# Evaluation of Potential Health Risks from Microplastics in Drinking Water

by

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# AUTHOR'S DECLARATION

I hereby declare that I am the soul author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Microplastics have been detected, often abundantly, in freshwater environments over the past decade. While understanding of the ecological health implications of microplastics in aquatic environments has advanced considerably, the health risks of microplastics in drinking water are not well understood. Direct health impacts are attributed to the ingestion of microplastics materials themselves. In contrast, indirect health impacts are attributed to the chemical contaminants that sorb on and in microplastics in the aquatic environment and are concurrently ingested. While it is desirable to evaluate both types of health risks, there are currently no available and conclusive toxicological investigations of the health implications of microplastics ingestion by humans; current understanding is limited to microplastics impacts on small organisms or cell cultures. In contrast, considerable information regarding the health effects of some contaminants that sorb on or in microplastics is available. Although this information has not been integrated to inform health risks associated with microplastics ingestion via contaminated drinking water, this integration is pressingly needed to guide risk management.

Here, the potential health risks attributable to chemical contaminants retained on or in microplastics in the aquatic environment and ingested via contaminated drinking water were assessed using a new concept developed in this research: the Threshold Microplastics Concentration (TMC). The TMC indicates the total number of microplastics particles per liter of water that, if ingested, constitutes exposure to potentially harmful concentrations of chemical contaminants retained on or in microplastics via sorption mechanisms. A TMC of 0.024 microplastics particles per liter was identified given currently available contaminant sorption data; this value increased to 2.550 microplastics particles per L in absence of antimony. Thus, these respective values indicate that source water concentrations of 24 or 2,550 microplastics particles per L or less should not pose health concerns attributable to sorbed chemical contaminants for well-operated conventional treatment systems in which a 3-log (i.e., 99.9%) reduction in microplastics concentration can be reasonably expected by physico-chemical filtration. Critically, a source water microplastics concentration that exceeds the TMC is not necessarily indicative of health risks from microplastics in drinking water; rather, it indicates that more detailed analysis may be warranted. For example, system specifics such as types of treatment implemented, sorbed contaminants present in the source water, size distribution of the microplastics, etc. affect the TMC. Notably, antimony was identified as a potential sentinel indicator of potential health risk from microplastics because it is especially toxic. Similarly, PVC was identified as a key microplastics type because of its contaminant sorption propensity. Only 11 contaminants and seven common microplastics materials were included in this analysis because of limited sorption and toxicity data for known chemical contaminants of human health concern; however, the “Microplastics Calculator” developed herein to calculate TMCs can be easily updated as chemical, plastics, and treatment data become available.

Microplastics are particles—in many ways they are not different than other particles removed during drinking water treatment. Their removal can therefore be explained by the physico-chemical processes that are involved in particle removal during filtration. Here, a synthesis of the current knowledge regarding the treatment of particulate contaminants including microplastics and a limited series of surface charge assessments and bench-scale coagulation and filtration experiments were conducted to confirm microplastics removal expectations during drinking water treatment. These experiments demonstrated the size dependency that would be expected by classical filtration theory: the order of particle removal efficiency by filtration was 45 µm > 10 µm > 1 µm. The surface charge of several common microplastics (polyethylene, polystyrene, acrylic, and polyetheretherketone) varied considerably and was impacted by the quality of the matrix in which they were suspended, as would be expected. Notably, however, coagulant addition at doses sufficient for achieving optimal particle destabilization in absence of the microplastics was also sufficient for destabilizing microplastics suspended at environmentally relevant concentrations in all matrices investigated (i.e., distilled deionized MilliQ$^{TM}$ water; 100 mM KCl electrolyte solution; low turbidity, low dissolved organic carbon (DOC) Lake Ontario water; and moderate DOC, higher turbidity Grand River water). Overall, this analysis confirmed that the removal of microplastics particles by engineered physico-chemical filtration processes should be consistent with that which would be expected of other particles and particulate contaminants.

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# DEDICATION

For my father AKM Shaiful Islam Chowdhury who is my role model and my biggest inspiration, and my mother Nazma Khanam Chowdhury for always encouraging me to be the best version of myself and always reminding me of the importance of being a good human being.

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# List of Acronyms

| **Abbreviation** | **Description** |
|---|---|
| A | Surface area of one particle |
| AC | Adsorption capacity |
| $AC_{LA}$ | Adsorption capacity (literature acquired) |
| $AC_{M}$ | Normalized adsorption capacity |
| ACR | Acrylic |
| ACS | American Chemical Society |
| AWWA | American Water Works Association |
| DI | Deionized water |
| DWEL | Drinking Water Equivalent Level |
| eff | Effluent |
| ES | Effective size |
| HA | Health advisory |
| HDPE | High density polyethylene |
| inf | Influent |
| IS | Ionic strength |
| IWA | International Water Association |
| lc | Long cylinder |
| LDPE | Low density polyethylene |
| MAC | Maximum Acceptable Concentration |
| MCL | Maximum Contaminant Level |
| MP | Microplastic |
| MS | Microsphere |
| N | Number of particles per gram |
| NOM | Natural organic matter |
| NS | Nanosphere |
| os_0.2 | Oblate spheroid with an ellipticity of 0.2 |
| os_0.9 | Oblate spheroid with an ellipticity of 0.9 |
| PC | Polycarbonate |
| PCP | Personal care product |

| | |
|---|---|
| PE | Polyethylene |
| PET | Polyethylene terephthalate |
| PEEK | Polyetheretherketone |
| PNEC | Predicted No Effect Concentration |
| PP | Polypropylene |
| PS | Polystyrene |
| PVC | Polyvinylchloride |
| PZC | Point of zero charge |
| $R_A$ | Adsorption capacity based on surface area |
| Rfd | Reference dose |
| sc | Short cylinder |
| sp | Sphere |
| $T_g$ | Glass transition temperature |
| $T_M$ | Melting temperature |
| TMC | Threshold Microplastics Concentration |
| TOC | Total Organic Carbon |
| $TSA_{LA}$ | Total Surface Area (literature acquired) |
| $TSA_M$ | Total Surface Area (based on assigned size, shape, and type) |
| UC | Uniformity coefficient |
| USEPA | United States Environmental Protection Agency |
| UV | Ultraviolet |
| V | Volume of one particle |
| WHO | World Health Organization |
| $\rho$ | Density |

# Chapter 1 Introduction

Drinking water utilities play a vital role in public health protection by supplying drinking water that conforms to regulated standards for physical, chemical, microbiological, and radiological water quality. Examples of emerging contaminants of potential health concern include pharmaceuticals and personal care products, industrial and household chemicals, pesticides, manufactured nanomaterials, and their transformation products. Over the past two decades, increasingly stringent discharge requirements have been imposed by regulatory agencies to limit both existing and emerging contaminants of ecological and human health concern from harming aquatic organisms and entering drinking water source supplies (Valbonesi et al., 2020). Concurrently, the quality of surface and groundwater source supplies is increasingly variable as a result of both anthropogenic (e.g., development, urbanization, and resource extraction) and natural, climate-change exacerbated (e.g., floods, wildfires) landscape disturbances (Emelko et al., 2011; Milly et al., 2008).

In recent years, plastics, specifically microplastics, have emerged as contaminants of health concern due to their ubiquitous presence in various environmental compartments, including aquatic environments (Wagner and Lambert, 2018). Plastic debris is globally widespread to the point that it has been suggested that this historical epoch can be described as the Plasticene (Haram et al., 2020). Microplastics research initially focused in the marine environment; a wealth of information regarding microplastics contamination and impacts on aquatic organisms in that setting has been documented (Andrady, 2011; Wright et al., 2013). More recently, microplastics in freshwater systems have become an additional focus (Eerkes-Medrano et al., 2015). Of particular note, microplastics particles are increasingly found in drinking water supplies and treated waters (Novotna et. 2019), thereby raising concerns about the potential human health implications of their ingestion.

Initial public awareness about the presence of microplastics in drinking water can be largely attributed to a 2017 investigation that reported the presence of microplastics in tap water from fourteen different countries (Orb Media, 2017). This was complemented by a report of widespread presence of microplastics in human consumables including tap water, beer and sea salt—that evaluation suggested that the average person ingests over 5,800 particles of microplastics debris from these sources annually, with tap water comprising the largest contribution (88%) (Kosuth et., 2018). Further investigations also have confirmed the presence of microplastics in drinking water (Eerkes-Medrano et al., 2019). Their health effects on marine life, turtles, birds and other animals have led to questions about the potential human health risks resulting from their ingestion (Bouwmeester et al., 2015a; Lehner et al., 2019a; Paget et al., 2015; Smith et al., 2018). Numerous routes of microplastics transmission to drinking water supplies and treatment plants have been identified (Figure 1.1). The apparent ubiquitous presence of microplastics in the aquatic environment underscores the need to evaluate the potential human health impacts attributable to their ingestion via treated drinking water.

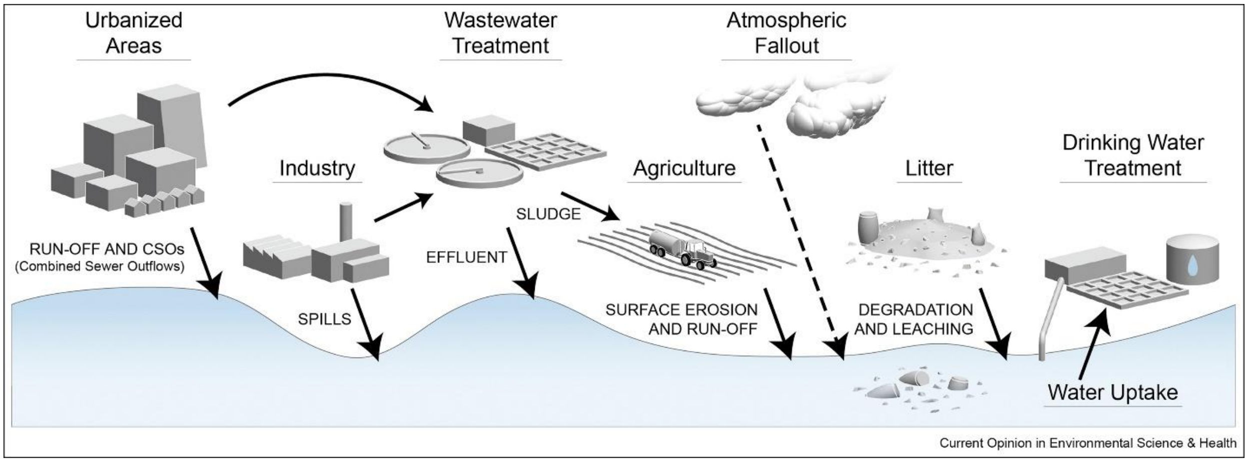


Figure 1.1: Routes of microplastics transmission to drinking water supplies and treatment plants. Reprinted from (Eerkes-Medrano et al., 2019).

Recognition of the importance of understanding microplastics risks to human health and the associated need to develop mitigation strategies is relatively recent. A January 17, 2021 search of the keyword “microplastics” (https://www.sciencedirect.com/) indicated a total of 7,051 research publications dated between 1997 and 2020, inclusively. Research interest and output in this area has been growing rapidly—approximately 74% of the publications on this topic have been published in just the past four years (2017 to 2020). Figure 1.2 illustrates the breakdown of microplastics research foci during this period; it indicates that approximately 55% of the global research effort in this area focused on microplastics occurrence in the environment and methods of quantification. Although drinking water treatment was the smallest focus area, the explosive growth of scientific research (Figure 1.2a) and public interest regarding microplastics more broadly underscores the need for utility and watershed managers, as well as regulators, to be informed and prepared to engage with microplastics as emerging particulate contaminants of potential health concern in source and treated waters. Guidance for evaluating and managing health risks attributable to microplastics in source and treated drinking waters is currently lacking, however.

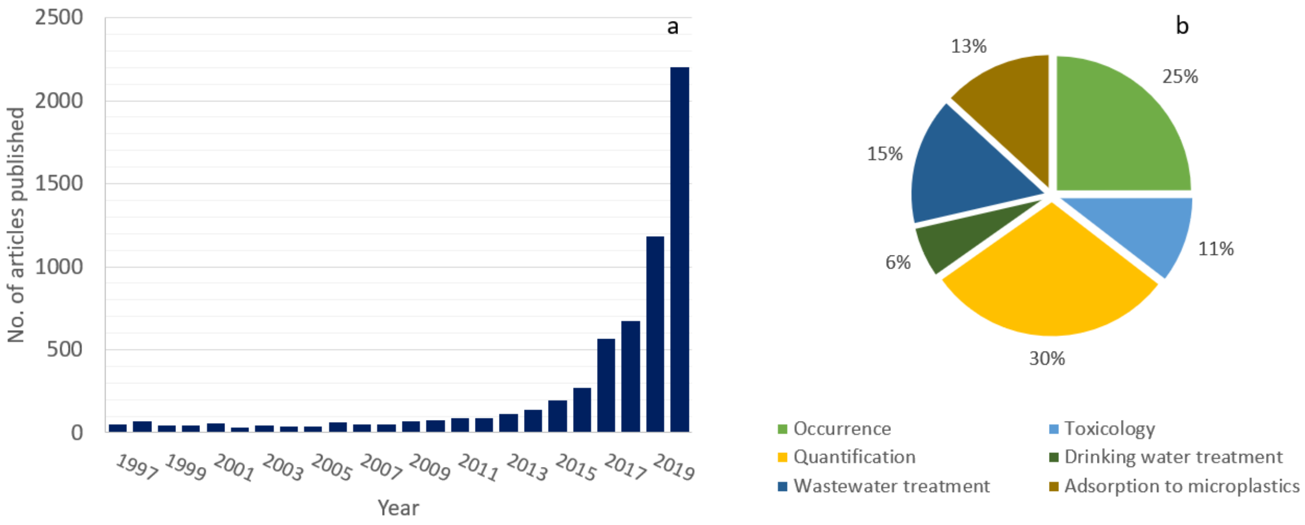


Figure 1.2: Increase in published microplastics research (a) and breakdown of microplastics research foci during the period (b) from 2017 to 2020, inclusive (https://www.sciencedirect.com/ accessed on January 17, 2021).

Health-based targets are essential components of drinking water safety approaches globally; they are especially relevant when reducing exposure to contaminants through the provision of safe drinking-water may appreciably reduce overall risks of disease (WHO, 2005). With increasing global evidence of microplastics contamination of source and treated drinking water supplies, it has become necessary to evaluate the health risks attributable to their presence in drinking water. It is important to recall that risk—the possibility of harm arising—is a function of both hazard and exposure and so, some presence of microplastics in drinking water is not *necessarily* indicative of adverse health effect. Currently, there are scant data available regarding both human and ecosystem exposure to and health hazards posed by waterborne microplastics; thus, health risk assessment focused on the microplastics themselves is not yet possible. Therefore, there are no regulatory guidelines or limits for microplastics in drinking water; more toxicological information is needed to meaningfully derive health-based targets, should they be warranted.

Notably, in addition to the health impacts induced as a result of the microplastics particles themselves, chemical contaminants on and within the microplastics may also have significant health effects (Revel et al., 2018; Teuten et al., 2009). While understanding of the direct health impacts of microplastics on living organisms (especially humans) is limited, the health effects of many of the chemical contaminants that they may sorb have been evaluated (Calderon, 2000; Goyer et al., 1950; Sundar and Chakravarty, 2010). Thus, preliminary assessment of these indirect health impacts posed by microplastics in drinking water can be conducted based on an understanding of contaminant sorption on plastic surfaces and within microplastics pores, and the occurrence of various types and sizes of microplastics in water supplies. Health effects would be theoretically induced if microplastics were ingested in sufficiently high concentrations such that sorbed chemical contaminants were accumulated at concentrations exceeding their maximum acceptable concentrations in drinking water. To date, no such analysis has been conducted.

## 1.1 Research Objectives

Microplastics are not currently monitored in either source or treated water supplies, and guidelines or regulations indicating maximum acceptable concentrations for microplastics in drinking water are not currently available. Surveys of microplastics occurrence in the environment, along with information on their type, shape, and characteristics are increasingly available, as is information regarding contaminant sorption. Given this, the primary goal of this research was to develop a broadly applicable, conceptual framework to support drinking water industry risk assessment and decision-making related to managing health risks from contaminants sorbed on and in waterborne microplastics. To address this goal, the specific objectives of this work were to:

1. Evaluate the potential indirect health impacts of consuming microplastics from drinking water by synthesizing available information on sorption of chemical contaminants on and in microplastics;
2. Establish the concept of a “Threshold Microplastics Concentration” (TMC) to indicate the concentration of microplastics that, if ingested, constitutes exposure to potentially harmful concentrations of chemical contaminants retained on or in microplastics;
3. Develop a conceptual model and framework for calculating the TMC for different microplastics types, shapes, sizes, and contaminants;
4. Evaluate and synthesize current knowledge regarding the treatment/passage of different types and sizes of microplastics by/through natural and engineered porous media systems respectively representative of groundwater aquifers and conventional treatment by filtration;
5. Synthesize current knowledge regarding the treatment of particulate contaminants including microplastics and evaluate expectations of microplastics removal by well-operated conventional drinking water treatment; and
6. Develop general guidance for the evaluation of potential health risks attributable to regulated and emerging contaminants sorbed to waterborne microplastics in drinking water.

### 1.2 Research Approach

The occurrence, abundance, and characterization of waterborne microplastics have been widely investigated in both marine and freshwater environments. Occurrence studies have established pathways for microplastics passage into water supplies and the human diet more broadly. While these studies have generated valuable information about environmentally relevant microplastics and advanced our understanding of these particles, they do not enable meaningful inference or analysis that can inform decision making for microplastics associated with drinking water. To address this knowledge gap, a conceptual framework was developed to synthesize the best available scientific data and develop a tool to evaluate the indirect health risks of microplastics ingestion through drinking water. Specifically, the “Threshold Microplastics Concentration” (TMC) concept was developed; it is a parameter analogous to a Maximum Contaminant Level (MCL), which is commonly applied to managing risks from chemical drinking water contaminants. The TMC indicates the total number of microplastics particles per liter of water that, if ingested, constitutes exposure to potentially harmful concentrations of chemical contaminants retained on or in microplastics via sorption mechanisms. It can be used as a relatively rapid indicator to assess if microplastics in source water is concerning from a human health perspective. To accumulate relevant sorption information, an extensive review of available literature was conducted. Finally, the current knowledge regarding the treatment/passage of different types and sizes of microplastics by/through natural and engineered porous media systems representative of groundwater aquifers and conventional treatment by filtration was synthesized. To confirm that the transport behavior of microplastics particles through these porous media systems is consistent with that of other particles and particulate contaminants that they remove, a particulate contaminants- and filtration-focused literature review, and limited series of surface charge assessments and bench-scale coagulation and filtration experiments were conducted.

### 1.3 Thesis Organization

This thesis is divided into five chapters, a list of references, and appendices.

Chapter 1 provides a brief introduction to and rationale for the research; it includes an overall goal and detailed objectives.

Chapter 2 includes a detailed review of the literature regarding waterborne microplastics (occurrence, abundance, characteristics, and evaluation), current and emerging contaminants that sorb to microplastics, health risk assessment, and particle and microplastics fate and transport in natural and engineered porous media systems respectively representative of groundwater aquifers and conventional treatment by filtration. Background information and current state-of-the-art is focused upon to further identify the knowledge gaps.

Chapter 3 outlines the research approach including the rationale, identification of foundational data, model development, and relationship to state-of-art understanding of natural and engineered porous media systems respectively representative of groundwater aquifers and conventional treatment by filtration.

Chapter 4 presents the research results and a discussion of their implications to the broader body of science and practice, as well as their limitations.

Finally, Chapter 5 summarizes of the major conclusions of the research, their implications to the water industry, and recommendations for applications and further research.

# Chapter 2 Literature Review

## 2.1 Microplastics

### 2.1.1 Description

Microplastics represent a diverse range of material types, shapes, colors, and sizes. To account for these complexities, they have been defined according to various criteria (WHO, 2019). Microplastics are generally characterized as water-insoluble polymer particles that are less than 5 mm in size with no formally defined lower boundary in size; thus, the term frequently includes the group of particles that may be referred to as “nanoplastics” (GESAMP, 2015; UNEP, 2016). While an upper size limit has been informally maintained at 5 mm, consensus regarding a lower size limit is lacking among the research community. For instance, according to the European Commission, microplastic particles are plastic particles in the range 100 nm to 5 mm. In one study, 1 mm was set as the upper size limit with no defined lower limit (Browne et al., 2011a). Several similar investigations used an upper size limit of 5 mm for microplastics with no defined lower limit (Murrell et al., 2018; Park and Kim, 2019; Smith et al., 2018; Wu et al., 2018). This inconsistency in microplastics size characterization across investigations highlights the absence of a broader, standardized definition of microplastics and their key attributes. The necessity of a consensus definition for microplastics was suggested by Frias and Nash, (2019); the following definition was proposed: “Microplastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water”.

Structured and consistent classification of microplastics across reporting in both research and practice is critical to enabling comparison and informing decision-making. Various microplastics attributes such as particle size can dictate their relevance in certain areas of research, such as health risk and treatment. For instance, in toxicological assays, plastics in the nanometer size range are typically studied (Auffan et al., 2009) while evaluations of microplastics occurrence in the natural environment typically focus on larger sizes that often depend on operational limitations such as mesh size used for sample collection (Rios Mendoza and Balcer, 2018). When considering treated drinking water, an upper size limit of 5 mm is largely considered irrelevant because particles of this size range are known to be well-removed by conventional treatment comprised of chemical coagulation, flocculation, clarification, and filtration processes (Stackelberg et al., 2007; Tobiason and O'Melia, 1988). It could be argued that simply using the "micro" prefix suggests that the particle size range should be from approximately one to <1,000 µm in their major axis (i.e., longest diameter). Given this large range, it is worthwhile and necessary to meaningfully characterize microplastics in water; several defining and non-defining criteria have been proposed in several scientific reports (Frias and Nash, 2019; Hartmann et al., 2019; Verschoor, 2015). These are summarized as follows:

Defining criteria

i. Substance – Plastic or polymer composition is a fundamental characteristic of microplastics particles; however, key attributes/properties of microplastics must be described and reflected in their characterization. The definition can then inform the specific types of microplastics that need to be taken account. Table 2.1 shows a non-exhaustive list of what this entails.

Table 2.1: Non-exhaustive list of different categories of plastics and their examples. Reprinted from (Board and Oceanic, 2020).

| **Derived monomer or physical constituent** | **Examples** |
|---|---|
| Petroleum | polyethylene, polypropylene, polyurethane, polyethylene terephthalate, polystyrene, polyvinyl chloride |
| Non-petroleum biologically derived chemicals | bio-polyethylene terephthalate, biopolyethylene, polylactic acid, polyhydroxyalkanoates |
| Inorganic or inorganic-organic hybrid polymers | elastomers such as silicone |
| Chemically modified natural polymers | dyed wool, dyed cotton |
| Chemically modified natural rubber | tire wear particles |
| Chemically modified cellulose | rayon, cellophane |
| Copolymers | acrylonitrile-butadiene-styrene [ABS], ethylene-vinyl acetate [EVA], styrene-butadiene rubber [SBR] |
| Polymer composites | nylon, glass fiber-reinforced polyester, graphite reinforced epoxy, cotton-polyester or wool-polyester textile blends |

ii. Dimension – An upper size limit of microplastics size of 5 mm has been commonly used in scientific literature (Hartmann et al., 2019) but the lower limit has been variable with respect to the context. For instance, the size range of concern for environmental concern is different from the size range which is concerning from a health/toxicity perspective (Bouwmeester et al., 2015b; Koelmans et al., 2019). Therefore, it is important to include dimensions within the definition of microplastics in different contexts.

iii. State – Plastic polymers can be solid, semi-solid, wax-like, or even liquid at room temperatures. Depending on their source, synthetic or natural, their state can vary, it can affect their sorptive capacities of contaminants and their removal during drinking water treatment. Therefore, In the context of drinking water, it is necessary to include all the different physical constituents of microplastics- rubber, semi-solid, elastomers, etc. in the definition to account for the wide variety of microplastics found in the aquatic environment.

Non-defining criteria

i. Morphology and color – These are useful descriptors for determining the source of microplastics and during toxicological assessments. This is helpful in tracking the source of these microplastics, which enables identification of the contaminants that maybe associated with the microplastics. Common morphological classifications associated with microplastics include:

| | |
|---|---|
| Pellet | every surface point has the same distance from the center |
| Fiber | length to diameter ratio >3 |
| Fiber bundle | typically inseparable group of >2 fibers |
| Fragment | particle with irregular shape |
| Film-planar | considerably smaller in one than in the other dimensions |
| Black rubbery fragment | typically anthropogenic crumb rubber derived from tires that is technically challenging to identify using common spectroscopic techniques. |

ii. Solubility in water– Conventionally, polymers are insoluble in water, but some synthetic polymers can readily dissolve (e.g., polyvinyl alcohol). This has implications on the water treatment processes for removal of these contaminants. This needs to be taken into consideration by assessing whether the solubility influences the investigation in the specific context being considered.

### 2.1.2 Environment

Microplastics can degrade or transform because of exposure to environmental factors such as waves, UV radiation, abrasion, biological activity, etc. Thus, their size and surface area can change over time, which effects their adsorptive capacities, as will be discussed in the following sections. Sources of microplastics found in freshwater environments and their properties are discussed below.

#### 2.1.2a) Source

Microplastics occurrence and source tracking reveal a correlation between population and urbanization with microplastics load from point and non-point sources (Kataoka et al., 2019). Different types of microplastics can be found in association with various industrial activities and their production has increased substantially over the years (Figure 2.1). As of 2017, total plastic production reached 348 million tons globally, which is several folds higher than the early 1950s (Plastics Europe, 2018). This has led to the ubiquitous presence of plastic particles in terrestrial and aquatic environments. Microplastics found in the environment are generally categorized as primary and secondary (Cole et al., 2011). Primary microplastics are manufactured specifically in the microplastics size range for certain industrial and commercial applications, such as microbeads in personal care products (PCP) or toothpaste. Secondary microplastics are formed from the fragmentation of larger plastic particles exposed to environmental stressors such as UV radiation, oxidation, and abrasion. Such environmental transformations contribute to the challenges associated characterizing microplastics sources and transport in the environment. Microplastics source apportionment approaches include investigation of their characteristics (type, size, color and shape), mass balance techniques, and surface properties (Fahrenfeld et al., 2019).

Wastewater treatment effluent water has been identified as a major pathway of microplastics releases to the environment. Most of these microplastics are derived from primary microplastics that are commonly used in cosmetic products as well as fibers shedding from clothes during washing. It has been estimated that on average, 2,162 particles predominantly composed of polyethylene (PE) plastics less than 350 µm in diameter can be found per gram of typical PCPs (Sun et al., 2020). Polypropylene (PP), polyethylene terephthalate (PET), poly methyl methacrylate (PMMA) and per- and polyfluoroalkyl substances (PFAS) are among the other common types of microplastics used in PCPs. Microplastics are also widely used in manufacturing textile and clothes can shed considerable amounts of fibers during domestic washing (Salvador Cesa et al., 2017). As a result, raw wastewater inputs are contaminated with primary microplastics used in cosmetic products, toothpaste (Duis, 2016) and textile fibers from washing machine effluent (Salvador Cesa et al., 2017). While wastewater treatments can remove waterborne microplastics (Carr et al., 2016; Talvitie et al., 2015), a high concentration of microplastics is still discharged in treated wastewater effluents (Murphy et al., 2016). It has been estimated that a daily discharge of 460 million microplastics particles from wastewater effluent that serves over 1 million people with a capacity of 308 ML/day (Ziajahromi et al., 2017). Another obvious pathway is urban and highway runoff, which conveys microplastics from urban sources to freshwater bodies during storm events (Liu et al., 2019). These microplastics are generated from tire and road wear material and comprise a considerable fraction of microplastics discharged to the environment and ultimately to receiving streams that serve as sources of drinking water (Järlskog et al., 2020).

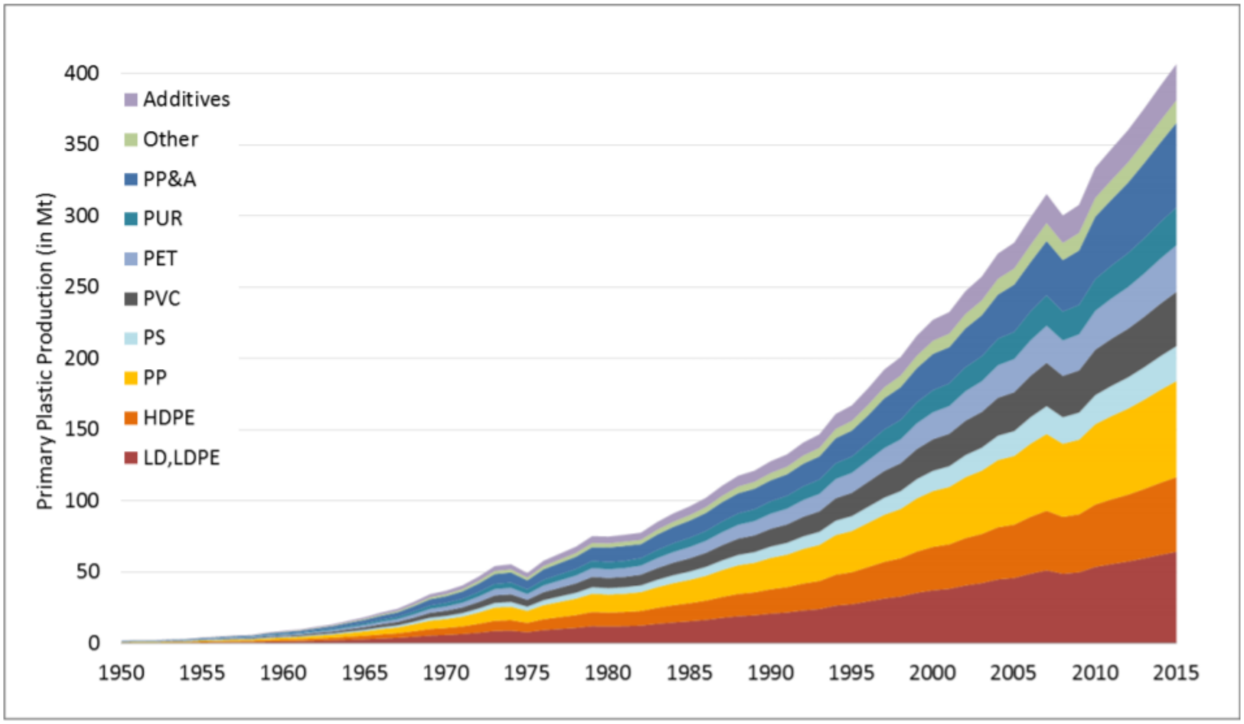


Figure 2.1: Global primary plastics production (in million metric tons) according to polymer type from 1950 to 2015. Reprinted from (Geyer et al., 2017) with permission from American Association for the Advancement of Science.

### 2.1.2b) Type

The most commonly detected microplastics in the environment are PE, PP, PS, PVC, and PET (Koelmans et al., 2019). This is in proportion to their production for different industrial applications as can be seen in Figure 2.1**,** which illustrates plastic production with respect to polymer type. Conventional plastics are petroleum-based and include the commodity plastics PE, PP, polyurethane, PET, PS, and PVC. Several broad classes of plastics are commonly used globally for packaging. They are also extensively used in different industries (Table 2.2) and their high-volume usage increases the probability that they will be discharged to the environment.

Table 2.2: Common sources of plastics and microplastics by usage sector. Reprinted from (GESAMP, 2015)

| **Category** | **Source sector** | **Description** |
|---|---|---|
| producers/ converters | plastic producers, fabricators & recyclers | pellets & fragments |
| sectoral consumers | agriculture<br>fisheries<br>aquaculture<br>construction<br>terrestrial transportation<br>tourism industry<br>textile industry<br>sport | greenhouse-sheets, pots, pipes<br>fishing gear, packaging<br>buoys, lines, nets, PVC pipes<br>eps, packaging<br>pellets, tires, tire dust<br>consumer goods, packaging, microbeads, textile fibres<br>fibres<br>synthetic turf |
| individual consumers | food & drink single-use packaging<br>cosmetics & personal care products<br>textiles & clothing | containers, plastic bags, bottles, caps, cups, plates, straws, spoons, etc.<br>microbeads, packaging, toothbrushes, etc.<br>fibres |
| waste management | solid waste<br>water & wastewater | unmanaged or poorly managed waste disposal<br>microbeads, fragments, fibres |

Densities of consumer plastics typically also find in the environment, range from 0.85 to 1.41 g/L (Table 2.3), where PP, LDPE and HDPE plastics have densities lower than 1 g/L, and PS, nylon 6, PVC, and PET have densities higher than 1 g/L. The types of plastic vary between industries which can be analyzed from consumption and waste generation. For instance, municipal waste is dominated by containers and films while the construction and demolition sector uses majorly PVC containing plastic such as PVC pipes and large plastic containers (Barnes et al., 2009). Sources for fibres and fragments of low-density plastics include bags, rope, netting, and milk/juice jugs, and sources for high-density particles include food containers, beverage bottles, and films (Andrady, 2011).

