Table 3. Abundance of Prey and Other Non-Plastics Found in the Guts of San Diego Bay Fish.

Species	white seabass	California halibut	spotted sand bass	round stingray
n =	1	16	17	45
	Percent of fish with items present			
Prey items				
sand-or-silt	100%	15%	0%	7%
pseudofeces	0%	0%	0%	1%
scales	0%	5%	10%	4%
shells	0%	0%	29%	35%
unk exoskeleton	0%	0%	10%	4%
Unk bone	0%	5%	0%	0%
unk organics/digested	0%	25%	0%	14%
eelgrass	0%	0%	6%	0%
otoliths	0%	0%	0%	1%
copepod	0%	0%	0%	1%
Musculista senhousia	0%	0%	3%	0%
razor clam	0%	0%	3%	0%
snail	0%	0%	6%	0%
unk worms	0%	5%	0%	9%
bristleworm	0%	0%	0%	4%
lizard fish	0%	5%	0%	0%
kelp fish	0%	0%	3%	0%
goby	0%	20%	3%	1%
flatworm	0%	0%	0%	1%
swimmer crab	0%	0%	3%	0%
unk whole crab	0%	0%	13%	1%
crab-pieces	0%	5%	6%	0%
shrimp-or-pieces	0%	15%	3%	1%
amphipods	0%	0%	0%	7%
other arthropods	0%	0%	0%	4%

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