Table 2.3: Densities of microplastics detected in the environment (Hidalgo-Ruz et al., 2012; http://www.goodfellow.com/E/Polyetheretherketone.html)

| Microplastic | Density (g/cm$^3$) |
|---|---|
| Acrylic | 1.09 - 1.20 |
| High density polyethylene | 0.97 |
| Polyamide (nylon) | 1.02 - 1.05 |
| Polycarbonate | 1.23 |
| Polyethylene | 0.86 |
| Polyetheretherketone | 1.26 |
| Polyethylene terephthalate | 1.37 - 1.45 |
| Polypropylene | 0.85 - 0.91 |
| Polystyrene | 1.02 - 1.08 |
| Polyvinylchloride | 1.16 - 1.58 |

The whole plastic family is composed of different polymers and depending on their composition, shape and density, and buoyancy, they are distributed throughout the water column (Khatmullina and Isachenko, 2017). Long-term exposure in the environment can affect their densities by formation of biofilms on their surfaces and fragmentation due to UV exposure (Weinstein et al., 2016) which can cause them to sink. Therefore, microplastics found in the environment are typically of a wide range of densities.

### 2.1.2c) Shape, size, and concentration in the environment

The shapes of microplastics particles depend on their source. Primary microplastics have a defined shape because they are manufactured according to specifications for certain applications. Typically marketed as ‘‘micro-beads,’’ ‘‘micro-exfoliates,’’ or “microspheres” these plastics can vary in shape, size and composition depending upon the product (Fendall and Sewell, 2009). For example, Gregory (1996) reported the presence of polyethylene and polypropylene granules (<5 mm) and polystyrene spheres (<2 mm) in one cosmetic product. More recently, Fendall and Sewell (2009) reported an abundance of irregularly shaped microplastics, typically <0.5 mm in diameter with a mode size <0.1 mm, in another cosmetic product.

Secondary microplastics can have varying shapes depending on their residence time in the environment. Overtime, a culmination of various physical, chemical and biological processes can affect their structural integrity, eventually causing fragmentation (Browne et al., 2011a), which can result in the formation of smaller microplastics of different irregular shapes. Larger particles have more elongated shapes and/or irregular surfaces while smaller particles are consistently more circular (Chubarenko et al., 2016). Irregularly shaped microplastics have been interpreted non-uniformly across studies and were described as nurdle, pellet, sphere, resins, or granules (Kooi and Koelmans, 2019). Generally, fragments, fibres, films and foams have been the most widely reported microplastics shapes found in freshwater environments (Koelmans et al., 2019). A synthesis of over 100 investigations in which microplastics were characterized indicated that fibers and fragments are among the most commonly detected microplastics in the environment (Kooi and Koelmans, 2019).

Microplastics sizes that have been in freshwaters are summarized in Figure 1.2. As would be expected, the relative abundance of smaller-sized microplastics is higher because larger microplastics particles can break apart to form multiple smaller particles (Enders et al., 2015). Population density, proximity to urban centers, residence time, water body size, waste management approaches, and sewage overflows all affect the abundance of microplastics in freshwaters (Eerkes-Medrano et al., 2015); in one study, the majority (96%) of which have been reported as smaller than 20 µm in size (comprising 90% of the total particles detected), with none exceeding 100 µm (Triebskorn et al., 2019). Notably, such observations may result from sample collection methodology, which varies across investigations. Nonetheless, it is clear that microplastics larger than 100 µm have been found abundantly in environments all around the world; in many cases, smaller microplastics also have been found (Figure 1.2). Improved environmental detection and enumeration of microplastics is currently an active and rapidly evolving area of research (Figure 1.2) (Murrell et al., 2018).

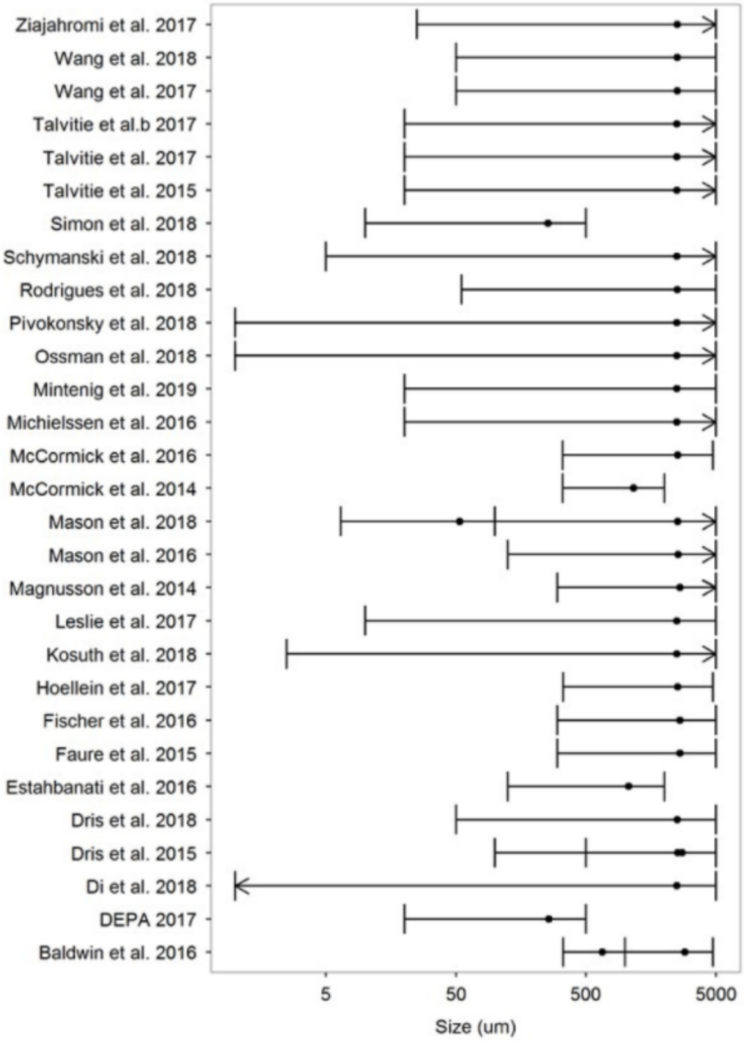


Figure 2.2: Range of microplastics size detected in drinking, surface and wastewater studies. Reprinted with permission from Koelmans et al., (2019).

Table 2.4: Microplastics type, size, and concentration in sea water, freshwater, drinking water, and wastewater.

| **Marine** | | | | |
|---|---|---|---|---|
| **Sample type and location** | **Type** | **Size and concentration** | **Observation/Comments** | **Reference** |
| Water from environment and mussels | fibre, fragment, bead<br>PES, rayon, PE, PVC and PP | 0.25 – 1 mm | in the lab experiments the mussels were not provided with particles which they consume normally as food and only plastics were added. Impact on consumption? | Qu et al., 2018 |
| Commercially consumed bivalves (Korea) | fragments and fibres<br>PE, PP and PS | 0.2 – 0.3 mm | | Cho et al., 2019 |
| Lagoon sediments (Venice) | PE and PP were abundant | > 15 µm | | Vianello et al., 2013 |
| Atlantic Ocean and Mediterranean Sea sediments | | 75 µm – 161 µm | | Van Cauwenberghe et al., 2013 |
| Beach sediments (India) | fibres<br>PE, PET, PS, PP, PVC | 36 µm to 5000 µm | correlation between population density, human practices and the presence of microplastics was established | Tiwari et al., 2019 |
| Surface water Yangtze estuary and East China Sea (China) | fibres | 0.5 mm – 5 mm | | Zhao et al., 2014 |
| Surface water Kingston harbor, (Jamaica) | PE, PP fragments, fibres, foams and beads | 335 to 5000 µm concentration: 5.73 particles/m$^3$ | 350 µm manta trawl was used | Rose and Webber, 2019 |
| Atlantic ocean, surface water | PE, PP | 10 - 500 µm concentration: 13 - 501 particles/m$^3$ | majority of the particles <40 µm | Enders et al., 2015 |
| Estuarine tributaries within Chesapeake Bay (USA) | PE | > 330 µm concentration: 39 particles/km$^3$* | 330 µm pore sized manta trawls were operated at a depth of 15 cm from the water surface | Yonkos et al., 2014 |

| **Freshwater** | | | | |
|---|---|---|---|---|
| **Sample type and location** | **Type** | **Size and concentration** | **Observation/Comments** | **Reference** |
| Laurentian Great Lakes<br>(USA) | pellets and fragments<br>PE | > 0.333 mm | manta trawls having 0.333 mm pore spaces were used which eliminated capture of smaller particles that could be present | Wilson et al., 2013 |
| Sediments of St. Lawrence River (Quebec City, Canada) | microbeads<br>PE | 0.4 – 2.16 mm | 500 µm sieve used.<br>particles were visually identified | Castañeda et al., 2014 |
| Fish<br>Lake Victoria (Mwanza, Tanzania) | PE, PU, PES, PP, silicone rubber | > 0.5 mm | possible underestimation of microplastics abundance due to constraints in measuring small particles and unknown feeding habits of fish | Biginagwa et al., 2016 |
| Surface water<br>Poyang Lake, (China) | PP, PE, Nylon and PVC | 0.1 – 0.5 mm<br>5 – 34 particles/L | | Yuan et al., 2019 |
| Surface water<br>Lake Bolsena and Lake Chiusi (Italy) | types were not identified | 300 – 500 µm<br>concentration: 2.68 to 3.36 particles/m$^3$ (Lake Chiusi) and 0.82 to 4.42 particles/m$^3$ (Lake Bolsena) | | Fischer et al., 2016 |
| Sediments<br>Lake Ontario<br>Canada | PP, PVC, PS sulfonate, PET, Polymethyl methacrylate | < 2 mm<br>28000 particles/kg of sediment | | Ballent et al., 2016 |
| Surface water<br>Carpathian Basin, Europe | PP and PE in waters-<br>PP and PS in sediments<br>PTFE, PAC and PES | 100 µm – 2 mm<br>concentration: 3.52 to 32.05 particles/m$^3$ | | Bordós et al., 2019 |
| Surface water<br>Yangtze River Estuary and East China Sea<br>Southern and northern parts of Suzhou River (China) | fibres<br>PE, Rayon, PP | > 20 µm<br>100 µm to 1 mm<br>concentration: 1.8 – 2.4 particles/L | microplastics concentration high in urban areas<br>Microplastics concentrations were higher in freshwater compared to estuarine or coastal waters | Luo et al., 2019 |

## Freshwater

| Sample type and location | Type | Size and concentration | Observation/Comments | Reference |
|---|---|---|---|---|
| Surface water<br>Laurentian Great Lakes, (Canada) | similar in size, shape and color to particles detected from facial cleansers | 0.355 mm – 0.999 mm | facial cleansers were analyzed, and the detected particles were compared with the environmentally obtained microplastics | Eriksen et al., 2013 |
| Surface water<br>Streams (Auckland, New Zealand) | fragments | 63 µm – 500 µm | no direct relationship was observed between human population or combined stormwater overflow and microplastics abundance | Dikareva and Simon, 2019 |
| River Trent and atmospheric fallout (UK) | natural fibres (non-plastic) | > 63 µm | | Stanton et al., 2019 |
| Surface area<br>Remote Lakes (Tibet Plateau) | PE, PP, PS, PET, and PVC | concentration: 8 ± 14 to 563 ± 1219 particles/m$^2$ | | Zhang et al., 2016 |
| Surface water<br>Atoyac River Basin (Mexico) | films, fragments and fibres | N/A | (Al, Fe, Mg, Ca, Na, Si, Ti, S, Cl & P) were sorbed on the surface of the microplastics | Shruti et al., 2019 |
| Sediments<br>River Rhine and Main (Germany) | PE, PP and PS<br>63 – 200 µm | 630 µm – 5000 µm<br>concentration: 4000 particles/kg | presence in freshwater indicates possibilities of microplastic entrance to drinking water treatment plants | Klein et al., 2015 |
| Surface water<br>Poyang Lake, (China) | PP, PE | >50 µm<br>Concentration: 5 - 35 particles/L | | Yuan et al., 2019 |
| Surface water<br>Lake Winnipeg (Canada) | | >333 µm<br>135 particles/km$^3$* | 333 µm pore sized manta trawls were operated at a depth of 18 cm from the water surface | Anderson et al., 2017 |
| Surface water<br>Antua River, (Portugal) | PE, PP, PS | >55 um<br>concentration: 58 - 1265 particles/m$^3$ | | Rodrigues et al., 2018 |

## Wastewater

| Location | Type and size | Influent-effluent-removal | Observations/Comments | Reference |
|---|---|---|---|---|
| River Clyde, Glasgow, (Scotland) | PES, PA, acrylic, PE, PP, PS, PVC<br>> 65 µm | inf: 15.7 ± 5.23<br>eff: 0.25 ± 0.04 MP/L<br>removal: 98.41% | stormwater runoff, daily flow variations and seasonal variations were not considered.<br>large amounts of microplastics can still be released with the effluent | Murphy et al., 2016 |
| USA | not reported<br>> 125 µm | inf: not investigated<br>eff: 0.05 ± 0.024 MP/L | as many as 1.5 × $10^7$ particles/day may be released from the wastewater treatment plants | Mason et al., 2016 |
| China | Polyolefine fibres, PE films, PS spheres, acrylic fibres<br>> 37 µm | avg. 22.7 ± 12.1 × $10^3$ particles/kg of sludge | fibres most abundant | Li et al., 2018 |
| Raritan River, New Jersey, US | microplastics were visually counted<br>125 µm to 2 mm | upstream: 24 ± 11.4 MP/$m^3$<br>downstream: 71.7 ± 60.2 MP/$m^3$ | collected downstream of wastewater treatment plant<br>concentration of 125 – 500 µm sized microplastics increased downstream | Estahbanati and Fahrenfeld, 2016 |
| Italy | PES, PU, PA, PP, PE | inf: 2.5 ± 0.3 MP/L<br>eff: 0.4 ± 0.1 MP/L<br>84% removal<br>113 ± 57 MP/g of sludge<br>> 8 µm | millions of microplastics can be released | Magni et al., 2019 |
| Gulf of Finland, Baltic Sea | not reported<br>> 20 µm | inf: 180 fibres/L and 430 synthetic particles/L<br>eff: 8.6 ± 2.5 synthetic particles/L and 4.9 ± 1.4 fibers/L | stereomicroscope used for visual identification<br>treated water were contaminated with microplastics | Talvitie et al., 2015 |
| Sydney, Australia | PET fibres and PE particles<br>25 µm - 500 µm | eff: 1.5 MP/L | PE similar to microbeads from personal care products<br>8.16 × $10^6$ microplastics/day may be discharged after treatment | Ziajahromi et al., 2017 |

## Wastewater

| Location | Type and size | Influent-effluent-removal | Observations/Comments | Reference |
|---|---|---|---|---|
| Denmark | Acrylates, PP, PE and PES<br>10 µm - 500 µm | inf: 7216 MP/L<br>eff: 56 MP/L<br>> 98% removal | treated wastewaters were filtered using 10 µm filters-<br>large amounts of MP released in effluent | Simon et al., 2018 |
| Detroit and Northfield WWTP | not reported<br>> 20 µm | Detroit<br>inf: 133.0 ± 35.6 MP/L -<br>eff: 5.9 MP/L<br>> 95% removal | 15 billion microplastics/day may be released into freshwater bodies | Michielssen et al., 2016 |
| Vancouver, Canada | PES<br>1 µm | inf: 31.1 ± 6.7 MP/L-<br>eff:<br>99 % removal | 0.03 ± 0.01 trillion MPs per day may be discharged through the effluent | Gies et al., 2018 |
| China | PP, PE, PS, PET<br>granules, fragments, fibres, pellets<br>43 –355 µm | inf: 1.57 – 13.69 MP/L<br>eff: 0.20 – 1.73 MP/L<br>79.3 – 97.8% removal | $6.5 \times 10^8$ MP/day released in total from seven different WWTPs<br>63 – 125 µm particles were abundant in influent<br>> 355 µm particles were abundant in effluent | Long et al., 2019 |
| Amsterdam | fibres were most common<br>10 – 5000 µm | inf: 68 – 910 MP/L<br>eff: 51 – 81 MP/L |  | Leslie et al., 2017 |

## Drinking Water

| Location | Type and size | Influent-effluent-removal | Observation/Comments | Reference |
|---|---|---|---|---|
| Germany | PE, PA, PES, PVC, epoxy resin<br>50 – 150 µm | inf: 0 – 7 MP/$m^3$ | likely that MP contamination occurred due to abrasion in different parts of the treatment train | Mintenig et al., 2019 |
| Czech Republic | PET, PP, PE<br>1 µm | inf: 1473 ± 34 to 3605 ± 497 particles/L<br>final eff: 338 ± 76 to 628 ± 28 particles/L<br>max removal was 85% | three treatment plants<br>particles <1 µm were excluded due limitations in detection method<br>effluent samples were taken post treatment<br>microplastics <10 µm accounted for >95% of all microplastics detected | Pivokonsky et al., 2018 |

inf – influent; eff – effluent; MP – microplastics; WWTP – wastewater treatment plan, *for microplastics concentration reported in units of particles per surface area, MP/$m^2$, MP/$km^3$ was calculated by multiplying the height of manta trawls/neuston nets to generate microplastics particles per volume of water

## 2.2 Contaminants associated with microplastics

### 2.2.1 Additives

Plastics manufactured for commercial and industrial applications are treated with certain additives, commonly known as plasticizers, which incorporated during their manufacture to impart certain desirable properties, as required for their intended application (Table 2.5). Functional additives include flame retardants, stabilizer, antioxidant, slip agent, lubricant, anti-static, curing agent, blowing agent, colorants including inorganic and organic pigments among others (Campanale et al., 2020). Commonly used additives include polybrominated diphenyl ethers, phthalates and the constituent monomer bisphenol A—they can leach from plastics and harm biota; they are known as endocrine disruptors that can potentially result in hormonal imbalances and have permanent health effects in organisms (Cole et al., 2011). Due to their health implications, many known chemicals associated with plastics manufacturing are regulated in drinking water.

Table 2.5: Commonly used plastic additives, their function and associated human health effects. Adapted from Board and Oceanic, 2020; Campanale et al., 2020; Herschy, 2012.

| Additive | Function | Types of plastics | Human health effects |
|---|---|---|---|
| Antimony | flame retardants and biocides | various plastics | carcinogenic |
| Arsenic | biocides | PVC, LDPE, Polyesters, Polyurethanes | congenital disabilities; Carcinogen: lung, skin, liver, bladder, kidneys; gastrointestinal damage; death |
| Benzene | byproduct in plastic manufacture | | acute exposure to humans causes effects in the central nervous system -potentially carcinogenic; induces chromosomal aberrations |
| Cadmium | heat stabilizers and slip agents | PVC | changes in metabolism of calcium, phosphorus and bone; osteomalacia and bone fractures in postmenopausal women; lipid peroxidation and in the promotion of carcinogenesis; cellular apoptosis; DNA methylation. |
| Chromium | pigments | PVC, PE, PP | allergic reactions to the body; nasal septum ulcer; severe cardiovascular, respiratory, hematological, gastrointestinal, renal, hepatic, and neurological effects and possibly death. |

| Additive | Function | Types of plastics | Human health effects |
|---|---|---|---|
| Cyanide | plastic component | PVC | thyroid toxicity due to inhibition of iodine uptake |
| Di(2-ethylhexyl)adipate | reagent | | induced carcinoma in mice |
| Di(2-ethylhexyl)phthalate (DEHP) | plasticizer | PVC | endocrine disruptors, and they are suspected of being endocrine disruptors, of affecting the reproduction of human beings, animals, or o being carcinogenic |
| Fluoride | component of fluoride containing plastics | polytetrafluoroethylene | dental fluorosis and that progressively higher concentrations lead to increasing risks of skeletal fluorosis |
| Lead | heat stabilizers, UV stabilizers and inorganic pigments | PVC and all types of plastics, where red pigments are used | Anemia (less Hb); hypertension; miscarriages; disruption of nervous Systems; brain damage; infertility; oxidative stress and cell damage. |
| Methyl tertiary-butyl ether | reagent to make plastic | cross bonded PE | carcinogenic response is evident only at high levels of exposure that also induce other adverse effects |
| Styrene | monomer for making PS plastics | PS | carcinogenic |

### 2.2.2 Sorbed chemical contaminants

Microplastics typically have large specific surface area (i.e., surface area per unit of mass) and hydrophobicity; thus, they can sorb a range of organic and inorganic contaminants (e.g., persistent organic pollutants and metals, respectively) via (1) hydrophobic partitioning interactions, (2) surface adsorption (electrostatic interactions, non-covalent bonding, hydrogen bonding, van der Waals attraction), and (3) pore filling (i.e., entrapment in pores).

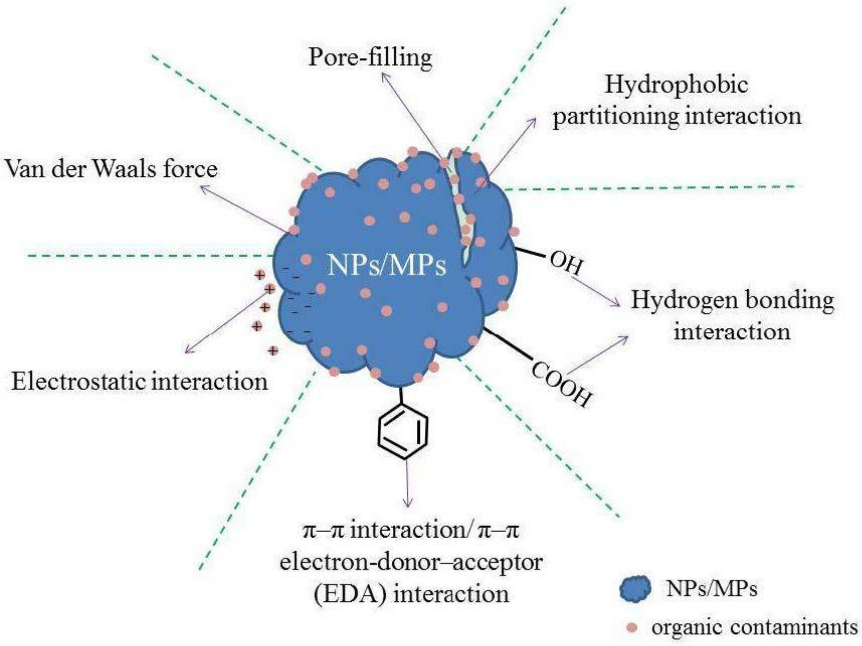


Figure 2.3: Sorption mechanisms of organic contaminants to nano/microplastics. Reprinted from Wang et al. (2020).

Experiments focused on the characterization of maximum adsorption capacity (AC) typically reflect all of these mechanisms without quantitatively differentiating between them. The sorption (i.e., adsorption and absorption; reflecting all of the mechanisms described above) behavior of organic contaminants on microplastics surfaces in water is affected by solution chemistry (e.g., pH, ionic strength, dissolved organic matter concentration) as well as the specific properties of the microplastics and organic contaminants (Ateia et al., 2020; Guo et al., 2012; Zhang et al., 2019).

Adsorption processes collectively serve as the major drivers of chemical contaminant association with microplastics (Wang et al., 2020). Adsorption is a surface process in which molecules move from the bulk fluid to a solid surface because of physical forces (physisorption) or chemical reactions (chemisorption) (Dąbrowski, 2001). Physisorption is a rapid process caused by nonspecific binding mechanisms such as Van der Waals forces. Chemisorption is characterized by a stronger chemical covalent or ionic bond due to chemical reaction that results in electron transfer between the adsorbent and adsorbate molecules. Some molecules are capable of both chemisorption and physisorption (Gaspard, 1982). Thus, these processes are reflected in hydrophobic partitioning interactions and surface adsorption, whereas pore filling pertains to absorption.

In aquatic environments, hydrophobic contaminants generally adsorb to non-polar surfaces of sediments or organic matter; however, they have a greater affinity for the hydrophobic surfaces on anthropogenic plastic matter (Hartmann et al., 2017); for example, hydrophobic contaminants preferentially adsorb to polyethylene, polypropylene, and polyvinylchloride microplastics over natural sediments (Teuten et al., 2009). Emerging contaminants such as PFAS and other chemicals found in PCPs also adsorb on microplastics (Llorca et al., 2018). These adsorbed organic and inorganic materials often attract bacteria and viruses that subsequently adhere to the microplastics surface (Frère et al., 2018). Thus, these sorptive properties of microplastics make them effective carriers of chemical contaminants, making them available to both human beings (especially through drinking water) and aquatic organisms.

#### 2.2.2a) Effect of aging

Microplastics are exposed to physical and chemical stressors in the environment; over time, their structural integrity and surface properties are affected, and this process is known as “aging”. Scanning electron microscopy of environmental microplastics has shown degradation patterns such as cracks, pits and particles adhering to the surface (Murrell et al., 2018). Oxidative breakdown on the surface of opaque plastics occurs due to UV exposure (Cunliffe and Davis, 1982) which results in a weak, brittle surface layer that develops numerous microcracks and pits. This fragile surface is susceptible to fragmentation by stress induced by humidity or temperature changes. Factors such as ionic strength, pH, and other physico-chemical properties of water impact the aging process and transformation of microplastics occurs more rapidly in freshwater than in marine environments (Gregory, 1999). Properties of microplastics such as size, crystallinity, glass transition temperature - the range where the polymer substrate changes from a rigid glassy material to a soft (not melted) material, and is usually measured in terms of the stiffness, or modulus (Campo, 2008). and functional groups of microplastics influence their AC of contaminants in the aquatic environment (Andrady, 2017; Zhang et al., 2019). These properties are altered as a consequence of the impacts of aging and therefore the adsorption capacities of environmental microplastics are different from those of microplastics that have not experienced environmental exposure (Wang et al., 2020). Critically, the AC of organic adsorbates and metal ions are generally enhanced on aged microplastics due to increases in total microplastics surface area, which have been attributed to the formation of surface cracks and surface deformation (Guo and Wang, 2019; Hüffer et al., 2018; Q. Wang et al., 2020).

### 2.2.2b) Effect of ionic strength

The ionic strengths of the water matrices in which microplastics are suspended affect the electrostatic interaction mechanisms that contribute to physisorption (Guo and Wang, 2019; Liu et al., 2019). The ions present in the aqueous environment may compete with other adsorbates for adsorption sites on microplastics. Therefore, at the higher ionic strength of the aqueous environment, adsorption of contaminants decreases (Llorca et al., 2018; Qiu et al., 2019). The role of ionic strength as well as other parameters such as natural organic matter (NOM) affect particle destabilization—these phenomena are well understood and described by Derjaguin-Landau-Verwey-Overbeek (DLVO) theory (Boström et al., 2006). Microplastics and nanoplastics particles are no different than other particles in this regard. For example, it has been shown that increased ionic strength significantly increased nanoplastics destabilization and led to increased hydrodynamic diameter and aggregation, while humic acid (i.e., a type of NOM) mainly exerted a stabilizing effect that precluded extensive aggregation (Wu et al., 2019). Thus, higher ionic strength/salinity may facilitate flocculation of microplastics with suspended sediments and subsequent settling, creating potential risks to the benthic environment. In addition, a higher hydrodynamic diameter results in particles having lower specific surface area for sorption, which can impede sorption of chemicals. In one investigation, increased ionic strength (NaCl, 0.05–3.5%) was shown to reduce adsorption of polyhalogenated carbazoles (PHC) on PP, PE and PVC (Qiu et al., 2019). Similarly, adsorption rates of non-steroidal anti-inflammatory drugs (NSAIDs) on four microplastics decreased at high ionic strength conditions (Elizalde-Velázquez et al., 2020). The adsorption of antibiotics also decreased in simulated seawater environment as shown by (Guo and Wang, 2019) where adsorption behaviors of sulfamethoxazole (SMX), sulfamethazine (SMT), and cephalosporin C (CEP-C) on aged polystyrene and polyethylene microplastics were examined. However, the extent of the effect of ionic strength varies with microplastics type, water quality characteristics, and the contaminant (Zuo et al., 2019). In general, the adsorptive capacity of different types of contaminants on microplastics in freshwater (generally low salinity) exceeds that in marine environments (high salinity). Collectively, these works highlight the possibility of relatively higher ecological and human health impacts attributable to chemical contaminants sorbed on/in microplastics suspended in fresh water supplies and underscore the importance of evaluating the health implications of microplastics in drinking water.

### 2.2.2c) Effect of pH

Microplastics surfaces have net positive or negative charge depending on solution pH ($pH_{soln}$). In natural waters, microplastics—like most particles—are typically negatively charged; this is because their surface charge is inversely proportional to $pH_{soln}$ and the pH at their point of zero charge ($pH_{PZC}$) is typically lower than $pH_{soln}$ in natural waters (Lu et al., 2018; Wu et al., 2020). If the chemical contaminants and microplastics surfaces are like charged, repulsion impedes adsorption. For example, Liu et al. (2019) reported that the adsorption of the antibiotic ciprofloxacin (CIP) on both pristine and aged PVC microplastics increased with increasing pH (over the range of 2 to 9) and then decreased at higher pH values (9 to 11). This is likely because, in the lower pH range, microplastics are negatively charged and $CIP^+$ is positively charged; at the lowest pH values, the high concentration of $H^+$ in solution could inhibit the adsorption of $CIP^+$, and AC increased with the decrease of $H^+$ concentration as pH increased. When the pH was further increased, the sorption efficiency rapidly decreased because $CIP^+$ becomes $CIP^-$, and electrostatic repulsion between CIP and the microplastics inhibited sorption. Acidic conditions are favorable for adsorption on pristine PS microplastics, while alkaline pH is favorable for contaminant adsorption on aged microplastics (Liu et al., 2019). Similar observations have been reported for other chemical contaminants; the relative charge differences between sulfamethoxazole (SMX), sertraline (SER), and propranolol (PRP), and PE microplastics also were shown to affect AC (Razanajatovo et al., 2018). In the case of metal ions, adsorption on PET microplastics was found to increase with pH increases from 3 to 7 because of the greater number of charged sites on the microplastics surfaces that enhanced the electrostatic affinity of the metal ions to the surfaces (Wang et al., 2020). Other reports have indicated that the adsorption behavior of bisphenol analogues on PVC was prohibited by electrostatic repulsion between anionic fractions of the bisphenols at neutral pH due to negative charge of PVC ($pH_{pzc} = 3.41 < pH_{soln} = 7.0$) (Pengfei Wu et al., 2019). Similarly, significant differences in adsorption of three different non-steroidal anti-inflammatory drugs (NSAIDs) on PE, PS and PP were also observed. The greatest amount adsorption was recorded at a pH of 2, which is below the $pH_{pzc}$ of PE (6.63), PS (6.69) and PP (6.76); hence, all of the microplastics were positively charged while the NSAIDs remained in their non-ionic state, facilitating partition onto the microplastics surfaces (Elizalde-Velázquez et al., 2020). It should be noted that these trends are plastic, contaminant, and suspension medium specific, however. For example, relative to adsorption on soil, atrazine and 4-(2,4-dichlorophenoxy) butyric acid (2,4-DB) adsorption on PE microplastics was not significantly impacted by solution pH (Hüffer et al., 2019).

#### 2.2.2d) Effect of microplastics type

Theoretically, for a given mass of microplastics, the total mass of chemical contaminant sorbed on smaller microplastics particles is expected to be higher than on larger ones due to larger surface area to volume ratios. In addition, monomeric composition of adsorbent particles also plays a vital role in the process and extent of adsorption (Mei et al., 2020). The importance of microplastics type was evident in a comparison of aliphatic and aromatic organic compound adsorption microplastics in which PS had ten times more AC than like-sized PE microplastics (Hüffer and Hofmann, 2016). This is explained by pi bonds and hydrophobic bonds in addition to Van der Waals forces on PS; collectively, they are stronger (i.e., more attractive) than Van der Waals forces alone that act on aliphatic PE (Hüffer and Hofmann, 2016). Compared to PP, PE and PS microplastics of similar sizes, PVC sorbed larger quantities of Tylosin (Guo et al., 2018). Aged PVC microplastics were found to sorb significantly greater concentrations of Cu compared to pristine PS microbeads—this was attributed to dipole induced dipole attraction (i.e., a type of Van der Waals attraction) of Cu by polar groups present in PVC (chlorine) (Brennecke et al., 2016). Polyhalogenated carbazoles, which are polar contaminants, have also behaved similarly; they sorbed more to PVC than PP and PE, which both had weak affinity for the contaminant (Qiu et al., 2019).

With decreasing microplastics size, adsorption generally increases due to greater surface area to volume ratio. However, this assumes that all surfaces are available. This is not always the case because particles, including microplastics and nanoplastics can often aggregate (Lin and Xing, 2008), which increases their effective size and decreases their surface area to volume ratio. This effect of decreasing AC with decreasing size has been has been reflected in some nanoplastics (Wang et al., 2019). Aggregation influences the heterogeneity of adsorptive sites on the surface of nanoplastics which may substantially change the adsorption process (Alimi et al., 2018). An important feature of microplastics that influences adsorption is crystallinity, which describes the degree of arrangement of the polymeric chain; it is higher for more ordered polymeric chains (Hartmann et al., 2017). The more disordered the polymeric chain, the larger the proportion of amorphous areas (Tourinho et al., 2019). Crystalline regions in polymers are associated with lower adsorption capacities (Mato et al., 2001) and hydrophobic organic contaminants are usually adsorbed in the amorphous regions (Guo et al., 2012). Furthermore, functional groups on microplastics can influence adsorption of contaminants. For instance, highly aromatic polystyrene microplastics have a greater affinity to polychlorinated biphenyls (PCBs) due to hydrophobicity and pi-interactions than polyethylene microplastics (Zhang et al., 2019). Their surface charge/zeta potentials are influenced by the charge of these functional groups (Lu et al., 2018). Other functional groups, such as those that contain oxygen, can act as hydrogen bond acceptors and interact with water molecules, causing the formation of water clusters that can reduce contaminant accessibility to adsorption sites on microplastics surfaces, thereby reducing their adsorption affinities (Hüffer et al., 2018). Thus, the specific composition of microplastics as well as the aging that they undergo will contribute to the overall chemical contaminant carrying capacity of the plastic, thereby further underscoring the diverse interplay between the plastic, contaminant, and suspension medium.

## 2.3 Sampling and identification of microplastics in the aquatic environment

Microplastics sampling methods for marine and freshwater environments are similar. Depending on the sample matrix (surface water, water column, or sediments), different approaches are required. Challenges with microplastics detection and identification include: 1) capturing/ concentrating microplastics particles from the environment; 2) separating the plastic fragments from other particles; and 3) identifying the number, types, and/or sizes of microplastics present (Eerkes-Medrano et al., 2015). Microplastics are concentrated from water and separated from other particles and debris using several methods including density separation, filtration, sieving and visual sorting (Prata et al., 2019; Shim et al., 2017). Like other waterborne particles and pathogens, the concentration of other suspended solids present in the matrix can make this process challenging and affect the extent and consistency of particle recovery from the matrix (Emelko, 2001; Emelko et al., 2010, 2005; Huck et al., 2001; Rios Mendoza and Balcer, 2019; Schmidt et al., 2010).

The separation of microplastics from bulk water and sediment matrices, and their subsequent identification are complex and time consuming. Frequently, only a fraction of collected samples is analyzed (Rios Mendoza and Balcer, 2019). There are several techniques that are commonly used to identify synthetic polymers which include Attenuated Total Reflectance with micro-Fourier Transform Infrared (ATR-mFT-IR) spectroscopy in combination with microscopy, µ-RAMAN spectroscopy, Focal Plane Array with FT-IR, Pyrolysis-Gas Chromatography coupled to Mass Spectrometry (GC/MS), Scanning Electron Microscopy (SEM) and combined with other instrumentation such as energy dispersive spectroscopy (SEM-EDS) or energy dispersive X-ray spectroscopy (SEM-XEDS) (Fries et al., 2013; Murrell et al., 2018; Tagg et al., 2015). All of these methods are qualitative analyses that identify particles similar to plastic, but they are not confirmatory tests, making them prone to misinterpretation. Semi-qualitative analysis methods can also be used to identify MP particles; these include Coulter counters), using stains such as Nile Red dye to enable identification and separation by visual sorting (Fischer et al., 2016). Microplastics of small sizes can be easily confused with natural debris; in one investigation, 20 to 40% of non-plastic materials were initially identified as microplastics (Rios Mendoza and Balcer, 2019).

## 2.4 Removal of Particles and Microplastics during Drinking Water Treatment

Drinking water treatment contributes to public health protection through the provision of safe drinking water. The treatment process removes physical, chemical, and biological contaminants from water before it is distributed. The series of treatment processes in conventional drinking water treatment (coagulation, flocculation, sedimentation and filtration) are effective in removing a wide range of contaminants including particles, thereby reducing turbidity and suspended solids concentrations (Amirtharajah and Jones, 2004). These processes also remove microplastics particles present in source water and prevent their transfer to drinking water. Microplastics, commercially known as "microspheres" or "microbeads," have been widely used in bench, pilot and field scale experiments to investigate particle transport through porous media (Bradford et al., 2003; Brown and Emelko, 2009; Emelko et al., 2003, 2005; Emelko and Huck, 2004; Stevenson et al., 2014; Zhang et al., 2017) . Microplastics are particles and in most ways they are not different from other particles removed during drinking water treatment. Their removal can therefore be explained by the physico-chemical processes that are involved in particle removal during filtration.

### 2.4.1 Physico-chemical filtration

The granular media filtration processes used in drinking water treatment are more formally described as physico-chemical filtration processes. They do not remove particles based on size exclusion; rather, they require adequate particle destabilization by coagulation so that the small, colloidal particles suspended in source water after clarification (typically by sedimentation) will be removed (Edzwald, 2011). In the United States and Canada, "well-operated" conventional filtration processes are prescribed treatment credits; 3-log (99.9%) removal credits are granted for the 4-6 µm oocysts of *Cryptosporidium* and the 10-12 µm cysts of Giardia (AEP 2012; Ontario Regulation 2020; USEPA 2002; USEPA 2006), both of which can be simply considered as bioparticles. Particle removal by granular media filtration involves two distinct steps: i) transport of particles to media grain or collector surfaces, and ii) attachment of particles on collector surfaces. In suspension, colloids are physically transported to the vicinity of the filter grain (collector). The chemical nature of filtration then influences the ability of particles to attach onto the collector surfaces which occurs if the net force acting on these particles is attractive. Particle attachment is a reversible process and detachment occurs when adhesive forces are exceeded by shear forces. The detached particles may re-attach at a further distance or pass through the effluent as particles travel along with the bulk solution (Amirtharajah, 1988). All of these mechanistic properties associated with physico-chemical processes involved in particle removal are processes that occur in both natural and in engineered (chemically-assisted filtration) systems. Transport of particles and their retention during granular media filtration in both natural and engineered systems can be approximated from our knowledge of particle mechanics under the influence of hydrodynamic and physico-chemical forces in porous media. Figure 2.4 illustrates the main mechanisms involved in particle removal by physico-chemical filtration. These mechanisms are relevant to both natural (e.g., subsurface) and engineered filtration, though significantly more particle removal is expected by engineered filtration processes because they are preceded by chemical pre-treatment with coagulants in order to destabilize particles to enhance their removal by filtration (MWH, 2012). Critically, microplastics are particles and these same forces and removal mechanisms apply to their removal by natural and engineered filtration, as has been extensively demonstrated in the literature (as discussed above).

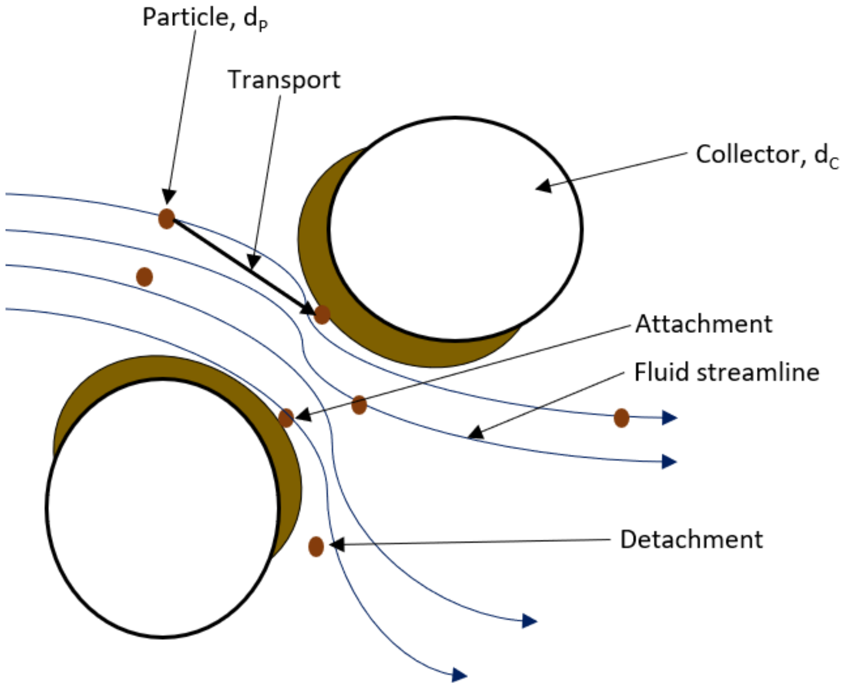
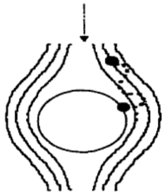
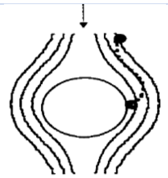
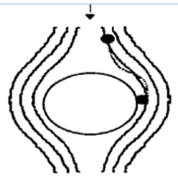
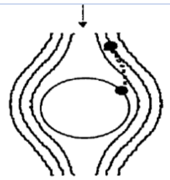
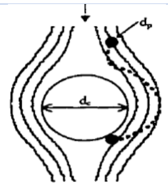


Figure 2.4: Schematic representation of physico-chemical filtration (after Amirtharajah, 1988).

### 2.4.2 Particle transport

The mechanistic basis for colloidal particle removal from a fluid suspension requires particles to be transported to within a close distance of a collector surface where attachment is possible (Elimelech et al., 1998; Payatakes et al., 1974). The processes that govern transport mechanisms: diffusion, interception, sedimentation, inertia, and hydrodynamics, are described schematically with descriptions in Table 2.6.

Table 2.6: Mechanisms of colloid transport to collector surfaces during physico-chemical filtration.

| Mechanism | Schematic | Definition and considerations | Reference |
|---|---|---|---|
| Diffusion |  | • Occurs as a result of Brownian motion which is relevant for particles smaller than 1 μm in size<br>• A primary mechanism in granular media filtration | Yao et al., 1971; Clark et al., 1992; Ives, 1965 |
| Sedimentation |  | • Transport of colloids vertically as a result of the net force of gravity and buoyant weight on particles<br>• Relevant for particles larger than 1 μm in size<br>• A primary mechanism in granular media filtration | Amirtharajah, 1988; Elimelech et al., 1998; Ives, 1965 |
| Interception |  | • Occurs when a particle in a streamline is close enough to a collector for attachment to occur<br>• A boundary condition for attachment resulting from diffusion and sedimentation<br>• Interception in laminar boundary layers is generalized to include the effect of inertia<br>• A primary mechanism in granular media filtration | Elimelech et al., 1998; O'Melia, 1985; Fernandez de la Mora, 1986 |
| Inertia |  | • Particles come into contact and attach to collectors as they deviate from streamlines due to their resistance to change in motion (inertia)<br>• Due to the relative slow flow in water treatment, this effect is usually ignored | Tufenkji and Elimelech, 2004; Tien and Payatakes, 1979 |
| Hydrodynamics |  | • Additional forces between colloid and collectors caused by non-uniform shear distributions and complex flow patterns<br>• Involves particle movement across streamlines and is a function of particle shape and interaction in the fluid field | Ison and Ives, 1969; Jegatheesan and Vigneswaran, 2005 |

### 2.4.3 Particle attachment

The attachment of particles is determined by the net force acting on them as they approach to the vicinity of collector surfaces. The forces arise due to a combination of short-range forces, long range forces, gravity and hydrodynamic forces (O'Melia and Stumm, 1967; Raveendran and Amirtharajah, 1995). Attachment of particles occur when the net force is attractive which results in particle removal from the bulk suspension (Rajagopalan and Tien, 1976). Particle detachment can occur when the shear forces overcome attractive forces causing particles to be transported back into the bulk suspension (Raveendran and Amirtharajah, 1995). The processes of attachment and detachment of colloids can occur repetitively during particle transport in porous media. Attachment of particles on collector surface or previously retained particles depends on the surface properties of these materials. There are several mechanisms that affect attachment during filtration as described below which include: London-van der Waals (LVDW) forces, electrical double-layer (EDL) forces, hydrodynamic forces, steric forces, Born forces, structural forces and chemical or bridging forces (Yao et al., 1971).

The LVDW and EDL forces are considered long-range forces (Raveendran and Amirtharajah, 1995). EDL forces develop between charged surfaces immersed in electrolyte solutions (O'Melia and Stumm, 1967). The LVDW forces are typically attractive in aqueous systems due to interactions between electronic dipoles of the surfaces and the solution (Tobiason and O'Melia, 1988). Dipole-dipole forces (i.e., Keesom forces), dipole-induced dipole forces (i.e., Debye forces), and induced dipole-induced dipole (i.e., London dispersion forces; the weakest intramolecular forces) forces are collectively referred to as VDW or LDVW forces (Yao et al., 1971).

The EDL forces arise as a result of interaction between the two diffuse ion layers that surround the colloids in suspension and the collector surfaces. When the double layer atmospheres are oppositely charged, it results in attractive force, otherwise the interaction is repulsive (O'Melia and Stumm, 1967). Factors such as separation distance between particle and collector, ionic strength, and the potential or charge at each surface affect the magnitude of the EDL forces (Tobiason and O'Melia, 1988). Hydrodynamic retardation slows down particles as they reach collector surface causing resistance to attachment. Furthermore, steric interactions of adsorbed macromolecules can result in repulsive forces (Tobiason and O'Melia, 1988). Particle attachment occurs due to the attractive forces that overcome this resistance.

Recent work has shown that, in addition to particle, suspension medium, and collector surface charge attributes, collector surface roughness can influence particle deposition in porous media. Media/collector surface roughness impacts particle deposition in a non-linear, non-monotonic manner, such that a critical roughness size associated with minimum particle deposition (Jin et al., 2016, 2015a, 2015b; Torkzaban and Bradford, 2016) Investigations of collector surface roughness impacts on particle deposition in porous media have indicated that description of non-DLVO forces such as hydrodynamics may help to more thoroughly describe particle removal by filtration (Jin et al., 2017) . Moreover, they have indicated that increased roughness density enhances particle retention by increasing the energy barrier against detachment (Torkzaban and Bradford, 2016); thus, greater particle retention/treatment efficiency may be expected.

### 2.4.4 Particle detachment

Particles attached onto collector surface can be detached and be transported to the bulk suspension. When particles attach to collector surfaces, they accumulate and can act as additional collectors (O'Melia and Stumm, 1967). Particles can detach from collector surfaces when the magnitude of hydrodynamic force is greater than the adhesive forces holding them together. As a result, the detached particles are transported further through the granular porous medium; an avalanche effect of arriving particles is also a likely alternative mechanism of detachment. Characteristics of the bulk suspension such as pH and ionic strength, which affect particle surface charge, were identified as factors that significantly affect particle detachment when a constant hydrodynamic force for detachment was applied (McDowell-Boyer 1982; Ryan and Gschwend, 1994). Other investigations showed increased particle detachment with increasing flow rate and particle size (Hubbe, 1982; Sharma et al., 1992). The removal of smaller particles increased while for intermediate sizes (such as those of *Cryptosporidium*), the removal increased initially but decreased substantially due to increasing deposition in the bed (Moran et al., 1993a). It was also concluded that particle detachment was predominant in intermediate and large particle size ranges (Moran et al., 1993b).

### 2.4.5 Particle surface charge/zeta potential

Charged particles in water accumulate a layer of oppositely charged ions to satisfy electroneutrality resulting in the formation of a fixed adsorption layer which is also known as the Helmholtz or Stern layer. Beyond this layer, where electroneutrality is satisfied, the diffuse ion layer which consists of ions that are more loosely attached compared to the adsorption layer (Helmholtz or Stern layer). Together the adsorption layer and the diffuse ion layer forms the electric double layer (EDL). When a particle moves in an electric field some portion of the water moves along with it, giving rise to the shear plane. Zeta potential is a measure of the potential that exists specifically at the boundary between the shear plane and the bulk solution and is calculated according to the equation:

$$\zeta = \frac{v^0 k_z \mu}{\varepsilon \varepsilon_0}$$

where $\zeta$ is the zeta potential (V), $v^0$ represents the electrophoretic mobility ($\frac{\mu m.cm}{V.s}$) which is calculated by $v_E/E$ and its value typically ranges from -2 to +2 ($\frac{\mu m.cm}{V.s}$), $v_E$ is the electrophoretic velocity of a migrating particle ($\mu m/s$), E is the electric field at particle (V/cm), $k_Z$ is a constant that is $4\pi$ or $6\pi$, $\mu$ is the dynamic viscosity of water ($N.s/m^2$), $\varepsilon$ = permittivity relative to a vacuum and $\varepsilon_0$ = permittivity in vacuum (MWH, 2012). Shown in Figure 2.5, it is used as a relative measure of a particle's surface charge. The stability of a colloidal system is determined based on the magnitude of zeta potential (MWH, 2012) and it has been identified as an important factor describing the stability of a potential surrogate in aqueous environments (Ryan and Elimelech, 1996).

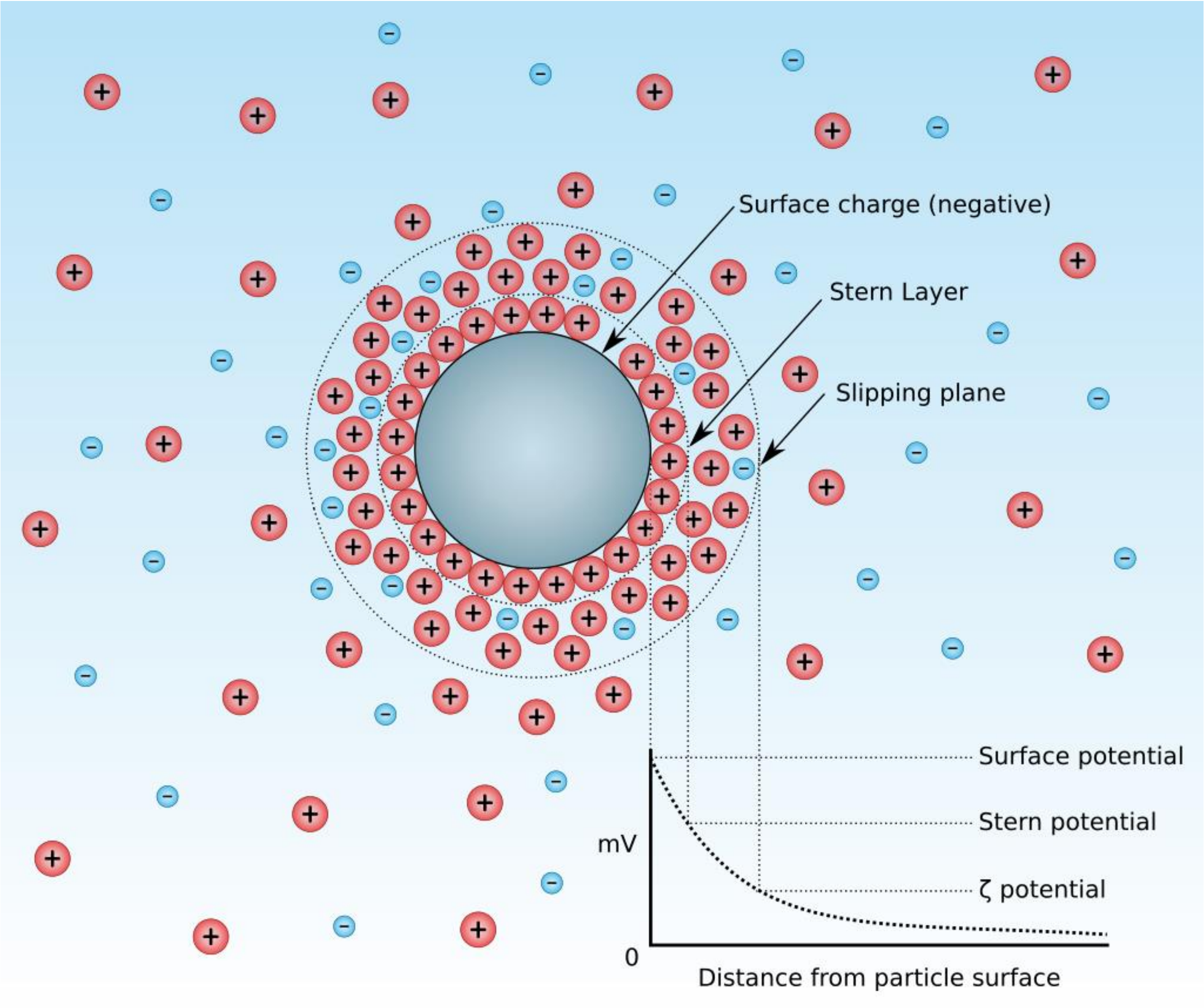


Figure 2.5: Zeta (ζ) potential is an indication of particles surface charge; it is the electric potential at the outer edge of the slipping plane (MWH, 2012).

Source water that enters drinking water treatment plants contains particles including suspended sediments, various microorganisms such *Cryptosporidium* oocysts*,* and increasingly, microplastics; almost all of these are negatively charged (i.e., $\zeta < 0$) in natural waters at near neutral pH. In order to remove these particles and generate drinking water conforming to health standards, it is necessary to neutralize their charge to enhance aggregation and subsequent removal of particles. The addition of coagulants directly affects the different particle attachment mechanisms that occur during filtration (O'Melia and Stumm 1967; O'Melia, 1985) and as would be expected, the type and concentration of coagulants, zeta potential and the removal of particles are linked (Cleasby et al., 1963; Gupta et al., 1973). Optimal coagulation and particle removal by physico-chemical filtration occur when the zeta potential is near the PZC; that is, when the negatively charged particles are destabilized (Cleasby et al., 1963). Particle removal by physico-chemical filtration is therefore enhanced by driving zeta potential to near the PZC; the range of PZC ± 4 mV is generally believed to be ideal for particle destabilization (Xagoraraki & Harrington, 2004).

Most particles occurring in natural water have negative zeta potentials with values typically ranging from -5 to -50 mV (Rice et al., 1996; Bustamente et al., 2001; Dai and Hozalski, 2003; Gallardo-Moreno et al., 2003). The zeta potential is influenced by particle size and shape, the solution pH and ionic strength and the types of ions present in solution. Dai and Hozalski (2003), in investigating the viability of microspheres as surrogates for oocysts in filtration experiments, found the zeta potentials of microspheres to be negative (-50.2 ± 5.1 mV). The values were found to become less negative with the increase of ionic strength of the solution. On the contrary, the presence of NOM was shown to decrease the zeta potential significantly for both oocysts and microspheres. Higher alum dosage was required to nearly neutralize microspheres (~3.5 mg/L as $Al^{3+}$) than oocysts (~2 mg/L as $Al^{3+}$) suggesting that microspheres could potentially exhibit lower removal efficiencies. Skaf *et al.* (2020), however, showed that the conditions which are suitable for the removal of kaolin (conventional oxide colloid), by alum coagulation, are also effective for the removal of model plastic spheres with surfactants. Zeta potentials were found to be similar at different values of solution pH (kaolin: -22mV to -40 mV at pH 4 to 10, microspheres: -14 mV to -35 at pH 5 to 10). Unmodified microspheres typically have a more negative zeta potential compared to modified microspheres with copolymer modified microspheres having the least negative zeta potential (-17 mV) (Liu et al., 2019a). Microplastics detected in the environment are similar to modified microspheres since they are derived from plastics that are usually modified to impart preferable characteristics (Hahladakis et al., 2018). Therefore, their zeta potentials, as summarized in Table 2.7**,** are not so extreme as to preclude them from sufficient charge neutralization by coagulants.

Table 2.7: Zeta potential values of microplastics/microspheres in water.

| **Material** | **Zeta potential (mV)** | **Experimental details** | **References** |
|---|---|---|---|
| Carboxylated latex MS | -50.2 to -7.4 | size: 5.0 µm,<br>pH: 6.7,<br>electrolyte solution: calcium concentration ($10^{-6}$ to $10^{-1}$ M) | Dai and Hozalski, 2003b |
| Unmodified PS MS<br>Glycoprotein modified PS MS | -56.5<br>-36.4 | size: 4.3 µm<br>DI water:<br>pH: 8<br>IS: 1 mM NaCl | Liu *et al.*, 2019 |
| Carboxylated PS MS | -41.4 | size: 4.36 µm<br>pH: 8.2<br>IS: 4.37 mM | Papineau, Tufenkji and Barbeau, 2013 |
| Fluorescent blue-green carboxylated PS MS | Uncoagulated:<br>- 41.2<br>Coagulated:<br>- 0.5 | size: 4.675 µm<br>pH: 7.2 | Amburgey *et al.*, 2005 |
| Carboxylated yellow-green PS MS | ~ -30 | size: 4.5 µm<br>pH: 7.5,<br>hardness of 200 mg/L as $CaCO_3$,<br>free chlorine of 2 mg/L | Lu and Amburgey, 2016 |
| PS | -80 to -30 | size - 0.3 – 0.4 µm<br>IS: 0.01 to 500 mmol/L NaCl, KCl and $MgCl_2$<br>pH: 2 to 8 | Lu *et al.*, 2018 |
| PS MS (surface modified carboxyl group) | -30 to -30.9<br>-23 to -26.4 | size: 0.8 µm, 1.5 µm<br>0.1 µm, 0.4 µm, 0.6 µm<br>salinity: 3.5, 7.5, 35 PSU | Dong *et al.*, 2018 |

| Material | Zeta potential (mV) | Experimental details | References |
|---|---|---|---|
| Fluorescent PS NS | -42 to -11 | 100 nm<br>pH: 4.97, 5.8, 6.57, 9.75<br>IS: 1 to 20 NaCl and $CaCl_2$ | Wu *et al.*, 2020 |
| Unmodified PS MS<br>Carboxylated PS MS | -33.9 and -30.7<br>-19.9 to -17.5 | size: 4.5 µm, 10 µm<br>pH: 6<br>IS: 1 mM KCl | Zhang *et al.*, 2017 |
| PE MS | -38.8 to -24.4 | 40 to 48 µm<br>IS: 0.01 to 0.05<br>Fulvic acid:<br>0, 5, 10 mg/L | Hou *et al.*, 2020 |
| Modified PVC (azodicarbonamide modified with 10% by weight of zinc oxide)<br>Unmodified PVC | 14.6<br>-9.59 | size was not reported<br>distilled water at 25°C, Conductivity:<br>0.056 µS/cm | Cai *et al.*, 2020 |
| PET<br>HDPE<br>PVC<br>PP | -120 to 20 | size: 2,540 µm<br>DI water,<br>pH: 3 to 10<br>zeta potentials were similar for all types | Lameiras *et al.*, 2008 |
| PE<br>PE with surfactants | -35 to -14<br>-5 to -9 | size - 5 µm<br>pH - 5 to 10 | Skaf *et al.*, 2020 |
| Unmodified<br>PET, PP, PS<br>HDPE<br>LDPE | -70 to -55 | foils of thickness 25 µm to 100 µm<br>pH: 6 to 6.2 | Kolska *et al.*, 2013 |

PS: Polystyrene; PSU: practical salinity units; MS: microsphere; NS: nanosphere; PE: polyethylene; PET: polyethylene terephthalate; PVC: polyvinylchloride; HDPE/LDPE: high/low density polyethylene; PP: polypropylene; PS: polystyrene; IS – ionic strength; DI – deionized.

## 2.5 Microplastics/microspheres removal by filtration

Microplastics have been widely used in research to study particle fate and transport in the subsurface (Auckenthaler et al., 2002; Dai and Hozalski, 2003a; Harvey et al., 2008, 1995, 1989; Mitropoulou et al., 2013) and to investigate the efficacy of particle removal by different physico-chemical treatment processes, especially filtration (Dai and Hozalski, 2003b; Emelko et al., 2003, 2005; Emelko and Huck, 2004; Jin et al., 2017; Logan et al., 2001; Wang et al., 2017). These particles are frequently referred to as microspheres, but they are microplastics; that is, plastic particles that are produced in the micrometer size range. Therefore, a wealth of information is available in the scientific and grey literature to describe microspheres transport in the natural environment and removal during drinking water treatment, especially physico-chemical filtration. Environmental microplastics may differ from microspheres commonly used in research as a result of environmental degradation and aging; specifically, their shape, surface roughness, and surface chemistry may be modified (Barnes et al., 2009). As a result, while microspheres are typically smooth particles with uniform shape (usually spherical) and specific functional groups, microplastics can have a wide array of shapes due to fragmentation, which further transforms their physical and chemical properties (Phuong et al., 2016). Nonetheless, they are fundamentally particles and have similar properties (plastic composition and sorptive capacities). The terms microspheres and microplastics will be used to refer microplastics used in experiments and microplastics found in the environment, respectively.

Microspheres have been widely used in bench-, pilot- and field-scale experiments as surrogates for *Cryptosporidium* oocysts in particular. The transport or retention of particles varies depending on the system, especially conventional water treatment (engineered) and transport in the subsurface (natural). In conventional drinking water treatment, coagulation causes destabilization of particles which enhances the physico-chemical processes involved in particle removal by porous media. In contrast, physico-chemical filtration in the subsurface is exclusively dictated by water quality, geological properties of the subsurface material, and particle surface properties.

In simulated natural systems, up to 2-log removal of copolymer modified and unmodified microspheres of small sizes (in the 5 µm range; used as *Cryptosporidium* oocyst surrogates) was observed during (non-chemically treated) flow through porous media (Gottinger et al., 2013; L. Liu et al., 2019b). Harvey et al., (1995) in a field-scale experiment investigating the transport of particles in the subsurface found retarded flow of microspheres due to interaction with grain particles. This included size exclusion as well as association of microspheres with organic contaminants, which reduced their mobility in the porous media (Keller et al., 2020; Ray et al., 2019). These interactions were ascribed to physico-chemical processes that resulted in attachment to grain particles. A positive correlation between iron (Fe)/aluminum (Al) oxide content of soil and retention of microspheres was observed (Wu et al., 2020). The Fe/Al oxides imparted a net positive charge on the soil particles, which resulted in increased electrostatic attraction between the negatively charged microspheres and the positively charged soil, thereby, enhancing particle attachment. Increasing the ionic strength of the suspension caused the zeta potential of microspheres and media grains to become less negative because of compression of the electrical double layer (Chu et al., 2019), resulting from charge neutralization by the ions in the suspension. The rate of flow also influences the transport of microspheres (Hou et al., 2020).

As expected, coagulation of water seeded with microspheres in engineered systems substantially increases the reduction of microspheres during filtration (Amburgey et al., 2005; Dai and Hozalski, 2003b; Emelko et al., 2003; Emelko and Huck, 2004; Lu and Amburgey, 2016; Wang et al., 2020; Wang et al., 2017; Zhang et al., 2017). This is ascribed to the particle destabilization effects of coagulation. Jar tests conducted by Ma et al., (2019) using large PE microplastics (0.5 – 5mm) and coagulant concentrations (11 mg $L^{-1}$ Fe and 135 mg $L^{-1}$ Al) resulted in microplastics removal efficiencies of ranging from 6 to 8%. The low removal efficiency was ascribed to the low density of PE microplastics (0.92-0.97 $g/m^3$), which impeded settling, as well as their relatively large size used in the experiment, which does not favor aggregation. It is important to recall that during drinking water treatment, coagulation/flocculation/clarification is almost always followed by filtration of some type, and it is surface charge that is important for particle removal by filtration (Amirtharajah and Jones, 2004), not settleability. In the case of plastics that float in water, dissolved air flotation can be used for treatment (Talvitie et al., 2017). Enhanced particle removal by physico-chemical filtration preceded by coagulation has been extensively documented; some of these investigations are summarized in Table 2.8 showing the removal of microspheres after chemically-assisted filtration, which shows higher retention of particles compared to particle transport in the subsurface (Table 2.9), as expected. For instance, this is observable in the Lu and Amburgey (2016) study that investigated microplastics removal with and without coagulation (Table 2.8 and Table 2.9).

Table 2.8: Microplastics removal by engineered filtration preceded by coagulation.

| **Particle type** | **Particle size (µm)** | **Experiment scale** | **Coagulant** | **Microplastics removal ($\log_{10}$)** | **Reference** |
|---|---|---|---|---|---|
| Carboxylated PS MS | 4.50 | pilot in-line filtration | not detailed | 2.04 | Amburgey et al., 2005 |
| Carboxylated MS | 4.5 | pilot-scale | none | 0.43 | Lu and Amburgey, 2016 |
| Carboxylated PS | 4.50 | pilot in-line filtration | alum and polymer | > 4 | Wang, et al., 2020 |
| Carboxylated PS | 4.68 ± 0.21 | pilot in-line filtration | chitosan | 2 – 3 | Brown and Emelko, 2009 |
| Carboxylated PS MS | 4.675 | pilot-scale | alum<br>activated silica | 4.7 – 5.8 | Emelko et al., 2003 |
| Carboxylated fluorescent PS MS | 4.675 ± 0.208 | pilot-scale | alum<br>activated silica | < 5 | Emelko and Huck, 2004 |
| Carboxylated fluorescent PS MS | 4.5 | pilot-scale | alum | 3 - 5 | Huck et al., 2000 |
| Copolymer modified MS | 4.5 | pilot-scale | alum | 4.5 | Liu and Liu, 2019 |

Table 2.9: Microplastics removal by porous media without coagulation to represent particle filtration in the subsurface.

| Particle type | Particle size (µm) | Experiment scale | Microplastics removal ($\log_{10}$) | Reference |
|---|---|---|---|---|
| Carboxylated latex | 0.20 – 1.36 | field-based | > 2 | Harvey et al., 1989 |
| Fluorescent carboxylated MS | 1.75 | bench-scale | ~ 3 | Ray et al., 2019 |
| Carboxylated PS MS | 0.2 - 1 | bench-scale | > 1.2 | Stevenson et al., 2014 |
| Carboxylated PS MS | 4.7 | bench-scale | 0.07 | Dai and Hozalski, 2003b |
| Carboxylated PS MS | 1.6 – 4.9 | field study | > 1.2 | Harvey et al., 2008 |
| Carboxylated MS | 0.7 – 6.2 | field- and bench-scale | > 2.9 | Harvey et al., 1995 |
| Carboxylated PS | 4.5 | pilot-scale | > 1 | Gottinger et al., 2013 |

PS – polystyrene; MS - microsphere

## 2.6 Exposure and direct and indirect health implications of microplastics

Plastic particles can be ingested by wildlife (Wright et al., 2013) and their fragmentation to microplastics makes them also available to small aquatic organisms, which consume them due to their color, shape, and size because of the similar appearance to food that they normally consume (Wright et al., 2013). Ingestion can be direct or indirect via trophic transfer (i.e., across the food web) (Pitt et al., 2018a). Microplastics concentrate in the digestive tracks of various marine species, including those commercially produced for human consumption (Neves et al., 2015). Hence, seafood has been identified as a source for microplastics in the human diet (Lavorante et al., 2018); despite this, an understanding of the extent of unintended human ingestion of microplastics and the associated health implications is not currently available.

Human health effects that are attributable to any contaminants depend on exposure conditions and the reactive properties of the contaminants being consumed (Villanueva et al., 2014). The extent of ingestion with food or water also contributes to exposure; however, in the case of microplastics this is not well known, thereby limiting toxicity assessment (Bouwmeester et al., 2015a; Lavorante et al., 2018; Lehner et al., 2019b; Revel et al., 2018). Accordingly, a significant fraction of microplastics research is focused on environmental occurrence of microplastics, as shown in Figure 1.2. In addition to the different routes of human exposure to microplastics shown in Figure 2.6, human beings ingest microplastics through different products including beer, salt, and tap water (Kosuth, et al., 2018; Eerkes-Medrano et al., 2019).

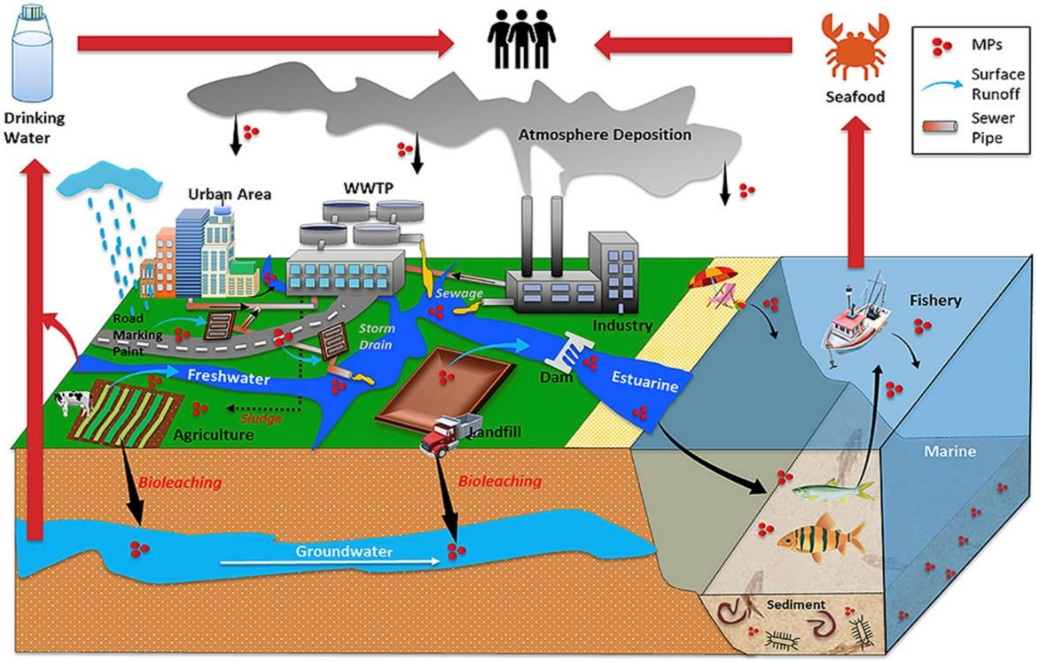


Figure 2.6: Routes of human exposure to environmental microplastics. Reprinted with permission from Wu et al. (2019).

The health implications of microplastics can be categorized as direct health implications resulting from the physical microplastic particles themselves, and indirect health implications arising from sorbed chemical contaminants on and in the microplastics. Several studies conducted on different aquatic species and small animals such as rats have been cited to speculate about the potential human health effects of microplastics (Wang et al., 2019). As would be expected, ingestion of microplastics can be detrimental for various animals. Microplastics of sizes less than 10 µm can translocate across the guts of mussels to the circulatory system (Browne et al., 2008). Nanoplastics are transferred to offspring in zebrafish and can bioaccumulate, causing ecological imbalances due to behavioral changes (Pitt et al., 2018a). Nanoplastics (25 and 27 nm) also have been shown to transfer across the food chain from algae to fish (Mattsson et al., 2015). Fish that ingested microplastic-fed daphnia showed abnormal hunting patterns and reduced activity. These behavioral disorders were linked with brain damage induced by penetration of blood-to-brain barrier by 52 nm plastic nanoparticles, while larger particles (120-330 nm) had no observable effects (Mattsson et al., 2017). Nanoplastic particles less than 300 nm were absorbed in the liver, bone marrow, spleen, and blood of rats (Jani et al., 1990). Larger particles in the microplastics range were also found to accumulate in the liver, kidney and gut of mice when exposed to a 0.5 mg/day dose of sizes 5 and 20 µm (Deng et al., 2017). The toxicological assessments on animals show that microplastics of the smallest size (1 – 20 µm) and nanoplastics (< 1 µm) can potentially have toxic implications. While human studies are not widely available, observations from animal studies suggest that some human health impacts are likely and microplastics ingestion should be generally avoided (Mahler et al., 2012; Pitt et al., 2018b; Schirinzi et al., 2017; Thubagere and Reinhard, 2010).

Toxicity assessments from *in vivo* and *in vitro* experiments on human cell lines have shown cytotoxicity, inflammation, and formation of reactive oxygen species which were considered as adverse effects of microplastics and nanoplastics exposure (Lehner et al., 2019a; Schirinzi et al., 2017). Notably, the available toxicity studies that have been conducted on small organisms or cell cultures have involved microplastics and nanoplastics concentrations that are several orders of magnitude higher than those detected in environmental matrices (Triebskorn et al., 2019). Furthermore, the majority of those studies have relied solely on PS microplastics and nanoplastics although there are several other environmentally relevant plastic particles, including PE, PET, PVC and PP (Lehner et al., 2019a). Due to their size (i.e., > 1 µm), microplastics are not expected to reach human organs because their transport across human cellular membranes is not expected;

hence, they may potentially cause local effects on the immune system or inflammation of the gut (Beirami et al., 2017; Deng et al., 2017).

In contrast to microplastics, nanoplastics, have greater potential to travel through cell membranes and accumulate in tissues and organs (Bouwmeester et al., 2015a); therefore, a focus shift from microplastics to nanoplastics may be suggested for toxicological assessments of microplastics. It has been suggested that nanoplastics under 30 nm should be of concern because at such small sizes their crystallization structure changes which gives rise to unique properties that might have health implications (Auffan et al., 2009). Taking the above into consideration, current evidence suggests that nanoplastics (< 1 µm) and microplastics of the smallest sizes (1-20 µm) are more relevant when considering direct health impacts and toxicity. Notably, the 1 to 20 µm size range is similar to that of many waterborne pathogens of concern, including *Cryptosporidium* and *Giardia* (oo)cysts; at least 3-log (i.e., 99.9%) of particles of these sizes should be removed by well-operated filtration when filtered water turbidities are less than 0.3 NTU (AEP 2012; Ontario Regulation 2020; USEPA 2006); at least 1- to 2-log removal (i.e., 90-99%) of the smaller sized particles would be expected because this would be consistent with the levels of bacteria and virus removals by filtration that have been widely reported (Hijnen, 2010)

In addition to the toxicity of microplastics particles themselves, the indirect health implications associated with microplastics sorptive capacity are of potential concern due to the physical and chemical toxicity of sorbed chemical contaminants (Smith et al., 2018). As indicated in Section 2.2, microplastics can sorb chemicals from the environment, thereby making them carriers of some chemical contaminants. This has human health implications because the sorbed contaminants will be ingested by humans through drinking water if it is contaminated with microplastics—the associated implications to human health have yet to be investigated. However, experiments on smaller organisms show that sorbed chemical contaminants from microplastics surfaces can transfer to animal tissues; accumulation can be lethal (Chua et al., 2014). For example, bioaccumulation of the antibiotic roxithromycin was enhanced in freshwater fish when PS microspheres treated with it were added to the water matrix (Jiang et al., 2018). Increased mortality and reduced antioxidant defenses were observed in fish exposed to PE microplastics (1 to 5 µm in size) at concentrations of 0, 18.4 and 184 µg/L which increased the bioavailability of pyrene and its consumption (Oliveira et al., 2013). Thus, analogous human health implications (Bakir et al., 2014) are an issue that the drinking water industry will likely need to manage as more information becomes available regarding environmental concentrations of waterborne microplastics and the potentially toxic contaminants that they carry.

## 2.7 Microplastics Regulations

Waterborne microplastics are not yet explicitly reflected in any water regulations globally, though many agreements, regulations, guidelines, and action plans refer to “all wastes” in general. The U.S. National and Oceanic Atmosphere Administration (NOAA) and the United Nations Environment Program developed the Honolulu Strategy in 2011; a global framework to reduce the ecological, human health, and economic impacts of plastics, especially microplastics, pollution in the marine environment (UNEP and NOAA, 2011). At the 4th UN Environmental Assembly in 2019, Environment Ministers from 157 countries reached a consensus to reduce the use single-use plastic products by 2030 (UNEP, 2019a).

The United Nations, World Bank, and the G7 have identified goals and strategies to tackle microplastics pollution with a focus on social awareness and investment in the better understanding of microplastics pollution and their impacts. Recent developments in the understanding of microplastics pollution and their environmental implications resulted in the implementation of regulatory measures on the usage of microbeads in products. The UK and the USA have put legislation in place to eliminate microbeads in personal care products (US Government, 2015; UK Government 2017) with the European Union (EU) following suit (ECHA, 2019). A 2017 report by the International Joint Commission (IJC) made recommendations to the Canadian federal and provincial governments and U.S. state governments regarding microplastics pollution in the Great Lakes. The recommendations focused on several areas, including:

1) Science
    a. develop standardized sampling and analytical methods
    b. develop transport models to identify sources and pathways of microplastics pollution
    c. assess ecological and human health impacts
2) Pollution prevention
    a. support extended producer responsibility
    b. support incentives to reduce plastic pollution
    c. promote good plastic and waste management policies
3) Education and outreach
    a. fund support for local programs and initiatives which foster education and promote the prevention of plastic and microplastics pollution in the Great Lakes.

A detailed report by the World Health Organization emphasized the importance of investigating potential health impacts of microplastics ingestion (WHO, 2019). The report focused on proper operation of treatment utilities and to prioritize pathogens and chemical contaminants that are known to impose significant risk to human health of most concern. The report draws from existing literature on microplastics which is very limited and the necessity of conducting further research has been echoed in the research community.

Taking into account the potential environmental concerns, the Government of Canada prioritized the review and regulation of manufacture, use and sale of microplastics in commercial products known as microbeads. Based on available information, microbeads were proposed to be added to the List of Toxic Substances under the Canadian Environmental Protection Act 1999 (Environment Canada, 1999). The “Microbeads in Toiletries Regulations” were published in the Canada Gazette, Part II: Vol. 151, No.12 on June 14, 2017. In the U.S., nine states including Illinois, Colorado, Wisconsin, Indiana, Maine, Maryland, New Jersey, Connecticut, and California have passed laws in the period from 2015 to December, 2019 that prohibit the sale and manufacture of microbeads in personal care products. On December 28, 2015, a U.S. federal bill (H.R. 1321) entitled “The Microbeads-Free Waters Act of 2015” was signed into law which places restrictions on the manufacture of rinse-off cosmetics containing plastic microbeads. Similarly, proposals for laws and regulations on the use of microbeads in cosmetic products was jointly called for in the European Union member states of Austria, Belgium, Netherlands, Luxembourg, and Sweden in

December 2014 (EU, 2015). In January 2019, the European Chemical Agency proposed a wide-ranging restriction on microplastics in products placed on the market to avoid or reduce their release to the environment (Environment Canada, 2015). Collectively, these regulations assertively aimed to reduce the quantity of plastic microbeads entering freshwater and marine ecosystems; given the extent of these concerns, analogous initiatives in the drinking water domain have been obvious next steps.

In September 2018, Safety Code section 116376 via Senate Bill No. 1422 was adopted by the California legislature which added microplastics regulations to California's Safe Drinking Water Act and on March 19, 2020, the California State Water Resources Control Board became the first regulatory agency in the world to specifically define "Microplastics in Drinking Water" (California Water Boards, 2020). The California Safe Drinking Water Act also requires the State Water Board to (1) adopt a standard methodology for testing drinking water for microplastics; (2) adopt a requirement for four years of testing and reporting of microplastics in drinking water, including public disclosure of the results; (3) consider issuing a notification level or other guidance to help consumers interpret the testing results; and (4) accredit laboratories in California to analyze for microplastics (California Water Boards, 2020).

### 2.7.1 Challenges of regulating microplastics

Microplastics are not rapidly biodegradable particles which are extremely persistent and may remain in the environment over very long periods of time (Browne et al., 2011b). They can also physically breakdown in the environment forming smaller sized microplastics (Fahrenfeld et al., 2019; Sait et al., 2021). Regulatory efforts should, therefore, focus on the long-lasting implications of microplastics in addition to current environmental concentrations. Pollutants regulated in freshwater systems and drinking water are usually dissolved chemicals or pathogenic organisms. The transferability of regulatory options for currently monitored contaminants need to be critically evaluated. The first step is to develop a commonly accepted definition for microplastics in drinking water.

The term "microplastics" encompasses a large group of polymers with various chemical and physical properties, originating from different sources and it is necessary for regulatory agencies to define them in the context of drinking water (currently only defined by California State Water Resources Control Board). Defining a lower size limit is tricky because it then excludes smaller particles from the regulation. Therefore, it is reasonable to define microplastics with respect to the context in which they are being considered, for instance drinking water contaminant, environmental/ecological implications, or health implications, because different aspects of microplastics are concerning in different types of assessment. There is also a need for a standardized procedure of microplastics sampling and analysis which is a prerequisite for reliable, generally accepted, and justiciable data acquisition. The absence of a standard method has led to inconsistency in sampling and analysis of microplastics across scientific investigations (Araujo et al., 2018; Lenz et al., 2015; Stock et al., 2019). As research with microplastics progresses, more information will become available, and it would be prudent to formulate information needs for regulations and what is beyond the scope of regulation instruments. Currently, microplastics are being actively investigated by researchers looking to answer open questions ranging from degradation processes, uptake by organisms, interaction with chemicals, etc. Given the wide scope of microplastics, it is evident that an interdisciplinary cooperation will be required to develop a comprehensive regulatory framework for microplastics (Harrison et al., 2018).

### 2.8 Health Risk Assessment (HRA)

USEPA (2014) defines health risk assessment as “the process to estimate the nature and probability of adverse health effects in humans who may be exposed to chemicals in contaminated environmental media, now or in the future”. The sequential flow of the framework leading to health risk assessment is outlined below:

1) Planning and scoping – important first step to ensure that each risk assessment has a clear purpose and well-defined vision.

2) Problem formulation – this step focuses on identifying the major factors that need to be integrated in the assessment and consists of two steps. A conceptual model is developed which identifies factors that are analyzed in the model as well as the aspects that are not considered. Then, an analysis plan is prepared.

3) Public, stakeholder, and community involvement **–** this stage focuses on engaging the stakeholders and convey the results of the assessment.

4) Risk assessment **–** this step includes four basic components:

   i. *Hazard identification* – It is the process of determining whether exposure to a stressor can cause an increase in the incidence of specific adverse health effects (e.g., cancer, birth defects). Key components analyzed in this step are toxicokinetics, toxicodynamics, mode of action and weight of evidence of the stressor to cause adverse human health effects.

   ii. *Dose-response assessment* – It describes how the likelihood and severity of adverse health effects (the responses) are related to the amount and condition of exposure to an agent (the dose provided).

   iii. *Exposure assessment* – It is the process of measuring or estimating the magnitude, frequency, and duration of human exposure to an agent in the environment or estimating future exposures for an agent that has not yet been released.

   iv. *Risk characterization* – It conveys the risk assessor's judgment as to the nature and presence or absence of risks, along with information about how the risk was assessed, where assumptions and uncertainties still exist, and where policy choices will need to be made.

As described by Thoeye et al. (2003), there are two approaches to evaluate the health risks attributable to contaminants in drinking water: parameter-based and effects-based. In the “parameter approach”, risk related to water ingestion is based on the presence of different parameters (i.e., chemicals and microorganisms) that are considered separately, and their concentrations are compared to reference concentrations. Reference concentrations are either (i) formalized in one drinking water quality standard/guideline/regulation or (ii) reflected in quantitative risk assessment, which integrates toxicological data, infectious doses, and acceptable risk as the reference conditions. In contrast, the “effects approach” involves using (i) biological tests to examine how water affects test organisms, cells or tissues; or (ii) epidemiological studies to examine the effects of water supplies on human populations.

The use of drinking water quality regulations/standards/guidelines (referred to as guidelines below) to assess the potential indirect health risks attributable to microplastics ingestion via drinking water has several advantages, which include:

- Documents are open source and easily accessible;
- Drinking water quality guidelines have been established for the protection of public health and through long periods of research which makes them reliable;
- They define a wide range of parameters to assess drinking water quality which provides options to choose a reference parameter depending on the objective; and
- This approach enables relatively simple analysis of available data to conduct a preliminary risk assessment.

While incomplete, critical information needed to evaluate the indirect health risks posed by chemical sorbed to microplastics is available and can be applied to develop a water-quality standards parameter approach for risk management. Specifically, several endpoint parameters have been developed to describe both waterborne chemical toxicity thresholds for acute and chronic health effects—these parameters are summarized in Table 2.10. For waterborne chemicals for which (1) toxicity thresholds have been established and (2) sorption to microplastics has been quantified or can be estimated, a threshold microplastics concentration (TMC) to indicate the concentration of microplastics particles in source or treated drinking water that can potentially result in health risk resulting from exposure to chemical contaminants sorbed on microplastics surfaces can likely be developed by integrating this information with additional data regarding microplastics type, size, and shape.

Table 2.10: Endpoint parameters used to describe waterborne chemical toxicity thresholds (reproduced from USEPA, 2018).

| Parameter | Definition |
|---|---|
| DWEL (Drinking Water Equivalent Level) (mg/L) | A drinking water lifetime exposure level, assuming 100% exposure from that medium, at which adverse, noncarcinogenic health effects would not be expected to occur. |
| MCL (Maximum Contaminant Level) (mg/L) | The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. |
| *RfD (Reference Dose) (mg/kg/day) | An estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. |
| One-Day Health Advisory (mg/L) | The concentration of a chemical in drinking water that is not expected to cause any adverse noncarcinogenic effects for up to one day of exposure. The One-Day HA is intended to protect a 10-kg child consuming 1 liter of water per day. |
| Ten-Day Health Advisory (mg/L) | The concentration of a chemical in drinking water that is not expected to cause any adverse noncarcinogenic effects for up to ten days of exposure. The Ten-Day HA is also intended to protect a 10-kg child consuming 1 liter of water per day. |
| Lifetime Health Advisory (mg/L) | The concentration of a chemical in drinking water that is not expected to cause any adverse noncarcinogenic effects for a lifetime of exposure, incorporating a drinking water RSC factor of contaminant-specific data or a default of 20% of total exposure from all sources. The Lifetime HA is based on exposure of a 70-kg adult consuming 2 liters of water per day. For Lifetime HAs developed for drinking water contaminants before the Lifetime HA policy change to develop Lifetime HAs for all drinking water contaminants regardless of carcinogenicity status in this DWSHA update, the Lifetime HA for Group C carcinogens, as indicated by the 1986 Cancer Guidelines, includes an uncertainty adjustment factor of 10 for possible carcinogenicity. |
| Predicted No Effect Concentration (PNEC) (mg/L) | The concentration of a chemical which marks the limit at which below no adverse effects of exposure in an ecosystem are measured. PNEC values are intended to be conservative and predict the concentration at which a chemical will likely have no toxic effect. |

*For analysis in this thesis, a 10 kg child was assumed to calculate a reference dose (RfD) in units of mg/day.

## 2.9 Observations and Research Needs

A total of 116 studies conducted with various sizes of microplastics and focused on the general domains of environmental occurrence, toxicity, and adsorption/desorption of contaminants are summarized in Figure 2.7. The majority of the toxicological assays report on plastic particles less than 1 µm because they are the most likely to have direct human health effects. At present, the environmental occurrence of microplastics smaller than 1 µm (i.e., nanoplastics) has not been described due to limitations of sampling and enumeration methods. Most chemical sorption and microplastics occurrence investigations that are relevant to evaluating indirect health impacts from waterborne microplastics have reported on microplastics in the size range from 100 to 500 µm. Microplastics larger than 500 µm have not been used in toxicity studies, though a number of sorption and occurrence studies have been reported.

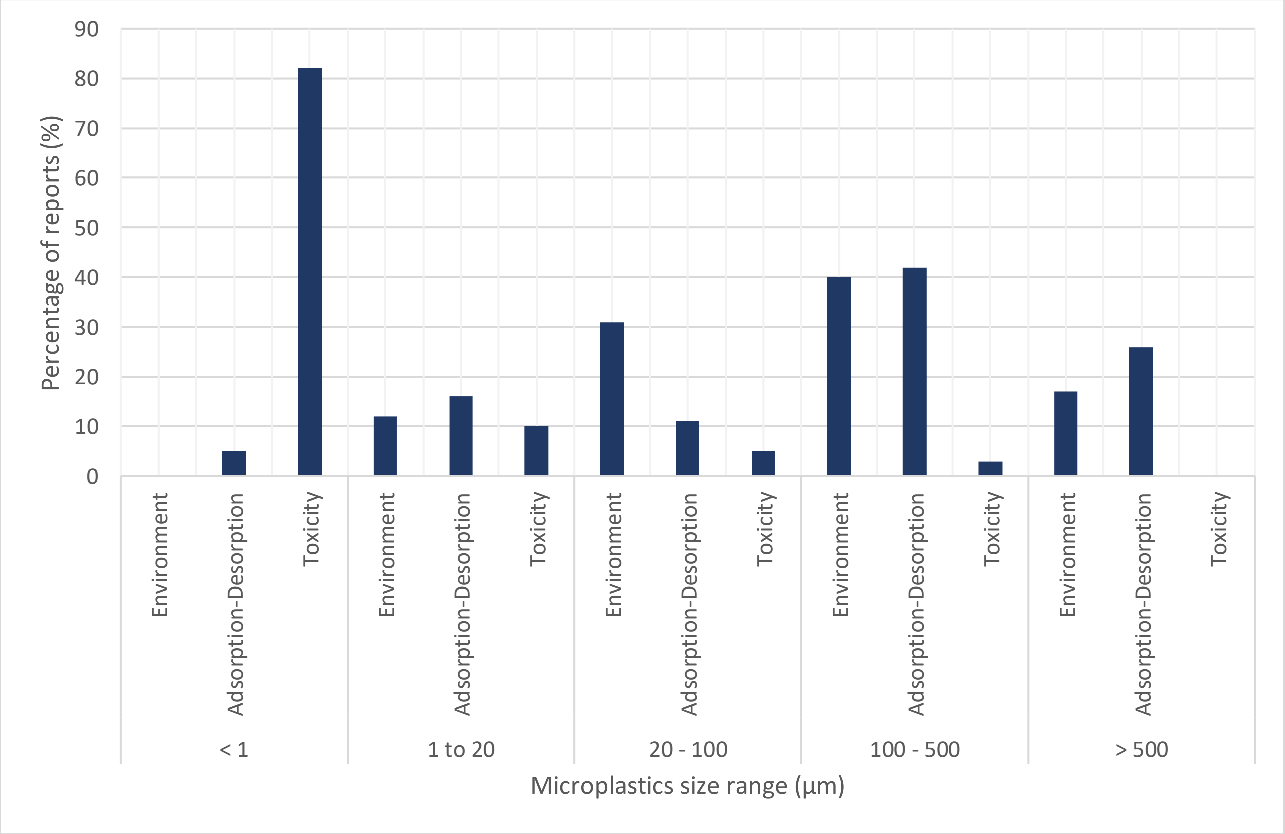


Figure 2.7: Particle size range investigated in various types of microplastics research in 116 studies published between 2001 and 2020.

Notably, toxicological investigations have frequently involved PS microplastics (Figure 2.8); 67% of the 116 studies examined involved PS. Limited toxicological information exists regarding other microplastics types. As several types of microplastics are present in freshwater and can potentially be consumed by humans via drinking water, more of these data are needed to better understand the potential direct and indirect health impacts of microplastics ingestion.

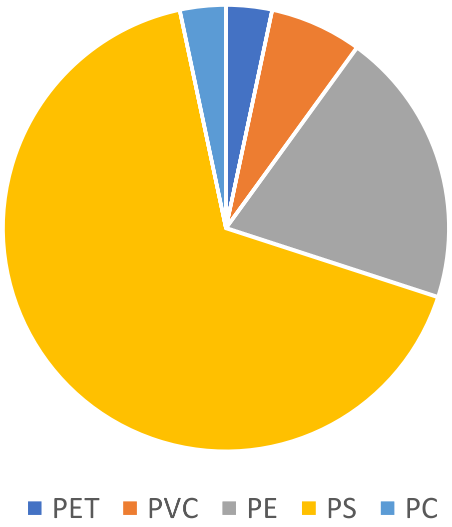


Figure 2.8: Microplastics types that have been evaluated in toxicological assessments in 30 studies between 2001 and 2020.

Even though data regarding the removal of certain types of microplastics by different drinking water treatment processes are somewhat scant (i.e., micron-sized PS microsphere removal by filtration is a notable exception that has been evaluated extensively), particle removal during drinking water treatment is well understood and can be described in accordance with an established mechanistic understanding of coagulation and filtration theory (Amirtharajah and Jones, 2004). Critically, there is no evidence to suggest that the microplastics removal during typical drinking water treatment would vastly differ from current expectations of particle removal. It is further promising that some information regarding the physical and chemical properties of microplastics, as well as the sorption of some regulated, waterborne contaminants that can sorb on them is available to assess potential health impacts. As would be expected, identification of chemical contaminants and microplastics combinations of greatest concern is critical. Based on currently available information, some key questions associated with microplastics in drinking water are:

- What is the human toxicity of waterborne microplastics and associated contaminants (i.e., direct and indirect health impacts)?
- What source and treated water concentrations of microplastics pose significant health threats?
- What are the sorption capacities of waterborne chemical contaminants on environmental microplastics?
- Are certain chemical contaminants sorbed on microplastics sentinel indicators of potential health threats?
- Are microplastics sufficiently removed during typical conventional drinking water treatment or is advanced treatment required?

While most current microplastics regulations are in the realm of waste management, evidence of microplastics in drinking water treatment plant intakes has drawn the attention of national and international regulatory organizations which govern surface and drinking water quality for public health protection (e.g., WHO; Health Canada, USEPA). While these agencies have created a multitude of laws, guidelines, and standards they do not include microplastics, leaving drinking water utilities without a guidance for managing the removal of microplastics through treatment. That said, it is difficult to develop water quality criteria or treatment requirements without adequate evaluation of health risk. A framework for managing health risks attributable to waterborne microplastics is currently lacking; however, an initial framework for evaluating the indirect health risks attributable to chemical contaminants sorbed to waterborne microplastics can be developed based on systematic integration of the required and available information. The goal of this research was to develop such a framework so that it is immediately available to inform decision-making in the water industry and modularize it so that new information can be readily integrated into it as it becomes available.

# Chapter 3 Materials and Methods

## 3.1 General Research Approach

To address the research objectives detailed in Chapter 1, a two-pronged approach was used.

First, a conceptual framework was developed to synthesize available scientific data and develop a tool to reflect the indirect health risks attributable to ingestion of waterborne microplastics, as laid out in Figure 3.1. The construction of the framework for evaluating the health risks attributable to ingestion of chemical contaminants sorbed on microplastics surfaces (i.e., indirect health risks from microplastics) in source and treated drinking water required seven key types of data: (1) microplastics types, (2) microplastics sizes, (3) microplastics shapes, (4) maximum contaminant AC on plastic surfaces, (5) extent of microplastics removal during drinking water treatment (if any), (6) human exposure to microplastics in distributed water, and (7) indicators of health risk attributable to exposure to contaminated drinking water (i.e., drinking water contaminant standards and human health advisories). These key data were collected, summarized, and integrated to enable the calculation (i.e., the back-calculation) of a "Threshold Microplastics Concentration" (TMC) to indicate the concentration of microplastics particles in source or treated drinking water that can potentially result in health risk resulting from exposure to chemical contaminants sorbed on microplastics surfaces.

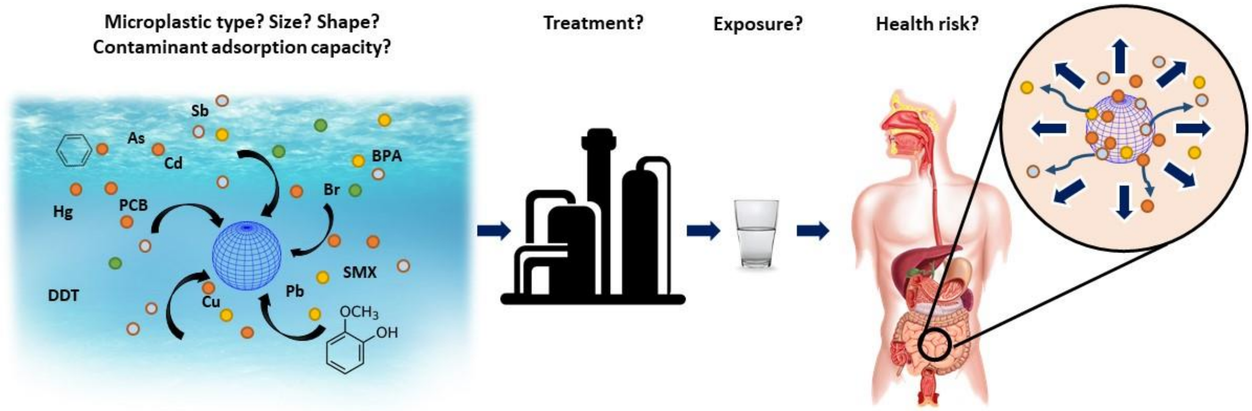


Figure 3.1: Conceptual model indicating the major information needs required to develop a framework and tool to evaluate the indirect health risks attributable to ingestion of microplastics in source and treated drinking water. Here, indirect health risks are those associated with chemical contaminants adsorbed on microplastic surfaces.

The TMC is analogous to Maximum Contaminant Levels (MCLs) or Maximum Acceptable Concentrations (MACs) that are used to manage risks from chemical drinking water contaminants in the U.S. and Canada, respectively (USEPA, 2018; Health Canada, 2012). The TMC concept can be used as a relatively rapid indicator to assess if microplastics in source water may pose risks to human health after or in absence of well-operated conventional treatment by filtration with chemical pre-treatment (i.e., coagulation, flocculation, clarification, and granular media filtration). Thus, it can be applied to a variety of surface and groundwater treatment scenarios.

The second phase of the research approach involved synthesis and confirmation of current understanding regarding the treatment/passage of different types and sizes of microplastics by/through natural and engineered porous media systems, respectively representative of groundwater aquifers and conventional treatment by filtration. A particulate contaminants- and filtration-focused literature review was conducted to synthesize the available knowledge regarding the transport behavior of microplastics particles in porous media systems such as granular media aquifers and engineered filters. A limited series of zeta potential analyses, and bench-scale coagulation and filtration experiments were conducted to further confirm that the fate, transport, and treatment of microplastics in natural and engineered systems is consistent with other particles and particulate contaminants removed (at least in part) in these systems.

## 3.2 Characterizing indirect health risks from microplastics

Key data relevant to the evaluation of health risks attributable to ingestion of chemical contaminants adsorbed on microplastics surfaces were collected, summarized, and integrated to enable the calculation of a TMC. The methods associated with the collection and organization of those data are described below.

### 3.2.1 Microplastics types, sizes, shapes, and contaminant adsorption/desorption capacity

A review of scientific literature focused on microplastics type, size, and abundance in aquatic environments including treated drinking water, and adsorption and desorption of chemicals to and from microplastics was conducted. ScienceDirect, American Chemical Society (ACS), Scopus, International Water Association (IWA) and American Water Works Association (AWWA) were among the databases that were accessed; the internal search engines present in their online platforms were used. The searches included key words and phrases such as “microplastics adsorption”, “chemical adsorption on microplastics”, “desorption of chemicals from microplastics”, and “plastic additives”. The terms “microplastics” and “plastics” were both searched, as were specific plastic types.

Sorption of specific contaminants was also investigated. For instance, while searching for data pertaining to antimony (Sb) the search phrases were “antimony sorption on plastics/microplastics”, “microplastics and antimony”, etc. From the identified documents, the highest value of adsorption/desorption capacities that would lead to the highest amount of contaminant release/desorption upon ingestion were used in performing calculations to yield the most conservative estimate of microplastics concentration that would lead to potential health risk. Drinking water guidelines and/or standards published by the World Health Organization (WHO), United States Environmental Protection Agency (USEPA), Health Canada, and Australian Drinking Water Guidelines were used to assess the potential human health risks attributable to the desorption of specific regulated contaminants from microplastics.

### 3.2.2 Microplastics removal during drinking water treatment

A literature review of microplastics/microspheres removal/transport in porous media systems representing the subsurface and engineered system was conducted. Experiments in bench-scale column tests and pilot-scale filtration systems were systematically reviewed to describe particle removal behavior. Data for microplastics removal during drinking water treatment are widely available from studies in which microplastics/microspheres have been used as surrogates of microbes. In addition, data from a few field-scale investigations in the natural environment of particle transport in the subsurface are available, all of which inform our understanding of microplastics removal during drinking water treatment. The reviewed data were categorized with respect to flow in the subsurface (groundwater system) and chemically-assisted filtration (engineered system). Treatment in groundwater systems is dictated by the physico-chemical interactions between microplastics/microspheres and, media grain particles and water quality. During flow in the subsurface particle removal occurs in the natural subsurface which is followed by disinfection in some cases (e.g., the U.S. does not require disinfection of water classified as groundwater whereas Ontario does require a minimum 4-log disinfection of viruses). Treatment of surface water follows conventional drinking water treatment in which particles undergo chemically assisted filtration. These systems were discussed in Chapter 2 and the data have been summarized in Table 2.9. The implications of these systems and interpretation of the analysis are presented in Chapter 4.

### 3.2.3 Human exposure to microplastics through ingestion of distributed water

Risk assessment approaches are commonly simplified by making assumptions when regular evaluation of a water quality parameter in finished water is not possible because of costs and the time-consuming nature of sample processing. There is a conceptual overlap in health risk assessment of microplastics, as considered in this assessment, and pathogens for which microbial risk assessments are commonly performed. The risk is assessed for drinking water and a general assumption is that the route of exposure is limited to consumption through drinking water. Typically, this requires an estimation of the volume of water consumed by an individual on a daily basis. This can be a fixed value or a distribution of values. For the purpose of indirect health risks of microplastics, which are imposed due to adsorbed contaminants, exposure is assumed in their established standard concentrations (Table 2.10). For instance, in determining the one-day health advisory of a drinking water contaminant, a daily consumption of 1 L of drinking water by a 10 kg child is assumed (USEPA, 2018). Similarly, for all other health standard concentrations enlisted in Table 2.10, an exposure is assumed in the original calculation performed to derive each of these concentration values.

### 3.2.4 Indicators of health risk attributable to exposure to contaminated drinking water

Drinking water standards and health advisories have been developed to ensure safe drinking water for consumption depending on various exposure conditions and target populations (USEPA, 2018; Health Canada, 2012; WHO, 2012). These standards, defined in Table 2.10, were used as reference concentrations for contaminants sorbed on and in microplastics to calculate total number of microplastics per liter of drinking water, the TMC, that might lead to their accumulation to concentrations that exceed these established reference health standards. In all cases, the health standard resulting in the most concerning (i.e., lowest) TMC was used in the calculation of the TMC. The other health standards can also be used in TMC calculations so that users may contrast the outputs based on various exposure durations and target populations. The calculation of TMC using these values is presented in Chapter 4.

## 3.3 Evaluating indirect health risks from microplastics

Microplastics types and maximum contaminant AC on plastic surfaces data were used to calculate the maximum sorption that could occur on various sizes and shapes of microplastics—MS Excel® spreadsheets were utilized to complete these calculations. Indicators of health risk attributable to exposure to contaminated drinking water (i.e., drinking water contaminant standards and human health advisories) and typical drinking water consumption rates were then used to generate (i.e., back-calculate) a Threshold Microplastics Concentration (TMC). The TMC concept is a key product of this thesis work and it is defined as the number of microplastics particles per liter of water that can potentially result in health risk resulting from exposure to chemical contaminants sorbed on and in microplastics surfaces. Specifically, TMC curves were generated by evaluating each combination of (1) microplastics type, (2) microplastics shape, (3) sorptive chemical, and (4) toxicity endpoint combination as a function of microplastics particle size. A microplastics calculator was additionally developed to automatically calculate TMC based on user input of variables using MS Excel® and a more user-friendly version was developed using Visual Basic®.

## 3.4 Surface charge assessments to confirm adequacy of microplastics destabilization by coagulation

### 3.4.1 Experimental Design

These experiments were designed to demonstrate that the presence of microplastics at environmentally relevant concentrations in the various source water matrices did not (1) preclude optimal particle destabilization (which enables optimal particle removal by physico-chemical filtration) or (2) alter the coagulant doses required to achieve optimal particle destabilization (i.e., PZC ± 4 mV) even though the addition of the microplastics would be expected to significantly change the net zeta potential of the particles suspended in the water matrices in some cases because the microplastics concentrations would be too low (relative the concentrations of other particles in the real water matrices) to substantially impact coagulant dosing requirements. The objective of coagulant addition in these experiments was not to identify an optimum dose for microplastics removal but to confirm that these particles do not exhibit unusual behaviors in water with respect to their destabilizing characteristics during chemical treatment. To achieve this, measurements of zeta potential of samples were taken in three stages: 1) raw water 2) raw water spiked with a concentration of 500 microplastic particles/mL and 3) after coagulation. The results of these experiments can then be analyzed to infer whether microplastics in water exhibit unusual behavior that may be of concern.

### 3.4.1a) Microplastics

Four types of microplastics commonly used in consumer products were used. Fluorescent YG polystyrene (PS) microspheres (nominal size 1 µm; 4.55 x $10^{10}$ particles/mL) in aqueous suspension was purchased from Polysciences Inc. (USA). Blue polyethylene (PE) microspheres powder (ranging from 10 to 27 µm in diameter; 8.31 x $10^{7}$ particles/g) was purchased from Cospheric LLC (USA). Recycled polyetheretherketone (PEEK) powder (median size of 16.92 µm with 80% of the particles smaller than 50.5 µm) was obtained from Powder Technology Inc. PEEK is a polymer used in aerospace, automotive, and medical applications. Finally, acrylic (ACR) nail dipping powder (mean size of 14.45 µm measured using LISST-200X Particle Size Analyzer, Sequoia Scientific Inc., USA) was also used.

### 3.4.1b) Water matrices

Four water types were investigated including (1) distilled, deionized MilliQ™ water (pH not adjusted), (2) 100 mM KCl electrolyte solution as an ideal matrix representing favourable conditions for particle destabilization, (3) low turbidity, low DOC Lake Ontario water, and (4) higher turbidity, moderate DOC Grand River water were used. The zeta potential of the particles suspended in these water matrices was evaluated in each matrix before and after the addition of the four microplastics investigated. The target microplastics concentration in the water matrices was 500 particles/mL, which is an elevated concentration compared to concentrations of microplastics typically detected in the environment (Anderson et al., 2017; Dikareva and Simon, 2019; Wilson et al., 2013; Yonkos et al., 2014; Zhao et al., 2014). Five replicates of each of the water matrices with and without each of the microplastics types were prepared in 500 mL beakers (i.e., 80 samples in total) to investigate if the presence of microplastics at environmentally relevant concentrations in the various source water matrices (1) precluded optimal particle destabilization and/or (2) altered the coagulant doses required to achieve optimal particle destabilization prior to physico-chemical filtration.

### 3.4.2 Microplastics suspension preparation

A total of 16 stock solutions were prepared by adding and thoroughly mixing 0.5 g of PEEK, 0.5 g of acrylic, 0.05 g of PE powder, and 1 mL polystyrene aqueous suspensions to separate beakers containing 500 mL of the different waters. The concentration of PS and PE microplastics in the stock solutions were extrapolated based on information provided by their suppliers (Polysciences Inc, 400 Valley Road Warrington, USA; Cospheric LLC, Santa Barbara, California, USA). The concentrations of PEEK and acrylic were determined using a hemacytometer (Bright-Line$^{TM}$, Sigma-Aldrich Canada Co., Oakville). They were enumerated at 200X magnification using a Zeiss Axioskop 2 microscope (Carl Zeiss Canada Ltd, Toronto). The particle concentrations in units of particles per mL were calculated using the equation:

$$\frac{\text{x particles}}{\text{5 squares}} \times \frac{\text{1 square}}{1\text{ mm } \times 1\text{ mm } \times 0.1\text{ mm}} \times \frac{1000\text{ mm}^3}{1\text{ mL}} \times \frac{1}{\text{Dilution}}$$

$$= 2000\text{x particles/mL}$$

Table 3.1: Microplastic stock solutions and their concentrations

| **Water type** | **Microplastic** | **Stock concentration (#/mL)** |
|---|---|---|
| MilliQ™ | PS | $9.10 \times 10^7$ |
| | PE | $8.31 \times 10^4$ |
| | PEEK | $9.16 \times 10^5$ |
| | ACR | $1.24 \times 10^7$ |
| Electrolyte solution (100 mM KCl) | PS | $9.10 \times 10^7$ |
| | PE | $8.31 \times 10^4$ |
| | PEEK | $1.05 \times 10^6$ |
| | ACR | $1.05 \times 10^7$ |
| Grand River | PS | $5.69 \times 10^7$ |
| | PE | $4.99 \times 10^3$ |
| | PEEK | $8.00 \times 10^4$ |
| | ACR | $9.96 \times 10^5$ |
| Lake Ontario | PS | $5.69 \times 10^7$ |
| | PE | $4.99 \times 10^3$ |
| | PEEK | $8.00 \times 10^4$ |
| | ACR | $9.96 \times 10^5$ |

### 3.4.3 Coagulant preparation and dosing

An alum stock solution having a concentration of 1 g/L was prepared by adding 500 mg aluminum sulfate hydrate ($Al_2O_{12}S_3.18H_2O$) (Fisher Chemical, Ottawa) to 500 mL MilliQ™ water. Aliquots were collected from the stock solution and added to each of the 500 mL beakers containing the various water matrices with and without environmentally relevant microplastics concentrations. Sufficient amounts of coagulant were added to achieve optimal particle destabilization for ensuring removal by physico-chemical filtration, which was a zeta potential of PZC ± 4 mV) (Xagoraraki & Harrington, 2004).

### 3.4.4 Coagulant preparation and dosing

Five replicates of diluted samples having a concentration of 500 particles/mL for all water matrices were prepared in 500 mL beakers for investigating the impact of alum addition on the zeta potential.

### 3.4.5 Zeta potential analysis and coagulation evaluation

Zeta potential was evaluated using a Zetasizer Nano (Malvern Panalytical, Toronto). Initial zeta potential measurements, before adding coagulant, (t = 0 minutes) were taken to compare the change after addition of coagulant (t = 10 minutes). Magnetic stir plates were used to control mixing of the solution after addition of coagulant. In the first trial, 2.5 mg/L alum was added to the solution which was rapidly mixed for 10 seconds followed by slow mixing for 10 minutes after which zeta potential was measured again. In each case, alum was dosed incrementally until the zeta potential approached zero. This was identified as the optimum alum dose for the water matrix being investigated. For the remaining replicates, the identified optimum alum dose was added, rapid mixed for 10 seconds followed by 10 minutes of slow mixing. This was repeated for all the water matrices and zeta potentials before and after coagulant addition were measured.

### 3.4.6 Data analysis

Welch's t-test with unequal sample variances was used to inform potential treatment impacts associated with the presence of microplastics in drinking water sources by evaluating the impact of microplastics addition on the zeta potential of particles suspended in the various water matrices investigated (1) before and (2) after microplastics addition and (3) after coagulant addition at doses representative of well-operated treatment focused on ensuring optimal particle removal by conventional filtration. A level of significance (α) of 0.05 was used in these analyses.

## 3.5 Confirmatory bench-scale column tests to evaluate microplastics removal by physico-chemical filtration in absence of coagulation (e.g., groundwater systems)

### 3.5.1 Experimental Design

Experiments were designed to quantify the retention of microplastics particles by saturated porous media in a controlled environment. Bench-scale column tests were conducted on microplastics particles suspended in surface water collected from Lake Ontario. This water was generally of high quality with an average turbidity of 0.24 NTU which is less than the 0.3 NTU filter effluent target set by Health Canada (2017). Total organic carbon (TOC) was typically lower than 2 mg/L and the water was slightly alkaline with a pH of 8. The water quality was not modified and, in all experiments, microplastics suspensions were made in the same batch of collected water. An initial concentration of $5 \times 10^7$ particles/mL was targeted for each experiment which was ensured by serial dilution and concentration measurements using spectrophotometry. Three different sizes of microplastics (1, 10 and 45 µm) of the same chemical composition (fluorescent polystyrene microspheres) were investigated. The column tests represented direct (non-chemically assisted) filtration and flow rates were set to simulate a groundwater flow rate. The goal of this work was to confirm our expected retention patterns of microplastics particles of different sizes from a source water matrix with no chemical treatment.

Table 3.2: Experimental design components and rationale for their choice.

| Experimental Element | Details | Rationale |
|---|---|---|
| Microplastics material | fluorescent polystyrene beads | polystyrene is commonly detected in different environmental matrices<br>commercially available in desired sizes<br>investigated as pathogen surrogate, hence reference data are available |
| Microplastics size | 1 µm, 10 µm, and 45 µm | microplastics as small as 1 µm are present in sources used for drinking water; unlikely that particles >45 µm will pass through typical drinking water filters |
| Filtration | Bench-scale<br>Single medium | simulating groundwater scenario and creating a basic condition to explain microplastics removal behavior |

### 3.5.1a) Microplastics

Three different sizes of surfactant-free fluorescent dyed polystyrene microspheres (Fluoresbrite YG microspheres, Polysciences Inc., Warrington, PA) were used: 1, 10 and 45 µm diameter. It is critical that surfactant-free microspheres are utilized to simulate microplastics surface characteristics which are not associated with surfactants. Stock suspensions of all the microplastics contained $4.55 \times 10^{10}$ microplastics/mL in deionized water (DI) water as indicated in the Materials and Safety Data sheet provided by the manufacturer. The microplastics had a density of 1.045 g/cm$^3$. In the filtration experiments all the microplastics stock suspensions were serially diluted to a concentration of $5.0 \times 10^7$ microplastics/mL using a representative surface water (Lake Ontario). The volume of microplastics required from the stock solution to prepare the target concentration of microplastics ($5.0 \times 10^7$ microplastics/mL) was calculated using the equation $C_1V_1 = C_2V_2$, where $C_1$ = concentration of the stock solution, $V_1$ = volume of stock solution to be extracted, $C_2$ = target concentration of solution, $V_2$ = intended volume of the solution to be prepared. This calculated volume of stock solution ($V_1$) was transferred to a 500 mL glass beaker containing a known volume of Lake Ontario water using a micropipette. The solutions prepared were continuously sonicated throughout the duration of the experiment to prevent aggregation of particles (Jin et al., 2015b).

#### 3.5.1b) Media preparation

White quartz sand (effective size [ES] of 0.21- 0.30 mm and uniformity coefficient [UC] less than 1.5) was used as media for all experiments (Sigma-Aldrich Inc, Darmstadt, Germany). Before each experiment, the columns were packed with a new batch of porous media. The porous media was treated before packing to remove contaminants that might influence particle transport. To remove contaminants, the sand was first soaked in 2% Extran (VWR Canada) for 30 min and then sonicated for 15 min to remove metal and organic impurities. It was then rinsed once with 100 mL of DI water repeated five times and soaked in 12 N HCL (Fisher Scientific Canada) for 12 h followed by a thorough wash with a volume of DI water sufficient to soak all of the sand particles which was then oven dried at 107°C for 12 h. After oven drying, the sand sample was placed in a furnace overnight at 550°C. Before using it for the experiment the sand was autoclaved and soaked in sample water overnight. The sand was placed in a beaker and then sample water added till a layer of water could be seen on the top of the sand to ensure that the porous media was completely saturated before conducting column experiments.

### 3.5.2 Column Tests

#### 3.5.2a) Column description

Adjustable-height glass chromatography columns (GE Health Care, C16/20) were used to conduct bench-scale column tests. The columns had in inner diameter of 1.6 cm and were packed with clean wet sand media to a depth of 15 cm. Sand was added to a depth of 2 cm and packed using mild vibration (Hitachi Magic Wand, Hitachi Limited, Ontario). This was repeated in 2 cm increments of media until a height of 12 cm and 3 cm for the topmost layer was achieved, in order to ensure no air entrapment. The top and bottom of the column was sealed with glass fiber sealed polypropylene stoppers. At the base and surface of the media column a circular fine mesh ($d_m$ = 15 mm) was placed to distribute water flow throughout the volume of the filter media and to prevent passage of media particles to the effluent collector tube. The columns and all components were thoroughly rinsed with water, soaked in 10% acetone overnight and washed with sterile water between experiments. The column was initially equilibrated by pumping through 10 pore volumes of particle free sample water at a constant hydraulic loading rate of 0.75 m/h using a peristaltic pump (Cole-Parmer Instruments Co., Montreal, Québec).

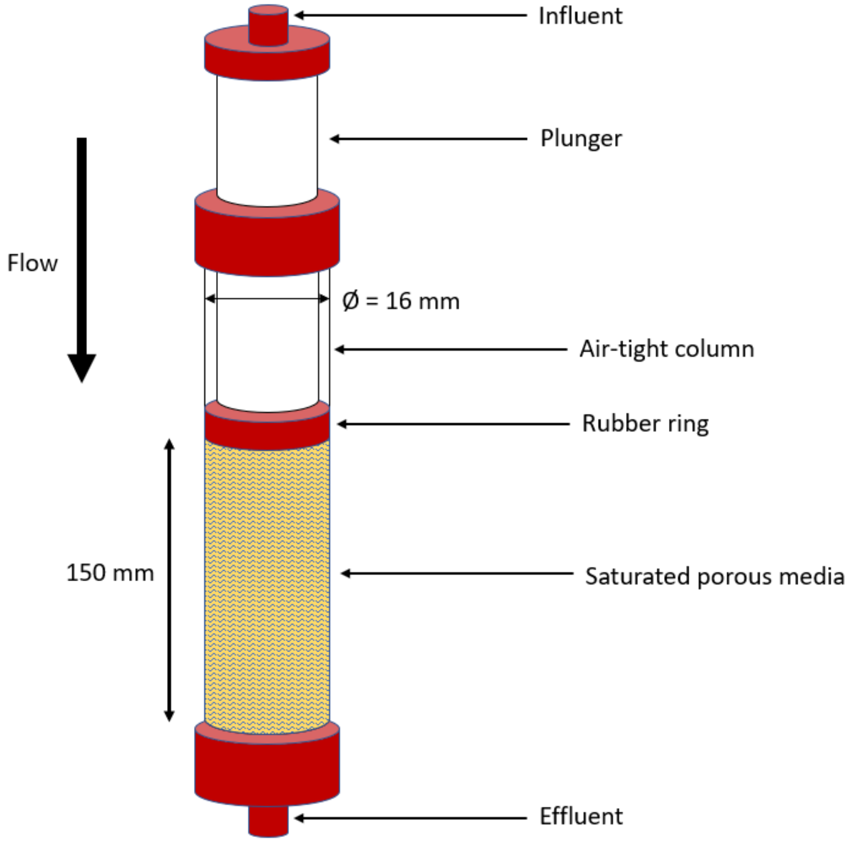


Figure 3.2: Schematic of bench-scale filtration column used to quantify the retention of microplastics particles by saturated porous media in controlled studies. More details about the column design can be found in Jin, 2014; Jin et al., 2017, 2016, 2015b, 2015a.

#### 3.5.2b) Column operation

A microplastics stock solution of known concentration, 5 x $10^7$ particles/mL, was prepared in a 500 mL glass beaker which was sonicated throughout the duration of the experiment to keep the particles suspended. New stock solution was prepared before conducting each experiment. This stock feed suspension was continuously sonicated to prevent particle aggregation and maintain a uniform influent microplastics concentration. The seed solution was fed continuously into the column and effluent samples were collected every two minutes in labelled glass tubes (until 5 pore volumes had passed). The samples were continuously sonicated throughout the experiment and vortexed for 20 s prior to measuring absorbance (described below). Each experiment was run for a total of 36 minutes with the last 6 – 8 minutes of flow with particle-free sample water.

After completion of the experiment, air was pumped through the influent port of the column to discharge remaining water from the column. Destructive sampling of the filter media was conducted whereby the top 3.0 cm of the filter media was extracted and the remaining length of the filter media was dissected evenly (2.0 cm segments) into a total of 7 segments. This was performed to determine the spatial distribution of microplastics retained along the depth of the media and to conduct a mass balance to identify loss of microplastics within the system. Each segment was collected in a 20 mL glass tube and the mass was recorded. A total of 10 mL of sample water was added to each sample which was then sonicated for 10 minutes and then vortexed for 20 seconds to dislodge attached microplastics in the supernatant. Samples (3 mL) were taken from the supernatant to quantify particles retained in the filter media.

### 3.5.3 Enumeration

#### 3.5.3a) Spectrophotometer calibration

Microspheres were enumerated spectrophotometrically by measuring their absorbance (HP Model 8453 UV-Spectrophotometer, Agilent, Canada). A range of microplastics particle concentrations were prepared from the original stock solutions of known concentration by serial dilution (Table 3.3). Standard rectangular optical glass cuvettes of 3.5 mL volume were carefully filled with the solutions by repeatedly wiping the surface to prevent interference from water on the surface of the glass. The cuvettes were rinsed with 10% acetone to dissolve microplastics from the previous run to prevent cross contamination. Then it was thoroughly rinsed with DI water before filling the next sample. Each of the prepared solutions was measured on the UV-Vis spectrophotometer to determine the instrumental response needed for the calibration curve. The data were recorded and used to generate a calibration curve using graphical functions in MS Excel® (Appendix A).

Table 3.3: Microplastics stock solution serial dilution data.

| Diluting solution (mL)* | Stock solution (mL) | Dilution factor |
|---|---|---|
| 2.50 | 2.50 | 2 |
| 4.00 | 1.00 | 5 |
| 4.50 | 0.50 | 10 |
| 4.75 | 0.25 | 20 |
| 4.90 | 0.10 | 50 |
| 4.95 | 0.05 | 100 |

*MilliQ™ water was used as the diluting solution.

### 3.5.3b) Absorbance measurement

Samples collected in glass tubes were sonicated throughout the duration of the experiment to prevent aggregation of the microplastics. After completion of an experimental run, each sample tube was analyzed spectrophotometrically to enumerate microplastics concentration. Absorption peaks were observed at 404, 343, and 364 nm for 1, 10, and 45 µm particles, respectively and the spectrophotometer was set at these values when measuring the absorbance of microplastics of the three sizes. Three readings for the same sample were recorded and averaged to represent absorbance of the sample being tested. After collecting absorbance data for all samples of an experiment, their corresponding concentrations were calculated using the developed calibration curves (Appendix A).

### 3.5.4 Data analysis

Microplastics data were examined using effluent concentration breakthrough curves. Normalized concentration ($C/C_O$) over time was plotted to obtain breakthrough curves and to identify pseudo steady state during microplastics removal (the plateau in the curves). The removal of different sized microplastics were obtained by plotting $\log_{10} C/C_O$ over time.

Here:

C = concentration of microplastics collected at the effluent in particles/mL

$C_O$= concentration of microplastics in the feed suspension in particles/mL

The breakthrough curves showed variability in the time to reach breakthrough and pseudo-state for different sizes of microplastics investigated.

# Chapter 4 Results and Discussion

## 4.1 Microplastics Indirect Health Risk Assessment (MIHRA)

The steps involved in development of a conceptual framework to assess potential indirect health impacts of microplastics ingestion through contaminated drinking water are presented here. The health risk assessment was conducted based on contemporaneously available information and the results are presented below. A "Microplastics Calculator" was developed that generates Threshold Microplastics Concentrations (TMCs) based on user input which enables analysis on a case-by-case basis.

To support decision making for utility operators with respect to microplastics in drinking water, a new framework, Microplastics Indirect Health Risk Assessment (MIHRA) was developed. The framework consists of three steps: (i) data collection, (ii) processing and mathematical analysis of collected data and (iii) decision making (Figure 4.1). The first stage includes collection of available data/information relevant to the assessment, such as the ACs of contaminants and microplastics type and size. The data collected is then stored in a separate database required for conducting this assessment. The second stage includes analysis of collected data and development of models that generate numeric values of potentially concerning numbers of microplastics per liter of water. In the final step, the output of model calculations from stage two can be used as a "rule of thumb" in preliminary decision making by utility operators or drinking water practitioners. Decision making can involve various stakeholders depending on the scale and scope of the assessment and it may vary on a case-by-case basis. This step (iii) is therefore beyond the scope of this thesis.

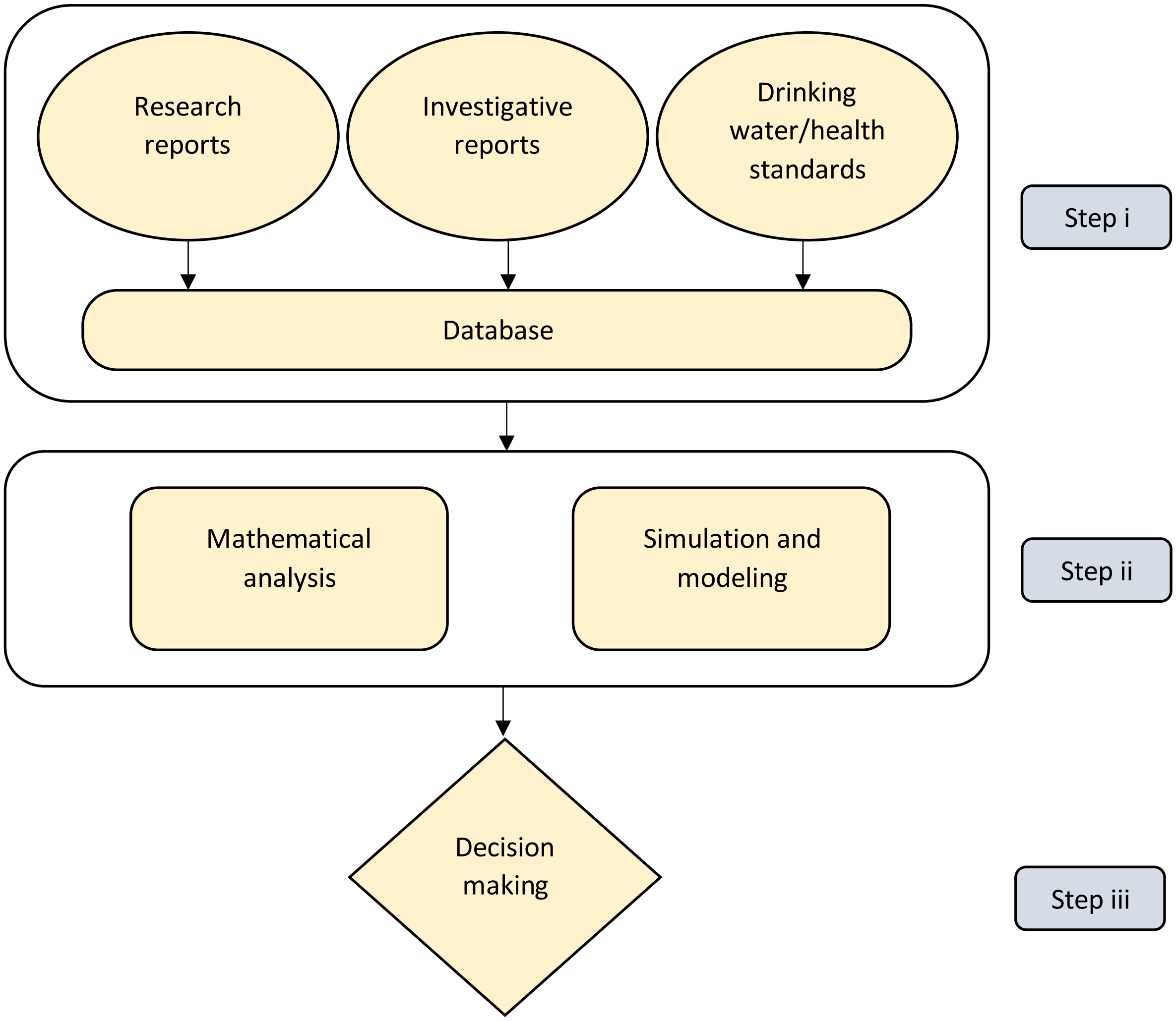


Figure 4.1: Overview of the Microplastics Indirect Health Risk Assessment (MIHRA) framework.

The framework developed here for the first time, MIHRA, specifically enables assessment of the indirect potential health risks from microplastics consumed in treated drinking water. The steps followed in developing this framework are discussed.

## 4.2 Conceptual Model

The drinking water pathway was chosen as the route for human exposure to microplastics since it constitutes a major proportion of microplastics consumed by human beings (Senathirajah et al., 2020). It is also relevant to study oral ingestion because it is considered the exposure pathway that leads to the greatest risk (Thoeye et al., 2003). The developed conceptual model, taking into consideration all of the associated factors discussed thus far, is represented in Figure 4.2.

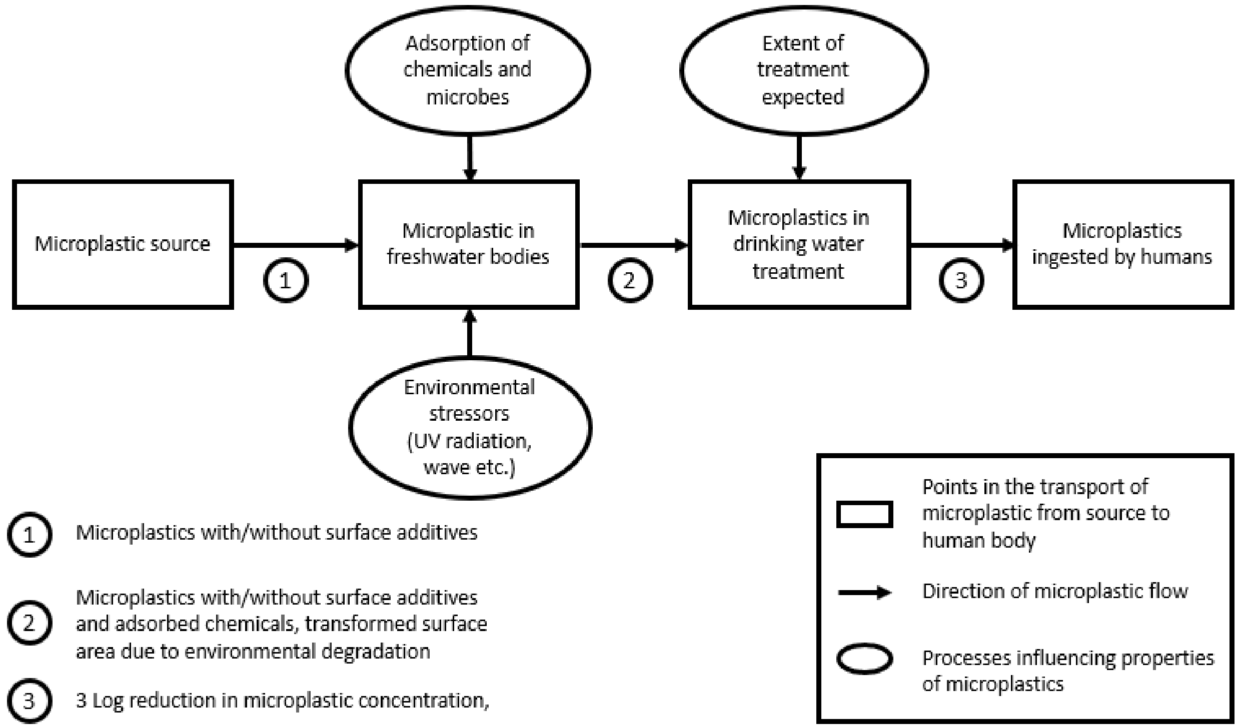


Figure 4.2: Conceptual model for human exposure to microplastics through drinking water based on the extent of treatment expected.

### 4.3 Analysis Plan

Existing water-quality standards (Section 2.8) enable health risk assessment. They were used to assess the indirect potential health risks from microplastics consumed in treated drinking water. Using available information regarding the sorption capacity of a contaminant on microplastics surfaces, the drinking water standard for a given contaminant was used to back calculate a concentration of microplastics in water that may lead to sorption of the contaminant at a concentration equal to its established drinking water standard. A wide range of microplastics shapes and sizes were evaluated. Drinking water standards from the WHO, USEPA and Health Canada were used. These guideline/standard concentrations can vary for any given contaminant. Typical guideline parameters and their values are shown in Table B1 (Appendix B). Choice of parameter depends on the intended outcome of the analysis; however, to be conservative (i.e., the most protective of public health), the lowest recommended value was used herein in order to ensure that the lowest guideline concentration (i.e., TMC) corresponding to the most concerning scenario was developed. The framework was then used to identify the most problematic contaminant based on sorption to microplastics and a numeric value of the concentration of microplastics that can potentially cause health impact was generated. Table 4.1 summarizes the available information that enabled contaminant inclusion in the health risk assessment according to the conceptual model and framework that were developed.

Table 4.1: Contaminants for which there are sufficient data (i.e., health-based drinking water guidelines and maximum sorption capacity on plastics) to conduct a health risk assessment.

| Contaminant | Guideline minimum concentration (mg/L)* | Maximum sorption capacity (mg/g) | Microplastics type | Microplastics size (µm) | Reference |
|---|---|---|---|---|---|
| Aluminum | 2.9 | 0.375 | PET | 2000 | Rochman et al., 2014 |
| Antimony | 0.004 | 27.8 | PVC | 1000 | James and Turner, 2020 |
| Arsenic | 0.003 | 1.12 | PS | 100 | Dong et al., 2020 |
| BPA | 0.00006 | 0.19 | PVC | 13.2 | Pengfei Wu et al., 2019 |
| Bromine | 0.04 | 13 | PS | 1000 | Massos and Turner, 2017 |
| Cadmium | 0.005 | 0.00014 | PP | 3000 | Rochman et al., 2014 |
| Chromium | 0.03 | 0.000454 | PET | 500 | Rochman et al., 2014 |
| Manganese | 0.12 | 0.13 | PET | 2000 | Rochman et al., 2014 |
| Mercury | 0.002 | 0.00125 | HDPE | 4.5 | Rivera-Hernández et al., 2019 |
| Propanolol | 0.0005 | 0.133 | PE | 45 | Razanajatovo et al., 2018 |
| Sulfamethoxazole | 0.02 | 0.087 | PE | 45 | Razanajatovo et al., 2018 |

*Where there are inconsistent regulatory targets, the lowest concentration was used in an effort to be conservative

Currently, information regarding both health-based drinking water guidelines for sorptive chemical contaminants and their maximum sorption capacity on plastics is limited. Thus, further investigation of sorption (adsorption/desorption) capacities of different types of chemical contaminants on various types of microplastics is necessary. Hence, the scope of the risk assessment that can be conducted using the MIHRA framework described above is constrained at present. Nonetheless, the developed framework enables an adaptable and readily updatable approach that can be utilized to conduct preliminary risk assessment. Even though microplastics are ubiquitous in freshwater, no drinking water quality guidelines for microplastics currently exist. Thus, the approach developed herein represents advancement in an area where there is a current void of approaches for risk management.

Considering the currently limited availability of requisite data, several assumptions were necessary to complete the preliminary risk assessment. The associated assumptions were mostly conservative and focused on worst-case-scenarios for health risk; they were as follows:

1. The entire surface area of the microplastics particles was assumed to be available for sorption and the maximum sorption capacities (ACs) obtained from the scientific literature were assumed to be homogenous across that surface area. In reality, sorption occurs only at available sites that do not necessarily include the entire particle surface area. This assumption can thus be considered as conservative.
2. The maximum sorption capacities (ACs) obtained from the scientific literature were maximum adsorption capacities that were assumed to reflect all sorption mechanisms, including chemisorption, physisorption, pore filling, and phase transition. This assumption enabled projection/calculation of contaminant sorption on different sizes and shapes of microplastics (assuming complete coverage of the microplastics particle surface area, assuming a smooth surface—this assumption is discussed below). The assumption that AC reflect all sorption mechanisms is reasonable because by definition, maximum adsorption capacity indicates is the maximum mass of adsorbate retained on (or within the pores of) the adsorbent per unit mass of the adsorbent. Experiments focused on the characterization of maximum adsorption capacity (AC) must reflect all of these

mechanisms even if they do not quantitatively differentiate between them. While chemical contaminant sorption on various materials (including plastics) at various environmental conditions has been widely reported, it is critical to note that evaluations of the maximum sorption capacities (ACs) of the adsorbent materials are not always conducted.

3. The surfaces of the microplastics particles were assumed to be smooth so that their surface area could be readily calculated for the various representative shapes that were reflected in the MIHRA framework and associated calculations of TMC. It is recognized that some microplastics particles degrade and have more porous/rougher surfaces that could have higher surface area available for contaminant sorption than the calculation of surface area based on assumptions of smooth surfaces would suggest. It is inappropriate to speculate about whether or not the assumption of entire surface coverage by the contaminant (#1 above) coupled with other assumptions related to exposure, contaminants sorbed to the microplastics, etc. sufficiently compensate for this assumption. Thus, this uncertainty remains a key consideration in the interpretation of TMC calculations—if relevant, a safety factor could be introduced to reflect this uncertainty; however, any such modification of the framework would require clearly developed rationale. This development was beyond the scope of the present investigation.
4. AC was assumed to only be a function of the total surface area per gram of microplastics (TSA) so that other factors such as competitive sorption, physico-chemical aspects of water quality, etc. did not affect sorption capacity. Thus, a single solute system in which only monolayer coverage is possible was assumed. Notably, however, environmental matrices often consist of multiple constituents that may compete/interfere with the sorption process, thus reducing the extent of contaminant sorption (Bakir et al., 2012). The potential for substantial multi-layer coverage in the systems has not been discussed extensively and requires further investigation that is beyond the scope of the present investigation; however, it should be noted that if it occurs it would likely be reflected in

evaluations of maximum AC and would not impact the outcomes of the developed MIHRA framework.

5. If data were only available for the AC of a contaminant on one type of microplastics surface and not others, the same AC was assumed for the contaminant on all types of microplastics. This may not be the case, as discussed in Chapter 2. Thus, this assumption should be revisited as new AC data become available.
6. A 3-log removal of particles was assumed to be reflective of well-operated conventional drinking water treatment. This is based on regulations developed for other particulate contaminants, particularly *Cryptosporidium* oocysts, which are typically only a few microns in size (EPA, 2002; Health Canada, 1984). It is both possible and likely that the removal of microplastics by some treatment processes may be substantially higher (Pivokonsky et al., 2018; Skaf et al., 2020).
7. It was assumed that all of the adsorbed chemicals are transferred to the human body after microplastics ingestion through drinking water.
8. A homogenous distribution of microplastics was considered. For instance, when analyzing spherical microplastics, it was assumed that all the microplastics were spheres and other shapes were not included. The same assumption was made for all microplastics types and sizes. Further analysis of heterogeneous suspensions can be readily conducted; however, that analysis was beyond the scope of this study.

Acknowledging the limitations arising from the assumption discussed above, the TMC calculated using the framework developed herein indicates the total number of microplastics particles per liter of water that, if ingested, would constitute exposure to potentially harmful concentrations of chemical contaminants retained on or in microplastics via sorption mechanisms that include hydrophobic partitioning interactions, surface sorption (electrostatic interactions, non-covalent bonding, hydrogen bonding, van der Waals attraction), and pore filling.

### 4.3.1 Development and structure of the mathematical analysis

Data collected from the extensive literature review were classified into two categories, literature-acquired, and processed/assigned, as shown in the Table 4.2. The collected data were specific and included information on microplastics type, size, chemicals, and their AC from published reports, papers, and books as well as health guideline and/or standard values obtained from various regulatory jurisdictions. Assigned parameters are those that were selected for analysis. They included: seven different microplastics types, five shapes for each microplastics type, and a range of diameters for each microplastics type. Processed parameters were values calculated using data from the collected and assigned parameters.

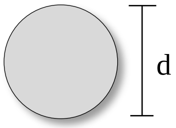
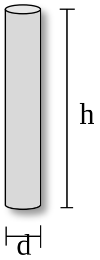
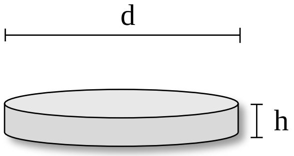
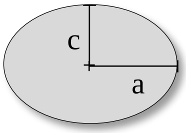
Table 4.2: Literature-acquired and processed/assigned data used in the calculation of TMC.

| | **Input parameters** | | **Output parameter** |
|---|---|---|---|
| | Literature acquired | Processed/assigned | |
| **Microplastics** | Type | Size range (1 µm – 750 µm) | Threshold Microplastics Concentration (TMC) |
| | Size | Shapes (sphere, long and short cylinders, oblate spheroids e = 0.1 and 0.9) | |
| | Density ($\rho$) | | |
| | | Surface area of one particle, $A_{ij}$ ($m^2$) | |
| | | Volume of one particle, $V_{ij}$ ($m^3$) | |
| | | Total particles per gram of microplastics (N) | |
| | | Total surface area per gram of microplastics calculated from literature-acquired data, $\mathrm{TSA}_{\mathrm{LA}_{\mathrm{ijp}}}$ ($m^2$/g) | |
| **Chemicals** | Adsorption capacity ($AC_{LA}$ mg/g) | Total surface area per gram of microplastics of assigned size range ($TSA_{ijp}$) ($m^2$/g) | |
| | | Normalized adsorption capacity $AC_M$, (mg/g) | |
| | Drinking water guideline/standard value ($H_x$) | | |
| | | Adsorption capacity based on surface area, $R_A$ (mg/ $m^2$) | |

i = size of microplastics (1 to 5000 µm for literature-acquired; 1 to 750 µm for assigned data;
j = shape of microplastics (sp, lc, sc, os_0.2 and os_0.9); p = type of microplastics (PS, PP, PE, PET, HDPE, PC, PVC)

A series of calculations were performed to generate TMC based on all the different combinations of microplastics type, shape, and size. Total adsorption/desorption of chemicals was assumed to be a function of only the TSA of microplastics. $AC_{LA}$ was assumed to be proportional to the calculated $TSA_{ijp}$ and $TSA_{LA}$. It was also assumed that $AC_{LA}$ was similar on different types of microplastics. The $TSA_{ijp}$ is a measure of the total surface areas of all microplastics particles per gram of a specific type and size of microplastic, calculated using its density ($\rho$). For a microplastics type, size and shape, the volume ($V_{ij}$) and surface area ($A_{ij}$) of a single particle was calculated using established geometric formula (Table 4.3).

Table 4.3: Shapes considered in the model and their formula for total surface area and volume.

| **Shape** | **Surface area (A)** | **Volume (V)** |
|---|---|---|
| Sphere<br> | $4\pi\times(\frac{d}{2})^2$ | $\frac{4}{3}\pi\times(\frac{d}{2})^3$ |
| Long cylinder<br> <br>d:h = 1:10 | $2\pi h\times(\frac{d}{2})+2\pi\times(\frac{d}{2})^2$ | $\pi\times(\frac{d}{2})^2\times h$ |
| Short cylinder<br> <br>d:h = 10:1 | | |
| Oblate spheroid<br> <br>a > c | $2\pi a^2+\pi\times\frac{c^2}{e}\log(\frac{1+e}{1-e})$<br>$e=\sqrt{1-\frac{c^2}{a^2}}$ | $\frac{4}{3}\pi\times a^2c$ |

The total number of particles per gram (*N*) was calculated as follows:

$$N_{ijp} = \frac{1}{\rho_p \times V_{ij}} \tag{1}$$

Here $V_{ij}$ corresponds to the volume of a particle which varies with shape (i) and size (j). The density of microplastic, $\rho_p$ , depends on the type of microplastic. The total number of particles per mass, $N_{ijp}$, using Equation 1, which is a function of the microplastics type, size, and shape.

$$TSA_{ijp} = N_{ijp} \times A_{ij} \tag{2}$$

The $TSA_{ijp}$ (Eq 2) is the total surface area per gram of a particular type, size, and shape of microplastics which is a product of $N_{ijp}$ and $A_{ij}$, where $A_{ij}$ is surface area of a single particle of a particular size and shape. Values of $TSA_{ijp}$ can therefore be calculated which varies with microplastics type, size, and shape.

$$AC_M = AC_{LA} \times \frac{TSA_{ijp}}{TSA_{LA_{ijp}}} \tag{3}$$

$AC_M$ was calculated to estimate AC for different type, size, and shape of microplastics using $AC_{LA}$. Total surface area per gram was normalized as, $\frac{TSA_{ijp}}{TSA_{LA_{ijp}}}$, to calculate the $AC_M$ from $AC_{LA}$ of a contaminant for a combination of microplastics type, size, and shape using Eq 3.

$$R_A = \frac{AC_{LA}}{TSA_{LA_{ijp}}} \tag{4}$$

Sorption capacity based on surface area, $R_A$ (mg/m$^2$) was derived using $AC_{LA}$ (mg/g) and $TSA_{LA_{ijp}}$(m$^2$/g) and hence was a function of microplastics size (i), shape (j), and type (p).

The total surface area per gram of microplastics based literature-acquired data, $TSA_{LA_{ijp}}$, was calculated using:

$$\mathrm{TSA}_{\mathrm{LA}_{\mathrm{ijp}}} = \mathrm{N}_{\mathrm{i,j,p}} \times \mathrm{A}_{\mathrm{i,j}} \tag{5}$$

Shapes of microplastics particles were not reported in research reports from where data were collected. Therefore, in calculating $\mathrm{TSA}_{\mathrm{LA}_{\mathrm{ijp}}}$ different shapes were assumed. While the microplastics types used for the experiments were reported, data for a contaminant was available for only one and not all the different types of microplastics that were considered in this analysis. So, it was assumed that the $AC_{LA}$ of a specific contaminant was the same on all the microplastics types, which may or may not be the case. $\mathrm{TSA}_{\mathrm{LA}_{\mathrm{ijp}}}$ was therefore a function of shape and type.

$$\mathrm{TMC} = \frac{\mathrm{H_x}}{\mathrm{AC_M}} \times \mathrm{N_{ijp}} \tag{6}$$

For the last step, drinking water guideline/standard values ($H_x$) of different contaminants were used to calculate the total number of microplastics particles per liter of untreated (source) water (Equation 6), expressed as the Threshold Microplastics Concentration (TMC), on which the mass of adsorbed contaminants would be equal to the lowest maximum contaminant level (MCL) or maximum acceptable concentration (MAC) of a regulated contaminant.

A simplified equation for TMC is:

$$\mathrm{TMC} = \frac{\mathrm{H_x}}{\mathrm{A_{ij}} \times (\frac{\mathrm{AC_{LA}}}{\mathrm{TSA_{ijp}}})} \tag{7}$$

A sample series of calculation to determine TMC is presented in Appendix B

The parameters analyzed using this model are shown in Table 4.4. A total of seven different types of microplastics based on chemical composition were assigned based on their abundance and relevance in freshwater environments. The size of particles was chosen to represent microplastics of sizes commonly encountered in freshwater environments and in the size range that could be of human health concern if consumed. A range of sizes enabled to investigation of trends based on particle size. For certain industrial and commercial applications, such as cosmetic products and paints, plastics are manufactured in specific shapes in a specific microplastics size range. In addition, plastics in freshwater and marine environments undergo physical and chemical stress due to UV radiation, and the mechanical action of waves which lead to their breakdown to form microplastics. As a result, they form irregular shapes and sizes. Microplastics are, therefore, found in the environment in regular and irregular shapes of varying surface areas. The shapes assessed herein were intended to represent the wide range of surface areas of different microplastics shapes typically found in the environment (Table 4.4). The spherical and oblate spheroids were representative of pellets and microbeads while long and short cylinders were analyzed to represent fibers and discs respectively, all of which are among the commonly detected shapes of microplastics in the environment (Chubarenko et al., 2016). Sizes were assigned to a certain dimension of the shape of microplastic. For instance, 1 µm for spheres, cylinders and oblate spheroids corresponds to the diameter, cross sectional diameter, and equatorial diameter, respectively.

Table 4.4: Microplastics types, diameters, and shapes, and chemical contaminants and associated health guidelines used the MIHRA assessment and TMC calculation.

| **MP type** | **Diameter (µm)** | **Shape** | **Contaminants** | **Health guidelines** |
|---|---|---|---|---|
| Polycarbonate (PC)<br>Polyethene (PE)<br>Polyethylene terephthalate (PET)<br>Polypropylene (PP)<br>Polystyrene (PS)<br>Polyvinylchloride (PVC)<br>High density polyethylene (HDPE) | 1<br>10<br>20<br>50<br>100<br>150<br>300<br>500<br>750 | sphere (sp)<br>long cylinder (fibres) (lc)<br>short cylinders (sc)<br>oblate spheroid (ellipticity = 0.2) (os_0.2)<br>oblate spheroid (ellipticity = 0.9) (os_0.9) | aluminum<br>antimony<br>arsenic<br>benzene<br>bisphenol A<br>bromine<br>cadmium<br>lead<br>manganese<br>mercury<br>propanolol | DWEL<br>reference dose<br>one-day HA:<br>ten-day HA:<br>lifetime HA<br>MCL<br>lowest PNEC |

DWEL: drinking water equivalent level; HA: health advisory; MCL: maximum contaminant level; PNEC – predicted no effect concentration

A total of seven different health guidelines from various regulatory agencies (USEPA, 2018; WHO, 2012; Australian Drinking Water Guidelines, 2013) were reviewed for every chemical contaminant included in the assessment—these are listed in Table 4.4. TMCs were calculated based on lowest value (most conservative) of the listed health guideline standards for a specific contaminant.

**Data organization**

A list of contaminants for which experimental $AC_{LA}$ on microplastics were available and their established health guidelines ($H_x$) were generated from literature. A comprehensive document containing all the required information was not available and had to be compiled from multiple sources. All relevant information, collected and calculated, was organized in MS Excel® and all subsequent calculations for the analysis were performed using functions in MS Excel®. The organized spreadsheet file formed the base of all subsequent calculations and analyses. A separate sheet (Table 4.5) was used to create a matrix for calculating TMCs based on all combinations of the factors (contaminant, shape, microplastics type and size). The sequence of calculations is represented in Figure 4.3 below.

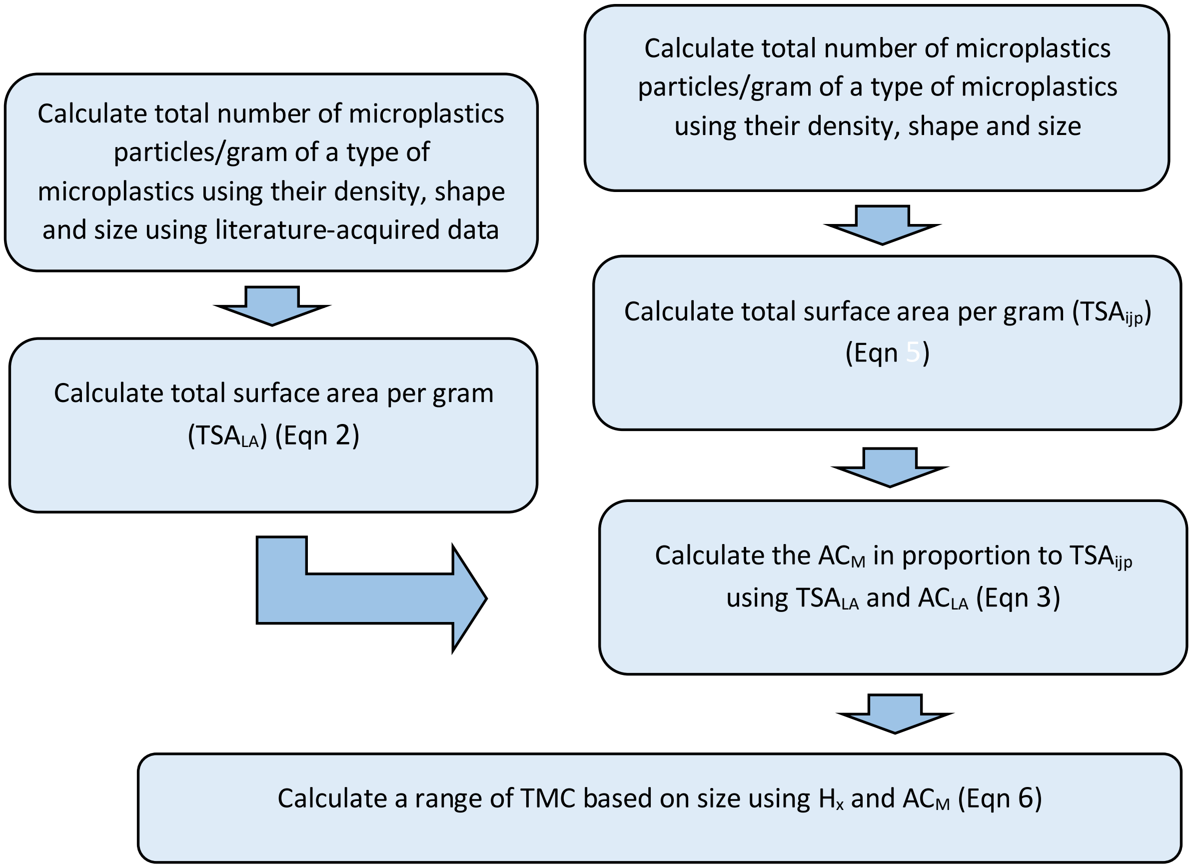


Figure 4.3: Overview of the TMC calculation process.

A matrix of calculated TMCs was prepared in MS Excel® as shown in Table 4.5 which represents the template used to calculate the TMC with respect to a given contaminant based on different combinations of factors. A complete data set consisting of TMCs for all the contaminants analyzed in this assessment was prepared and then used to plot TMC curves with TMC on the y-axis and microplastics size on the x-axis. TMC curves could then be plotted for different combinations of factors, individual contaminants, or a plot consisting of all the contaminants chosen for assessment.

Table 4.5: A data matrix template for calculating TMCs from different combinations of contaminants and microplastics types, shapes, and sizes.

| | | | **TMC (particles/L)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Size of microplastics (µm)** | | | | | | | | |
| **Contaminant** | **Microplastic** | **Shape** | **1** | **10** | **20** | **50** | **100** | **150** | **300** | **500** | **750** |
| aluminum | HDPE | SP | | | | | | | | | |
| | HDPE | LC | | | | | | | | | |
| | HDPE | SC | | | | | | | | | |
| | HDPE | OS_0.2 | | | | | | | | | |
| | HDPE | OS_0.9 | | | | | | | | | |
| | PC | SP | | | | | | | | | |
| | PC | LC | | | | | | | | | |
| | PC | SC | | | | | | | | | |
| | PC | OS_0.2 | | | | | | | | | |
| | PC | OS_0.9 | | | | | | | | | |
| | PE | SP | | | | | | | | | |
| | PE | LC | | | | | | | | | |
| | PE | SC | | | | | | | | | |
| | PE | OS_0.2 | | | | | | | | | |
| | PE | OS_0.9 | | | | | | | | | |
| | PET | SP | | | | | | | | | |
| | PET | LC | | | | | | | | | |
| | PET | SC | | | | | | | | | |
| | PET | OS_0.2 | | | | | | | | | |
| | PET | OS_0.9 | | | | | | | | | |
| | PP | SP | | | | | | | | | |
| | PP | LC | | | | | | | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | PP | SC | | | | | | | | | |
| | PP | OS_0.2 | | | | | | | | | |
| | PP | OS_0.9 | | | | | | | | | |
| | PS | SP | | | | | | | | | |
| | PS | LC | | | | | | | | | |
| | PS | SC | | | | | | | | | |
| | PS | OS_0.2 | | | | | | | | | |
| | PS | OS_0.9 | | | | | | | | | |
| | PVC | SP | | | | | | | | | |
| | PVC | LC | | | | | | | | | |
| | PVC | SC | | | | | | | | | |
| | PVC | OS_0.2 | | | | | | | | | |
| | PVC | OS_0.9 | | | | | | | | | |

### 4.3.2 Threshold Microplastics Concentration (TMC)

The concept of a Threshold Microplastics Concentration (TMC) was developed as a result of the analysis based on the MIHRA framework. TMC indicates the total number of microplastics particles per liter of untreated (source) water, which if consumed may lead to exposure to potentially harmful concentrations of chemical contaminants because of the sorbed contaminants on and in microplastics. As summarized in Table 4.4., the reference chemical concentrations used to derive a TMC were collected from heath guideline documents issued by the World Health Organization, United States Environmental Health and Protection Agency, and Health Canada. The TMC is analogous to the Maximum Contaminant Level (MCL) which is the maximum concentration of a contaminant that is acceptable in drinking water. A low TMC is indicative of higher risk, meaning that a small number of microplastics particles can potentially lead to exposure to contaminants at concentrations that exceed drinking water guidelines. To calculate the TMC, seven types of microplastics (PE, PET, HDPE, PP, PC, PS and PVC), five shapes (sphere, long and short cylinder, oblate spheroid (ellipticity, e=0.1 and 0.9)) and a range of size

(1 to 750 µm) were identified as factors to adequately describe a TMC and calculate values for different combinations of microplastics and contaminants. The output of the model calculation allows for the identification of a microplastics concentration of concern in different systems (surface water or subsurface environment) that can be used as guidance for operators in utilities when source water also contains elevated concentrations of regulated chemical contaminants.

### 4.3.3 Microplastics Calculator

Based on the outlined conceptual model for evaluating potential health risks from contaminants sorbed on and in microplastics, a "Microplastics Calculator" was developed. This is a program developed in MS Excel® which takes microplastics type, shape, and size as well as contaminant type and AC as inputs and calculates a TMC for the selected type of microplastics in the size range 1 µm to 750 µm. The Microplastics Calculator is divided into four sections. The first is for data input; these data are used to calculate intermediate values using pre-set equations that are automatically called by the program based on conditional statements that determine which equation should be used based on the input parameters. For instance, if a spherical shape is chosen, equations for calculating surface area and volume of a sphere are automatically identified and calculated. The first section is for user input as shown in Table 4.6 where the "Input Parameters" are microplastics type, shape, contaminant, $AC_{LA}$ and size of the microplastics particles used in the sorption study from where data was acquired. Data from "Input Parameters" and "Processed Data" were fundamental for subsequent calculations. Output of calculations from these pre-set equations are presented Table 4.7 and Table 4.8.

Table 4.6: Example of data utilized to calculate the TMC using the Microplastics Calculator.

| **Input parameters** | | **Processed data** | |
|---|---|---|---|
| Microplastics type | Polyvinylchloride | Volume ($cm^3$)/g of microplastics | 0.72 |
| Microplastics shape | Sphere | Volume per particle ($\mu m^3$) | 523598776 |
| Contaminant | Antimony | Surface area per particle ($\mu m^2$) | 3141593 |
| AC (mg of chemicals/g of microplastics) | 27.8 | No. of microplastics/g (N) | 1375 |
| Microplastics size in report (µm) | 1000 | Total surface area ($m^2$)/g | 0.00432 |
| | | Polar radius (for oblate spheroids) | Only for oblate spheroids |

The second section of the microplastics calculator is programmed to automatically calculate particles/g, TSA ($m^2$/g), $AC_M$ and $R_A$ for microplastics in the size range 1 µm to 750 µm (Table 4.7). $R_A$ is calculated for all the contaminants analyzed to account for different particle shapes and sizes. The literature-acquired data did not contain information of microplastics shape, so normalization from reported unit of mg/g to mg/$m^2$ ($R_A$) was done assuming a particular shape and calculated according to Equation 3 and (*4*.

Table 4.7: Example processed data outputs from the Microplastics Calculator.

| Size (µm) | Particles/g | TSA ($m^2$/g of microplastic) | $AC_{LA}$ (mg of chemicals/g of microplastic) | $AC_M$ (mg/g) | $R_A$ (mg/$m^2$) |
|---|---|---|---|---|---|
| 1 | 1.4E+12 | 4.32 | 27.8 | 27800 | 6435 |
| 10 | 1.4E+09 | 0.43 |  | 2780 |  |
| 20 | 1.7E+08 | 0.22 |  | 1390 |  |
| 50 | 1.1E+07 | 0.09 |  | 556 |  |
| 100 | 1.4E+06 | 0.04 |  | 278 |  |
| 150 | 4.1E+05 | 0.03 |  | 185 |  |
| 300 | 5.1E+04 | 0.01 |  | 93 |  |
| 500 | 1.1E+04 | 0.01 |  | 56 |  |
| 750 | 3.3E+03 | 0.01 |  | 37 |  |

In the third section, TMCs are calculated for different sizes of microplastics with based on the shortlisted health guideline of all the contaminants analyzed in this research. Health guideline data are stored in a separate sheet and linked to the “Contaminant” field in “Input Parameters” and the field “Standard value” (Table 4.8) was automatically populated with data based on the contaminant selection in the first section of the microplastics calculator. At least one reference health standard was available for all the analyzed contaminants. Finally, all of the calculated values are used to generate a matrix of TMC based on size and health standard.

Table 4.8: Example Microplastics Calculator calculations of health-based guideline concentrations (Table 2.10) for a given contaminant.

| **Health guideline reference** | One-day (mg/L) | Ten-day (mg/L) | RfD (mg/day) | DWEL (mg/L) | Life-time (mg/L) | MCL (mg/L) | Lowest PNEC (mg/L) |
|---|---|---|---|---|---|---|---|
| **Standard value** | 0.01 | 0.01 | 0.004 | 0.01 | 0.006 | 0.006 | 0 |
| **Microplastics size (µm)** | TMC | | | | | | |
| 1 | 4.946E+08 | 4.946E+08 | 1.979E+08 | 4.946E+08 | 2.968E+08 | 2.968E+08 | 0.000E+00 |
| 10 | 4.946E+06 | 4.946E+06 | 1.979E+06 | 4.946E+06 | 2.968E+06 | 2.968E+06 | 0.000E+00 |
| 20 | 1.237E+06 | 1.237E+06 | 4.946E+05 | 1.237E+06 | 7.420E+05 | 7.420E+05 | 0.000E+00 |
| 50 | 1.979E+05 | 1.979E+05 | 7.914E+04 | 1.979E+05 | 1.187E+05 | 1.187E+05 | 0.000E+00 |
| 100 | 4.946E+04 | 4.946E+04 | 1.979E+04 | 4.946E+04 | 2.968E+04 | 2.968E+04 | 0.000E+00 |
| 150 | 2.198E+04 | 2.198E+04 | 8.794E+03 | 2.198E+04 | 1.319E+04 | 1.319E+04 | 0.000E+00 |
| 300 | 5.496E+03 | 5.496E+03 | 2.198E+03 | 5.496E+03 | 3.298E+03 | 3.298E+03 | 0.000E+00 |
| 500 | 1.979E+03 | 1.979E+03 | 7.914E+02 | 1.979E+03 | 1.187E+03 | 1.187E+03 | 0.000E+00 |
| 750 | 8.794E+02 | 8.794E+02 | 3.517E+02 | 8.794E+02 | 5.276E+02 | 5.276E+02 | 0.000E+00 |

In the fourth section, a graph of TMC as a function of microplastics size (Figure 4.4)—the TMC curve—is automatically plotted. For all cases, the lowest TMC (i.e., the most concerning TMC reflecting the greatest potential health risk) was associated with the health-based standard with the lowest value, as would be expected. For instance, as can be seen in Table 4.8**,** the lowest TMC was calculated for an RfD assuming a 10 kg child having a value of 0.004 mg/day. In all cases, the lowest health-based guideline reference was used to generate TMCs.

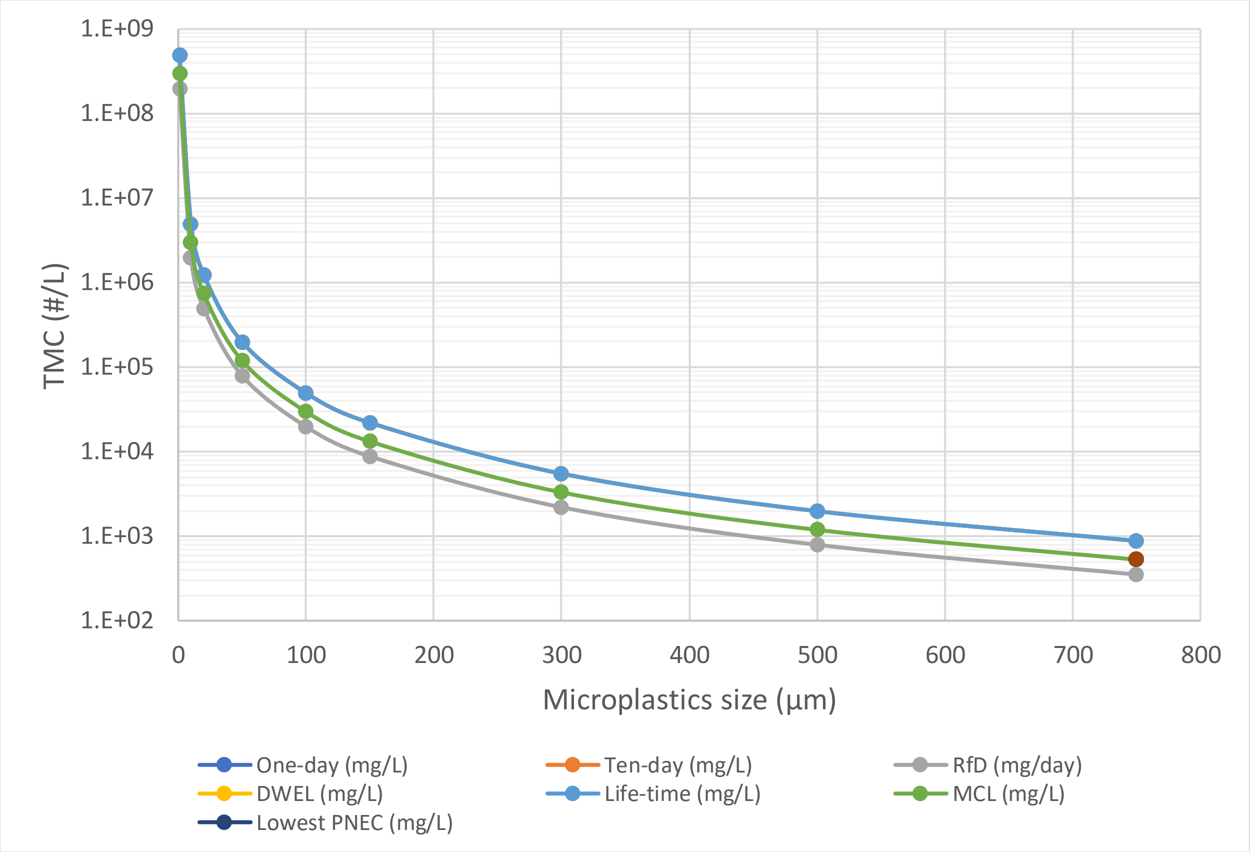


Figure 4.4: An example of TMC curves generated by the Microplastics Calculator.

The Microplastics Calculator enabled analysis of the impacts of various factors (e.g., $AC_{LA}$, TSA, $H_x$, shape and size of microplastics) on TMC. It can work as a tool to calculate TMCs based on contaminants sorbed on microplastics on a case-by-case basis. It is also modular, thereby readily enabling updating as more contaminant sorption and toxicity data become available.

A user-friendly version of the Microplastics Calculator was developed using Visual Basic®. The program initiates with a screen (Figure 4.5) asking for user input of data such as: microplastics type, microplastics shape, contaminant, AC and microplastics size.

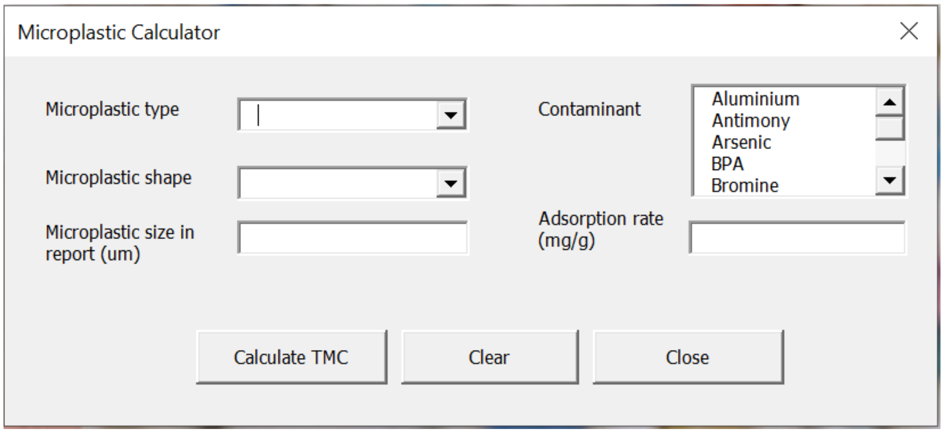
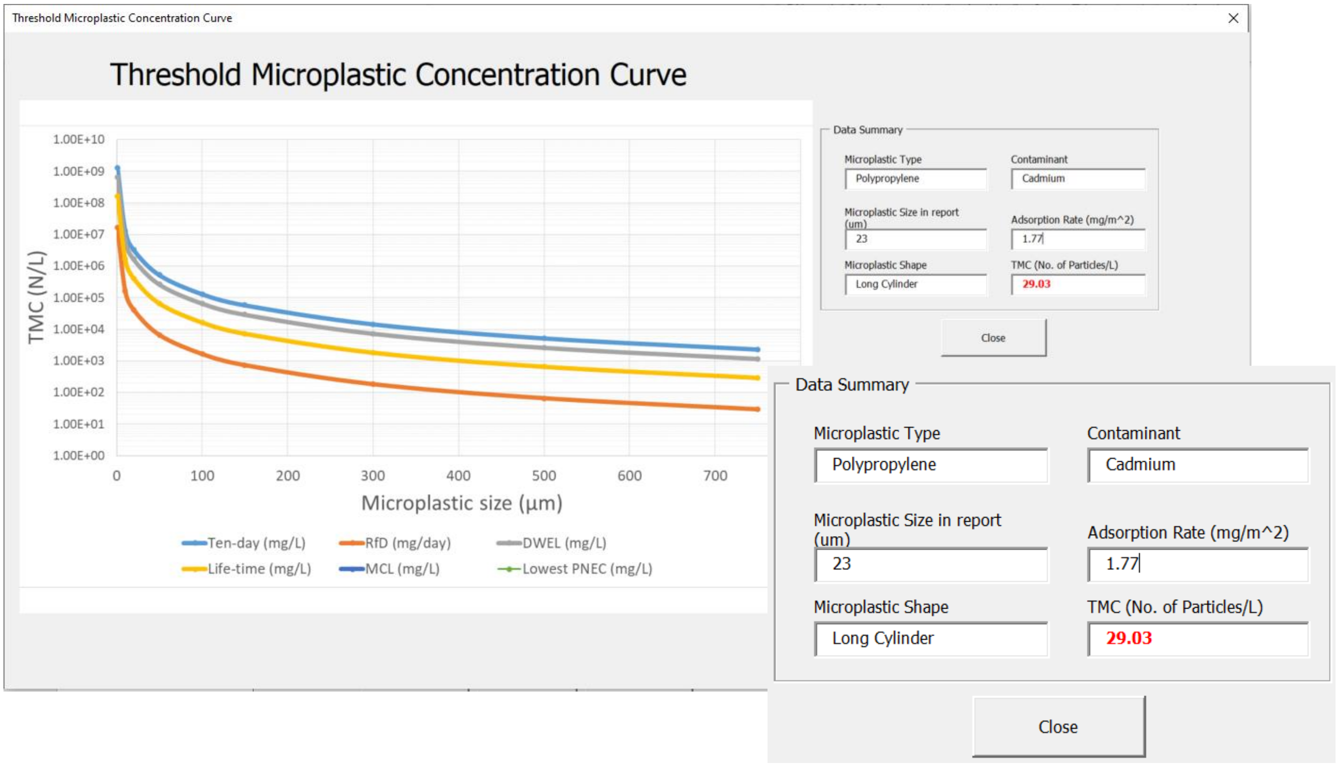


Figure 4.5: Microplastics Calculator user input screen.

Based on input data in the designated fields, an output window is generated (Figure 4.6) upon clicking the ‘Calculate TMC’ command button. This window shows a TMC curve along with a summary section consisting of important data relevant to the case.



Microplastic Type: Polypropylene

Contaminant: Cadmium

Microplastic Size in report (um): 23

Adsorption Rate (mg/m^2): 1.77

Microplastic Shape: Long Cylinder

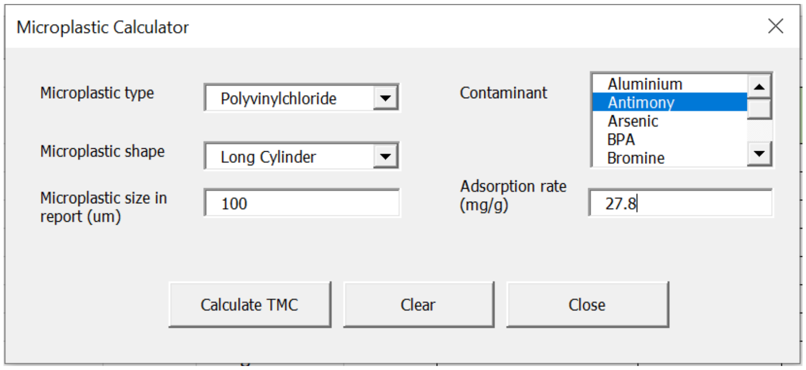
TMC (No. of Particles/L): **29.03**

Figure 4.6: Microplastics Calculator output page consisting of a TMC curve and summary of data associated with its calculation.

Box: Case study

A sample from a drinking water treatment plant influent port was found to be contaminated with microplastics. The type of microplastics was not identified but a concentration of approximately 35 particles per liter of water was quantified. Water quality reports revealed the presence of antimony in water samples collected at the same time. Preliminary visual identification suggested that the microplastics ranged approximately between 20 µm to 750 µm. From available database, the $AC_{LA}$ (mg/g) of antimony onto 100 µm sized polyvinylchloride microplastics was reported to be 27.8 mg/g.

Microplastics calculator:



Microplastic Calculator

Microplastic type: Polyvinylchloride

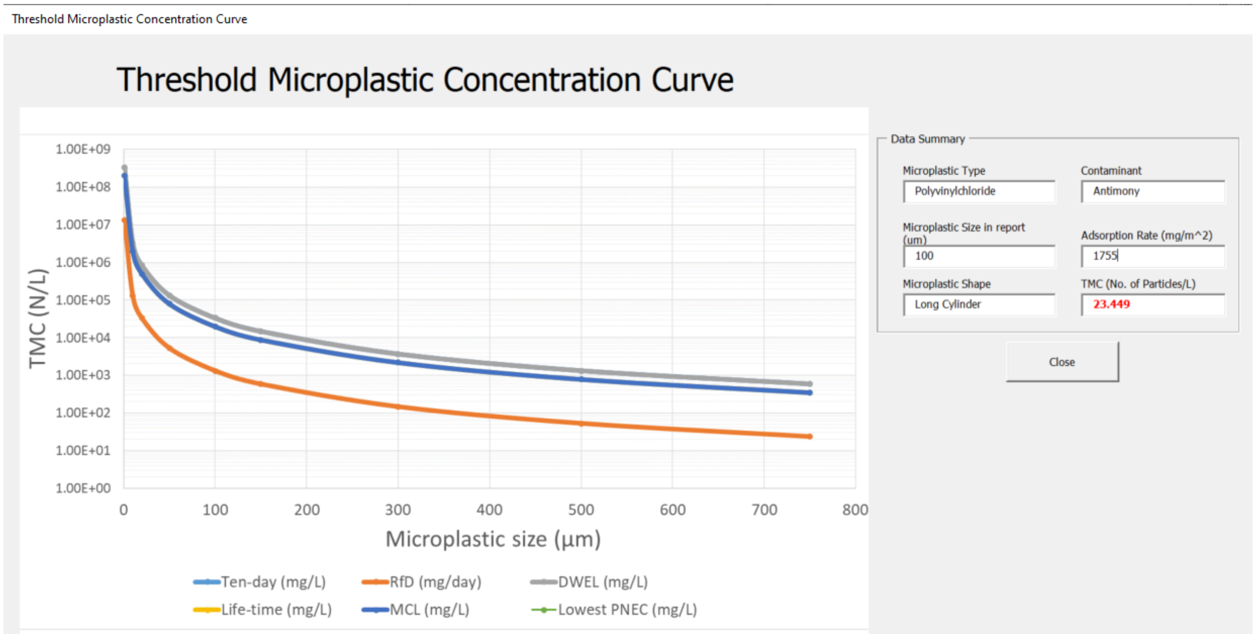
Microplastic shape: Long Cylinder

Microplastic size in report (um): 100

Contaminant: Antimony

Adsorption rate (mg/g): 27.8

Since the type and shape of microplastics in the influent water has not been identified, it is reasonable to use PVC and long cylinders to calculate the most conservative estimation of *TMC*. After all relevant information is entered into their appropriate fields, 'Calculate TMC' command is clicked which results in:



Threshold Microplastic Concentration Curve

Data Summary

Microplastic Type: Polyvinylchloride

Contaminant: Antimony

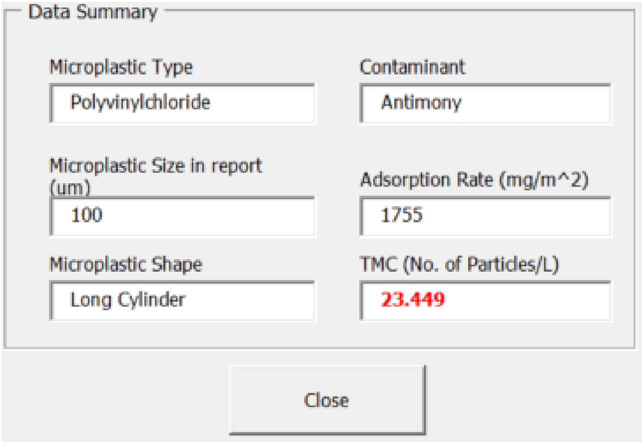
Microplastic Size in report (um): 100

Adsorption Rate (mg/m^2): 1755

Microplastic Shape: Long Cylinder

TMC (No. of Particles/L): 23.449

…continued


Data Summary

Microplastic Type: Polyvinylchloride

Contaminant: Antimony

Microplastic Size in report (um): 100

Adsorption Rate (mg/m^2): 1755

Microplastic Shape: Long Cylinder

TMC (No. of Particles/L): 23.449

Calculations based on data from this case result in a TMC of ~ 24 particles per liter of source water and the detected concentration of 35 particles/L is higher than the TMC. Interpretation of what this means is discussed in section 4.3.5.

### 4.3.4 Analysis of calculation parameters

The relative effects of all the parameters contributing to TMC calculation—a model sensitivity analysis— are presented in this section. The discussion is conducted in two parts. In the first part, the data and calculations used to generate processed data are analyzed. In the second part, the output from the model (the TMC) is analyzed with respect to the associated factors and observations are discussed.

**i) Literature acquired, assigned, and processed data**

#### 4.3.4a) Total surface area ($TSA_{ijp}/TSA_{LA}$)

The total surface area per gram of microplastics ($TSA_{ijp}/TSA_{LA}$) decreases with increasing size of the particles. The decrease in TSA is as expected because, for a given microplastics type and shape, there are a greater number of particles of small size compared to particles of large size for the same mass (Equation 2). Figure 4.7 illustrates this and it can be seen that the decrease follows a log-linear relationship.

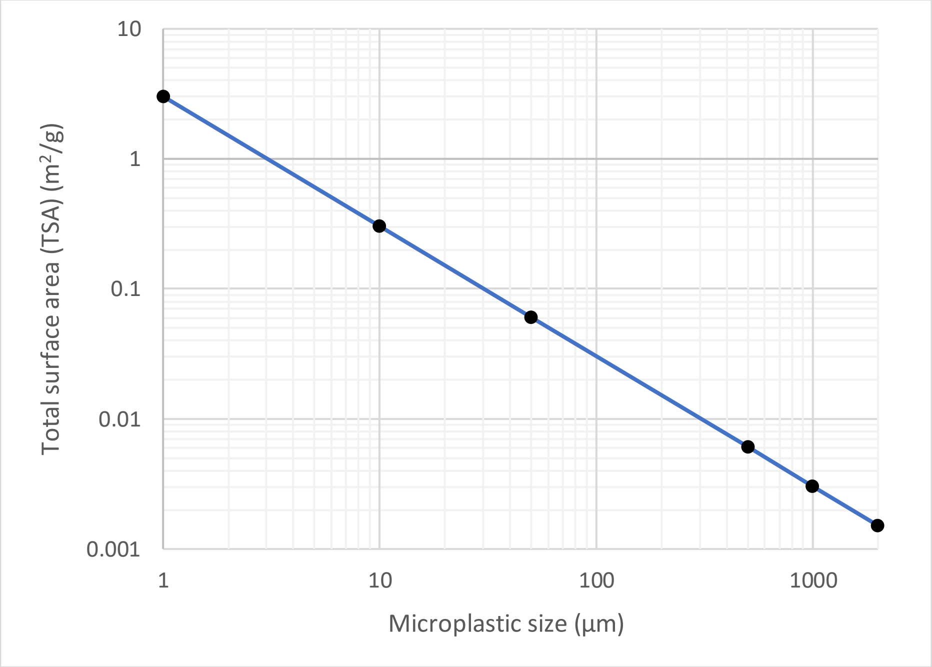


Figure 4.7: Total surface area of LC shaped PVC microplastics of varying particle size on a log-log scale.

### 4.3.4b) Total number of microplastics per gram (N)

The total number of particles per gram of a microplastics (N) (Equation 1) varies with respect to microplastics type, size, and shape. With increasing particle size, N decreases. This is because larger microplastics have higher volume compared to smaller microplastics of same type and shape which results in fewer number of particles per gram. With respect to the microplastics type, PVC had the least number of particles per gram with PET having a slightly higher value. The maximum number of particles was found for PP and this was attributable to their densities. Particles of higher densities are expected to have fewer N compared to particles of lower densities of same shape and size. The calculations confirm this as can be seen in Figure 4.8b**.** Long cylinders and short cylinders were found to result in the least and highest N, respectively. The relative N with respect to shape is attributable to their volume. In increasing order of volume of a single particle, the N based on shapes followed the order LC < SP < OS_0.2 < OS_0.9 < SC (Figure 4.8).

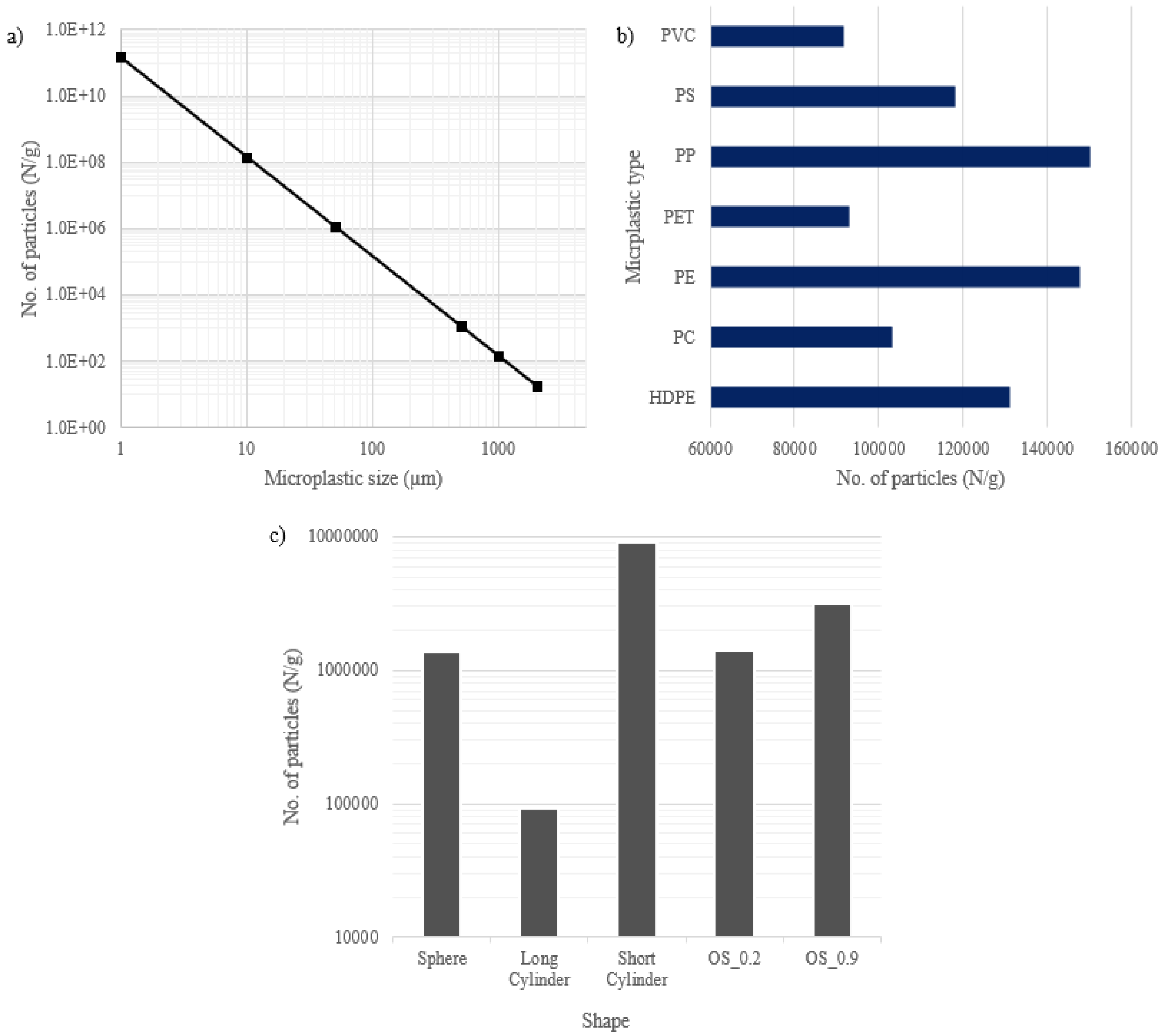


Figure 4.8: Total number of microplastics particles per gram of microplastics presented with respect to microplastics size (a), type (b), and shape (c).

### 4.3.4c) Adsorption capacities (AC and $R_A$)

$AC_{LA}$ were reported as milligrams of contaminant per gram of microplastics (mg/g) which was used to convert to $R_A$, (mg/m$^2$) based on microplastics size and assuming the different shapes identified for this study (Equation 4). $R_A$ was therefore dependent on the size of microplastics. For different microplastics sizes, the total surface areas changed, as did the AC. For instance, considering the sorption data collected for aluminum, 0.375 mg/g of aluminum is assumed to be adsorbed onto the total surface area per gram of 2 mm sized PET microplastics. The $AC_{LA}$ of

0.375 mg/g converted to mg of aluminium per total surface area per gram of 2 mm sized spherical PET microplastics is 171.2 mg/m$^2$. This value changes to 85.6 mg/m$^2$ when 1 mm size of the same microplastics is used in the calculation. This explains the effect of microplastics size used in experiments on their $R_A$. As illustrated in Figure 4.9, $R_A$ is proportional to the size of microplastic. When large microplastics sizes were used in original sorption experiments, a higher $R_A$ is derived.

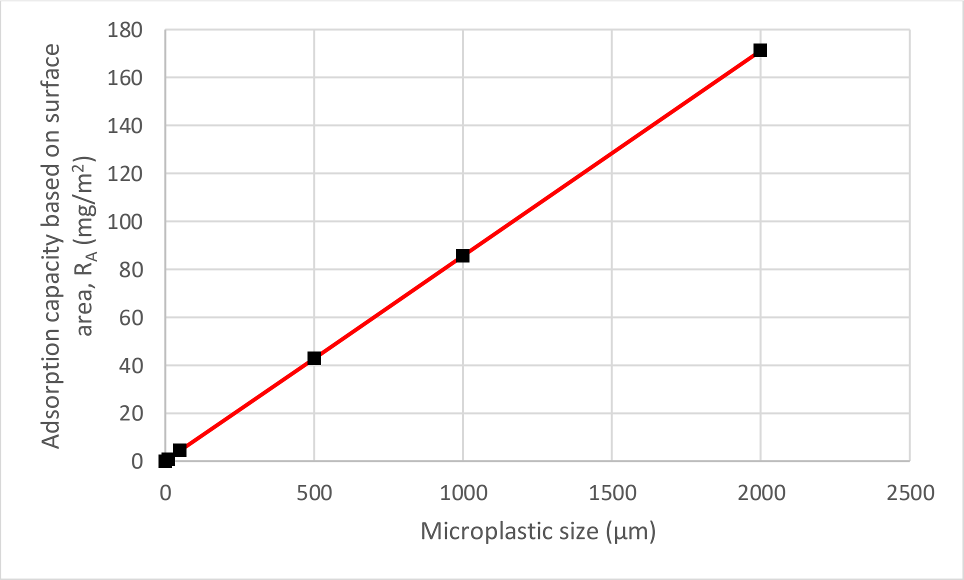


Figure 4.9: $R_A$ of aluminum on spherical polyethylene terephthalate (PET) microplastics.

### ii) Effects of factors on TMC

The entire set of TMC curves generated in this analysis was plotted as a function of microplastics size (Figure 4.10). Here the x-axis (microplastics size) was evaluated for the purpose of curve visualization—the sizes of microplastics that were evaluated were arbitrary. These curves will be presented as continuous functions to facilitate interpretation in the discussion below.

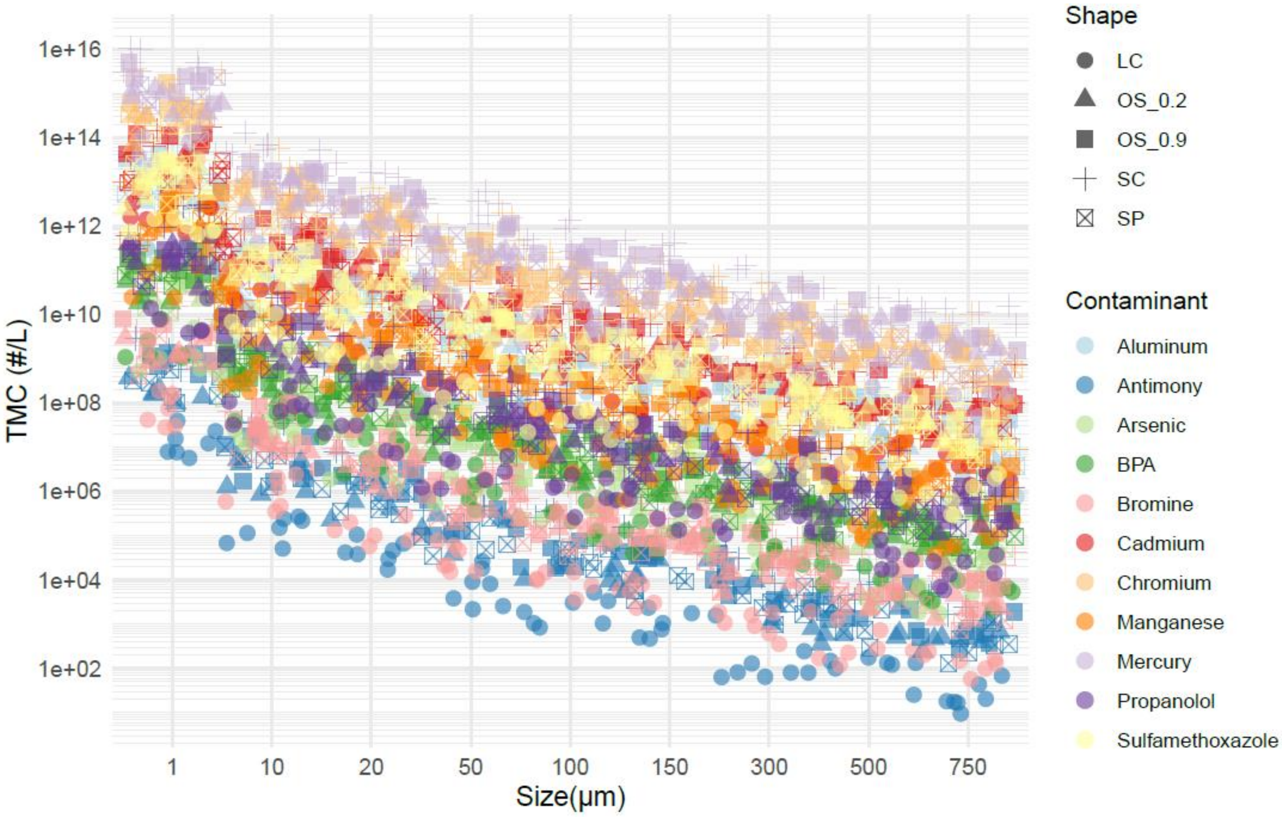


Figure 4.10: Threshold microplastics concentration (TMC) curve for all combinations of chemicals and microplastics sizes, shapes, and types included in the Microplastics Calculator.

In general, TMCs decrease as the microplastics size increases. For all combination of factors, the lowest (most concerning) and highest (least concerning) TMC were associated with the presence of antimony and mercury, respectively. Notably, the lowest and highest TMCs were respectively calculated for long and short cylindrical particles, regardless of the contaminant, and as would be expected based on available, smooth sorptive surface area.

#### 4.3.4d) Size

The effect of size on TMC is based on literature-acquired data and the assigned size range (1 µm to 750 µm). A large microplastic size meant that more contaminants were distributed per surface area than when smaller microplastics were used. This is due to the fact that for larger particle sizes, there are fewer numbers of particles per gram compared to particles of smaller size. This results in a larger total surface area per gram for smaller particles than larger particles. As a result, the TMC was found to be higher for the same $AC_{LA}$ when the literature-acquired size of microplastics is smaller. This is represented in Figure 4.11 which illustrates the variation of TMCs for 750 µm, LC shaped PVC microplastics using sorption data for antimony that have been reported in the literature.

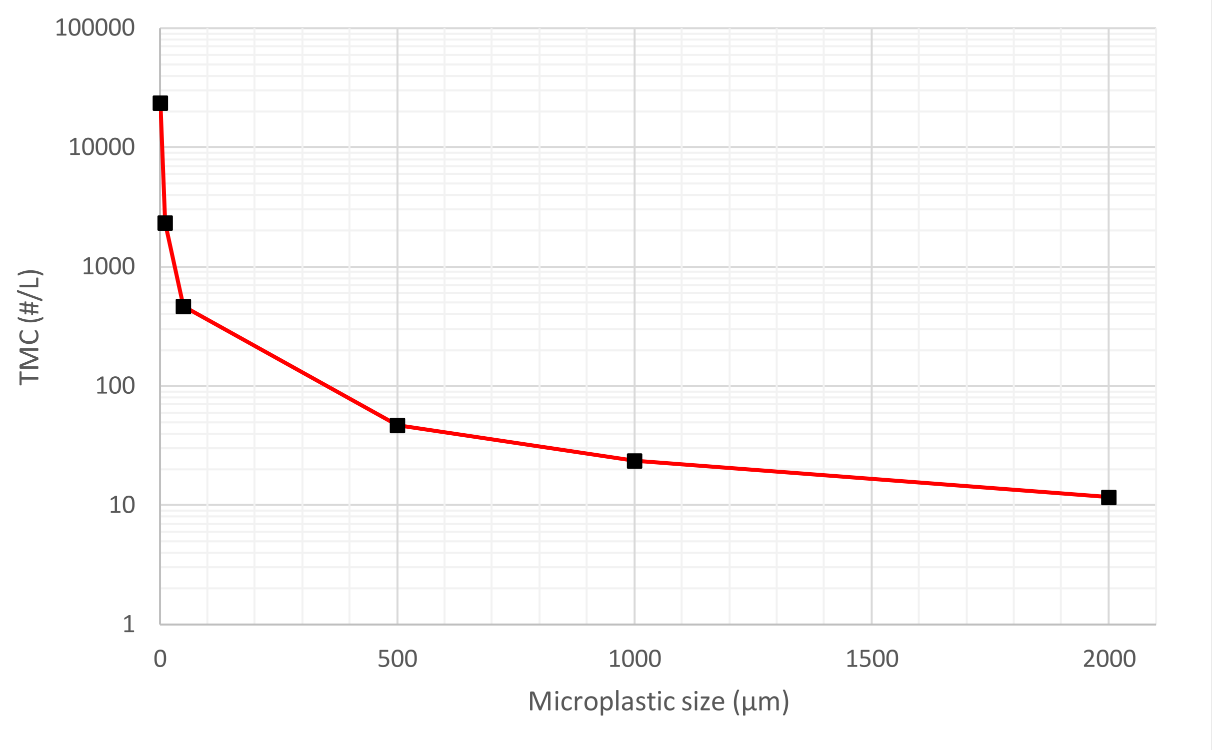


Figure 4.11: TMC with respect to microplastics sizes from literature acquired data generated using the Microplastics Calculator.

TMC also varied similarly with microplastics size—sizes of 1 µm to 750 µm were examined herein because larger microplastics particles would be readily removed during drinking water treatment (MWH, 2012). The mass of contaminants sorbed on microplastics was assumed to occur throughout the total surface area of microplastics. Therefore, for larger microplastics the total contaminant adsorbed is expected to be higher than that of smaller microplastics. This implies that TMC will be high for small microplastics compared to the TMC calculated for large microplastics. The results from the model are illustrated in Figure 4.12, which shows TMC curves for antimony based on all combinations of microplastics type and shape. As microplastics size increased, the corresponding TMC decreased. The highest decrease with increase in microplastics size was found to be the between 1 and 100 µm with a 4-fold decrease in TMC. This was true for all combinations of factors considered in this analysis.

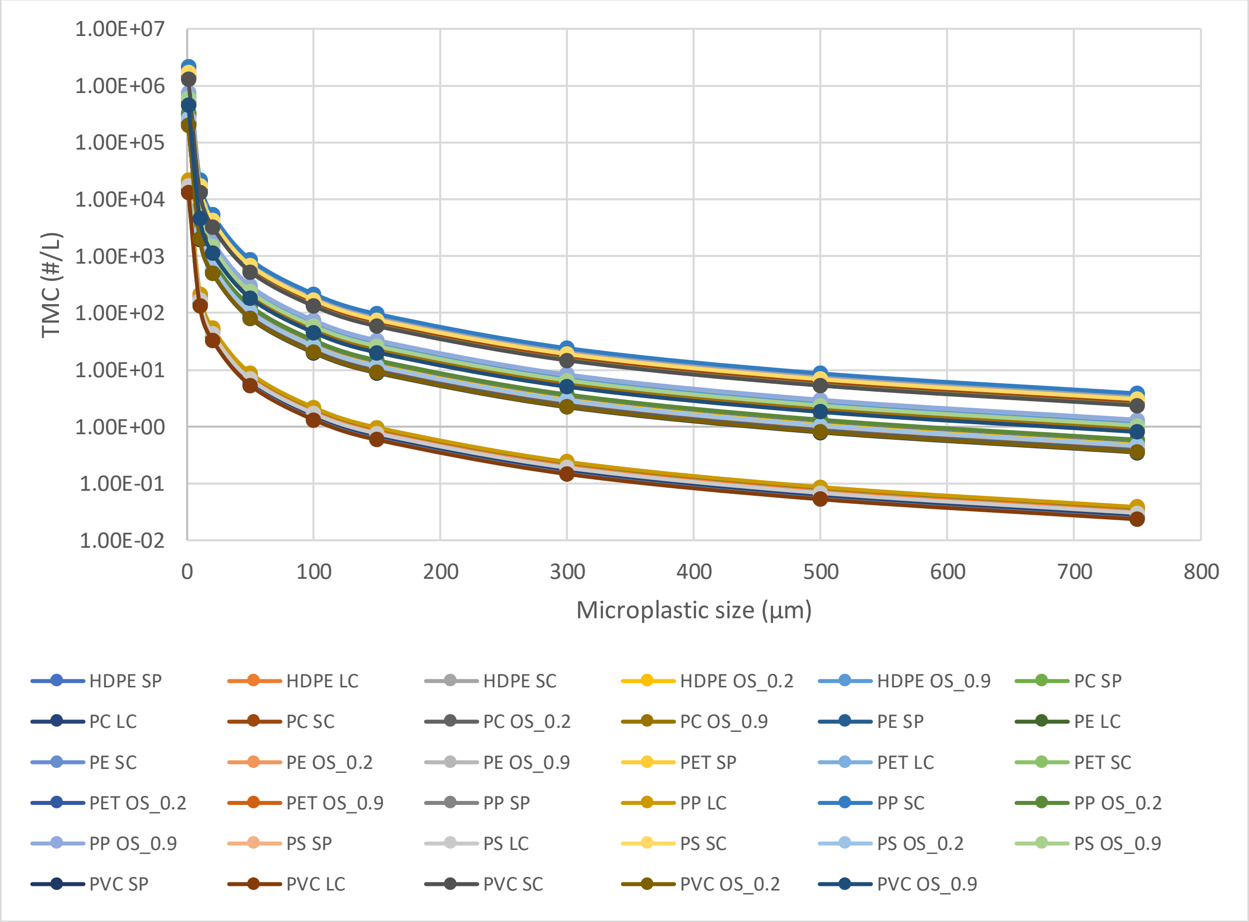


Figure 4.12: TMC curves generated by the Microplastics Calculator for all combinations of microplastics types and shapes using $AC_{LA}$ and health guideline references for antimony.

#### 4.3.4e) Shape

Long cylinders representing fibers were found to generate the lowest TMC values in all of the assessed combinations of contaminants and microplastics types, shapes and sizes. Long cylindrical microplastics particles had the largest individual and total surface area per gram among all the shapes considered in the model which explains their low TMCs. The order of total surface area per gram ($TSA_{ijp}$) of a substance of the shapes analyzed followed an order opposite to their TMC, that is to say high surface area equated to low TMC and higher potential health risk. This was expected since sorption was assumed to occur on all of the available surface area and a larger surface area allows higher quantities of contaminant to be sorbed. Figure 4.13 shows that the TMC for LC microplastics of all types were less than 50% of TMCs calculated for every other shape. The highest TMC was calculated for short cylindrical (disks) microplastics particles. Oblate spheroids with an ellipticity of 0.2 and spheres showed similar results for TMCs. This was because oblate spheroids with no ellipticity (a = c) essentially represents a sphere and with increasing ellipticity (a > c) they become oblate spheroids. Oblate spheroids with an ellipticity of 0.9 followed long cylinders in terms of magnitude of TMC. The sequence of the magnitude of TMC followed the order long cylinder < sphere < oblate spheroid (e=0.2) < oblate spheroid (e=0.9) < short cylinder where highest risk is attributable to the lowest TMC.

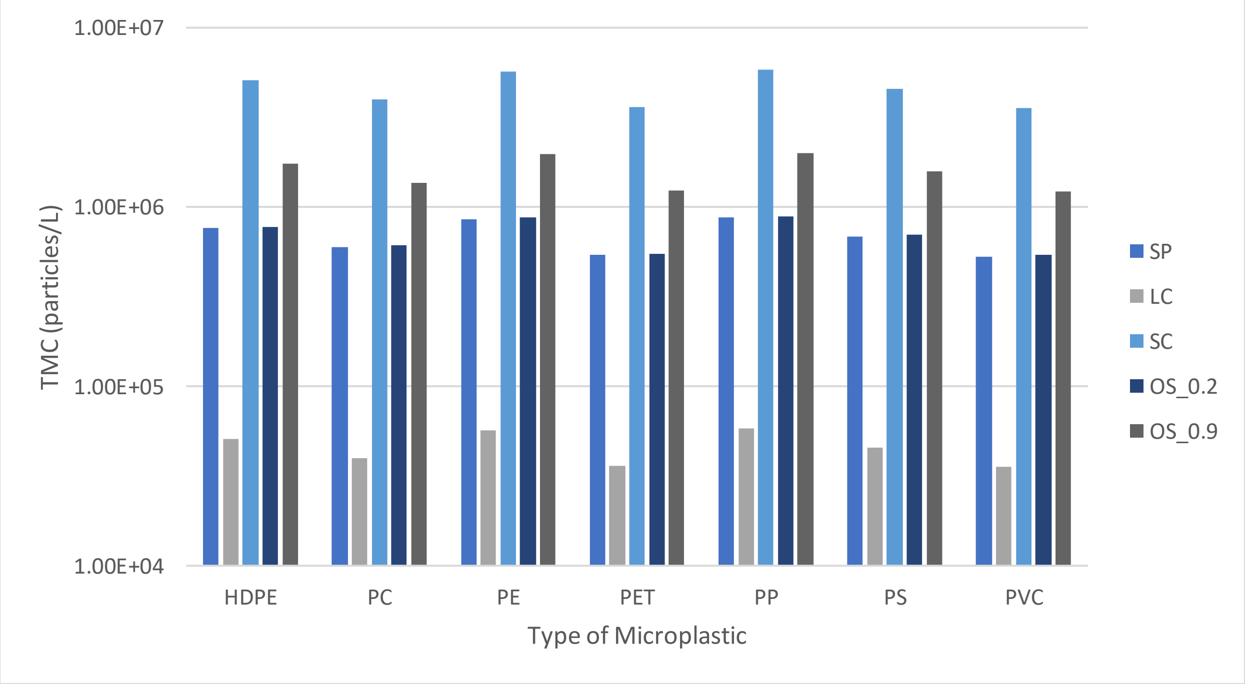


Figure 4.13: Average calculated TMCs based on microplastics shape for the different types of microplastics using sorption data for aluminum.

#### 4.3.4f) Type

TMCs were found to vary with microplastics type based on their density. Microplastics types with the highest densities were found to generate the lowest TMCs when all combination of factors was considered. A high density for a given shape implies that there are fewer number of particles per mass (per gram in this case) of that type and shape of microplastics compared to a microplastics type of low density of the same shape. Therefore, microplastics of higher densities were expected to generate lower TMCs than microplastics of lower densities. The calculated sequence of higher potential health risk attributable to lower TMCs based on microplastics type was thus: PVC < PET < PS < HDPE < PP < PE. PVC microplastics particles were shown to generate the lowest TMCs (most concerning) among all the microplastics types analyzed. Sorption capacities of a contaminant on all the types of microplastics analyzed in the assessment were not available. To account for missing data, similar sorption capacities of a contaminant across other types of microplastics were assumed as previously discussed. For instance, an AC of 0.375 milligrams of aluminum per gram of PET microplastics having mean hydrodynamic diameter of 2 mm was reported by (Rochman et al., 2014). Since ACs were not available for aluminum on other microplastics types, it was assumed that the AC was similar on all the other types of microplastics considered in this analysis. The same quantity of contaminants adsorbed on a lesser number of microplastics particles of high density compared to ACs of the same contaminant on a microplastics of low density, and hence, based on insufficient data and simplifying assumptions, TMCs of a given contaminant varied with the type of microplastics based on their densities.

#### 4.3.4g) Contaminant

From a total of eleven chemical contaminants analyzed, antimony was found to be the most concerning with regards to TMC. Figure 4.14 shows the mean TMC of different microplastics types and associated contaminants and it can be seen that TMCs calculated for antimony sorbed on the seven types of microplastics were the lowest. TMCs for mercury sorbed to different microplastics had the highest value.

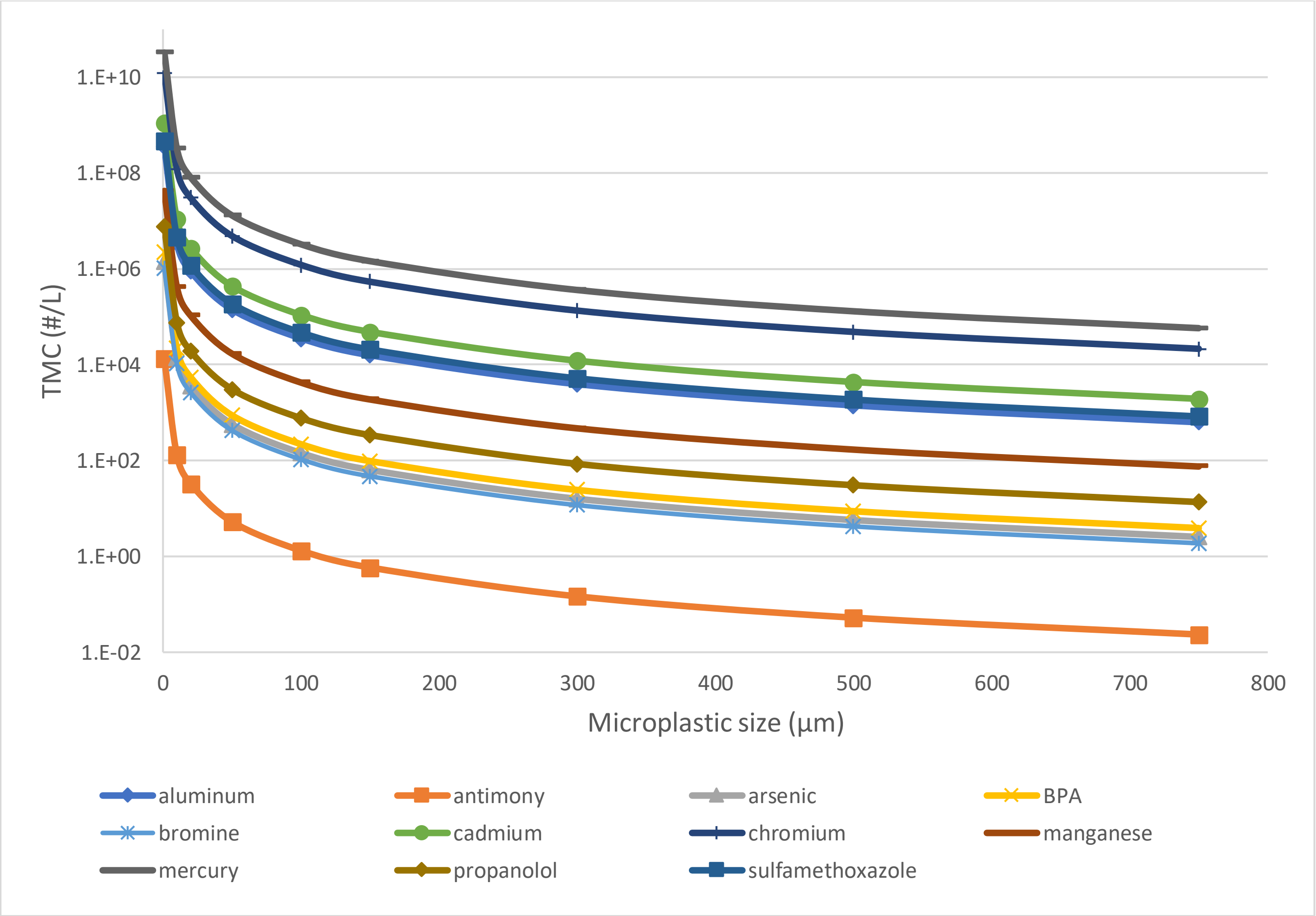


Figure 4.14: TMC curves for long cylindrical PVC microplastics using sorption data for all contaminants.

The potential health risks attributable to TMCs were influenced by sorption capacities of contaminants, their drinking water guideline, particle type, shape, and size. The calculated surface area based sorption capacities ($R_A$) in units of mg/m$^2$ was also a function of the size of microplastics from literature-acquired data as shown in Figure 4.9. A negative correlation was observed between TMC and $AC_{LA}$ (Figure 4.15) as would be expected since a higher AC equates to a higher quantity of contaminant sorbed. Based on available data, contaminants were distributed into three clusters (Figure 4.15) and their positioning in the graph is a function of their regulated concentration, $AC_{LA}$, and microplastics type, shape, and size.

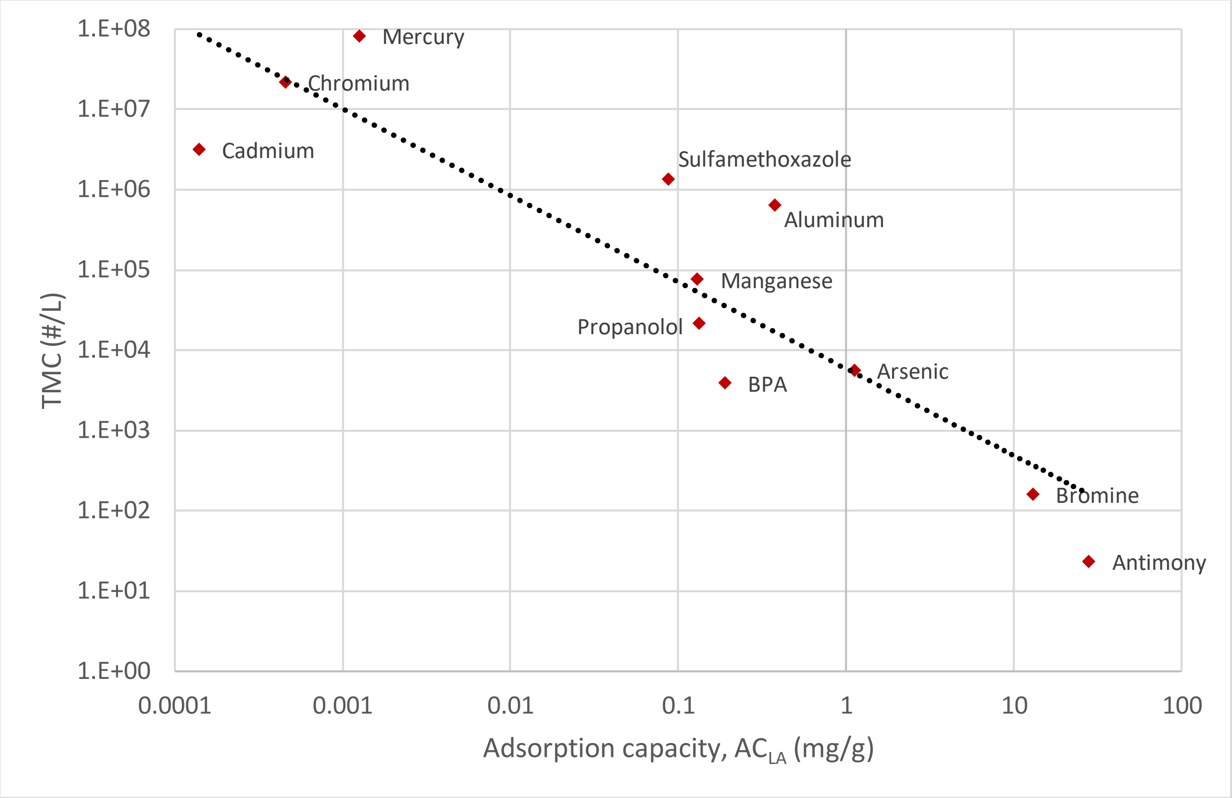


Figure 4.15: Relationship between TMC and $AC_{LA}$ of the contaminants that could be included in the MIHRA analysis.

### 4.3.4h) TMC and environmentally relevant microplastics concentration

The lowest TMC that was calculated in this investigation was 0.0234 LC shaped PVC microplastics particles per liter of untreated water—this was obtained when all of the contaminants, including antimony were reflected in the analysis. This TMC value suggests that for source waters contaminated with antimony that sorbs to microplastics, a concentration of 0.0234 microplastics particles per liter of water or greater could result in microplastics ingestion at a concentration that may reflect exposure to a potentially harmful concentration of antimony. Antimony was identified as the contaminant of highest indirect health concern from microplastics in drinking water at present. Antimony has the lowest health-based guideline (Rfd 0.004 mg for a 10 kg child per day) of the contaminants included in this analysis due to its high toxicity; it is also the most sorptive (27.8 mg/g) of the contaminants analyzed. When antimony is not a concern in source water, the TMC was found to be 2.55 particles per liter of source of water—this TMC is 100 times higher than the TMC that was calculated when antimony was considered in TMC calculation.

These TMCs were compared with concentrations of microplastics from sources relevant to drinking water, as shown in Figure 4.16**.** It can be seen that in both cases (with and without antimony)—without any level of drinking water treatment—the TMCs are within the range of microplastics concentrations reported in surface waters. Of course, the TMC values can be readily modified to reflect the extent of microplastics removal that would be expected during drinking water treatment. For instance, in assuming a well-operated drinking water treatment that achieves 3-log removal of particles, the TMC would be three orders of magnitude higher than the values originally calculated, resulting in a TMC of ~24 particles/L and 2,550 particles/L in cases with and without antimony, respectively. With respect to that the highest concentration of 187 particles/L found in the Dutch river delta and Amsterdam canals (Leslie et al., 2017), this concentration of microplastics was substantially lower than the calculated TMC, 2,550 particles/L that assumes well-operated treatment and no significant risk from antimony. The TMC of 24 particles/L in the case of antimony in source water is then comparable to environmentally relevant microplastics concentrations which were lower than the microplastics concentrations detected in several locations (Kosuth et al., 2018; Yuan et al., 2019). This discussion underscores that microplastics concentrations higher than 24 particles/L do not necessarily equate to unequivocal health risk. Rather, in these cases, further investigation of water quality may be warranted. For example, more detailed information regarding the presence of specific contaminants, their sorption capacities, types of microplastics present, and an assessment of drinking water treatment efficiency are integral to system specific management if indirect health risks posed by microplastics in source water. Thus, information regarding the sorptive properties of the most concerning contaminants (i.e., those that are most toxic and sorptive to microplastics), antimony in the present analysis, is critical to further advancing this type of risk management.

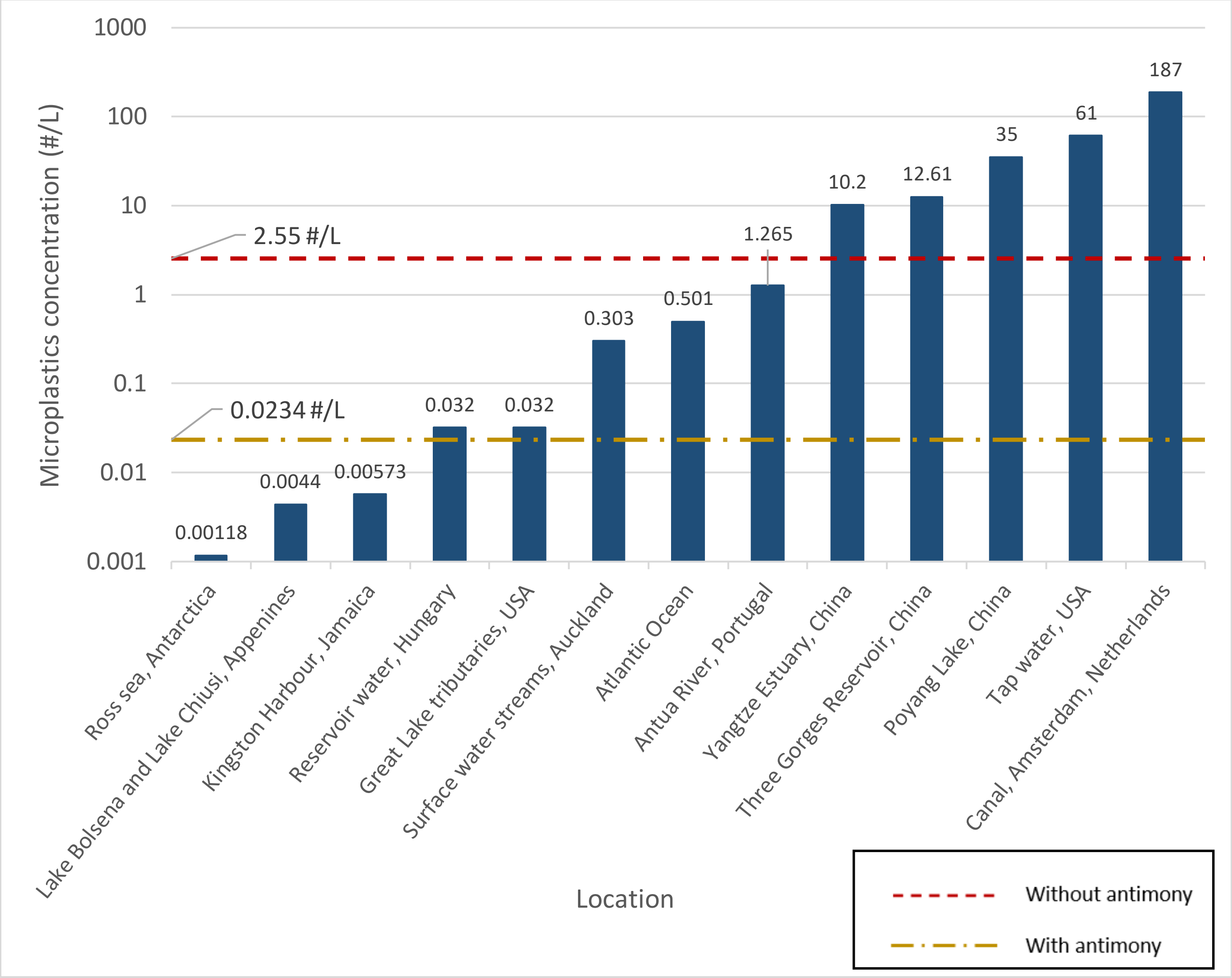


Figure 4.16: TMC with and without antimony compared to environmentally relevant concentrations of microplastics

#### 4.3.4i) Expressing Threshold Microplastics Concentration (TMC)

To confirm the relationship between number of particles and their mass with respect to sizes of microplastics particles, the TMCs which were calculated in units of particles per liter of water were converted to mass per liter (g/L). As discussed earlier, microplastics of larger sizes yielded lower TMCs than smaller microplastics. When the TMCs are converted to their masses i.e., in units of grams of microplastics/L, it was seen that for the sorption of same amount of a contaminant, smaller microplastics corresponded to a smaller mass than larger microplastics. Figure 4.17 shows the TMC for antimony in both g/L and particles/L. The TMC curve for mass-based concentration follows an opposite trend to the TMC curve in units of particles/L. This can be explained by the higher surface area to volume ratio of smaller particles which gives them a larger surface area per unit mass compared to particles of larger sizes. The larger surface area equates to a higher sorption as per the assumptions of this assessment (sorption throughout the surface area). For instance, as illustrated in Figure 4.17, for particles having a size of 750 µm, a TMC of approximately 0.0001 g/L of microplastics was calculated to result in desorption of antimony in concentrations that could potentially be concerning. To impose the same potential health risks, particles having a size of 1 µm required a TMC of approximately 1 x $10^{-7}$ g/L. The TMC in g/L for a specific size of microplastics was the same for all types and shapes of the microplastics being analyzed. This is as would be expected and can be observed from the simplified formula (Eq 7) for calculating TMC which is a function of the surface area or the size of particles and $AC_{LA}$.

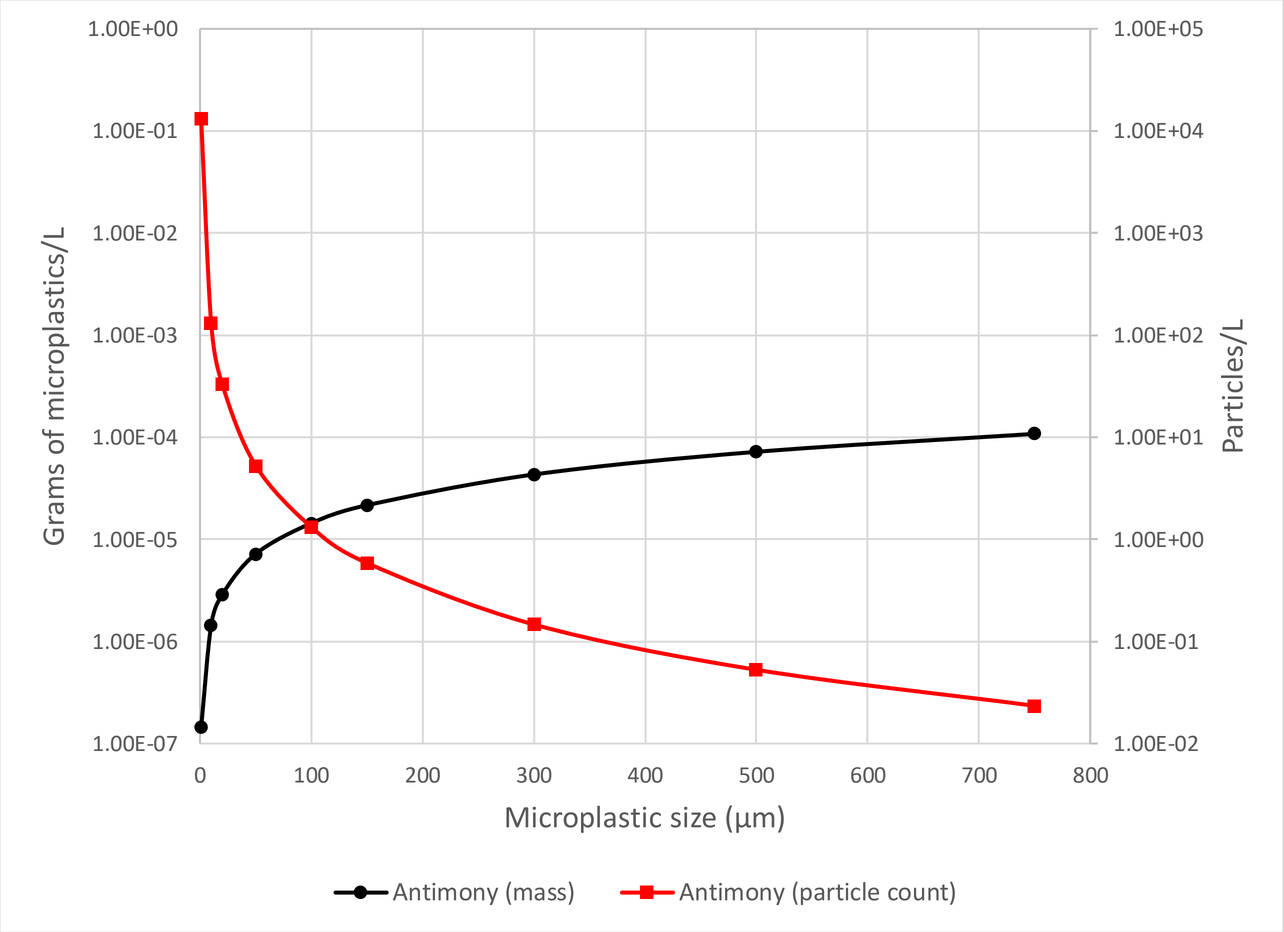


Figure 4.17: Mass-based and particle count based representation of TMCs for long cylindrical PVC microplastics particles in units of particles/L vs. g/L of water respectively.

### 4.3.5 Interpreting TMC

It is important to consider the type of water system when interpreting the results of TMC (subsurface or surface water). The calculation of TMC in this assessment was done in the context of source water without treatment and hence no particle removal. This maybe be applicable for groundwater systems without treatment. The TMCs for contaminants are therefore expected to be higher for systems involving treatment and some degree of particle removal. However, the flexible nature of the framework developed herein takes into account the varying levels of treatment (e.g., log removals) depending on the type of system being investigated. Furthermore, the choice of reference health standard concentration also needs to be considered while interpreting the TMC. Each health standard has been developed considering certain contaminant exposure conditions and target populations and these need to be considered when describing the calculated TMC. Even though the lowest TMCs for all cases have been analyzed in this thesis, the flexible nature of the framework allows users to calculate TMCs based on these different scenarios, such as different combinations of contaminants and microplastics, while conducting health risk assessment.

For any system ranging from subsurface (i.e., limited or no particle removal) and surface water (i.e., where well-operated treatment can be optimized to maximize particle removal), if the concentration of microplastics in influent water is less than the TMC, it means that, based on all the conservative assumptions, the microplastics in the source water are not of sufficiently high concentration to result in desorption of contaminants to an extent that may lead to adverse health impacts. However, if the concentration of microplastics in source water exceeds the TMC, it is not necessarily indicative of acute or chronic health risk. It warrants further investigation into water quality and treatment efficiency. As discussed above, more detailed information regarding the presence of specific contaminants, their sorption capacities, types of microplastics present, and an assessment of drinking water treatment efficiency are integral to system specific management if indirect health risks posed by microplastics in source water.

## 4.4 TMC discussion based on a practical scenario (3-log particle removal)

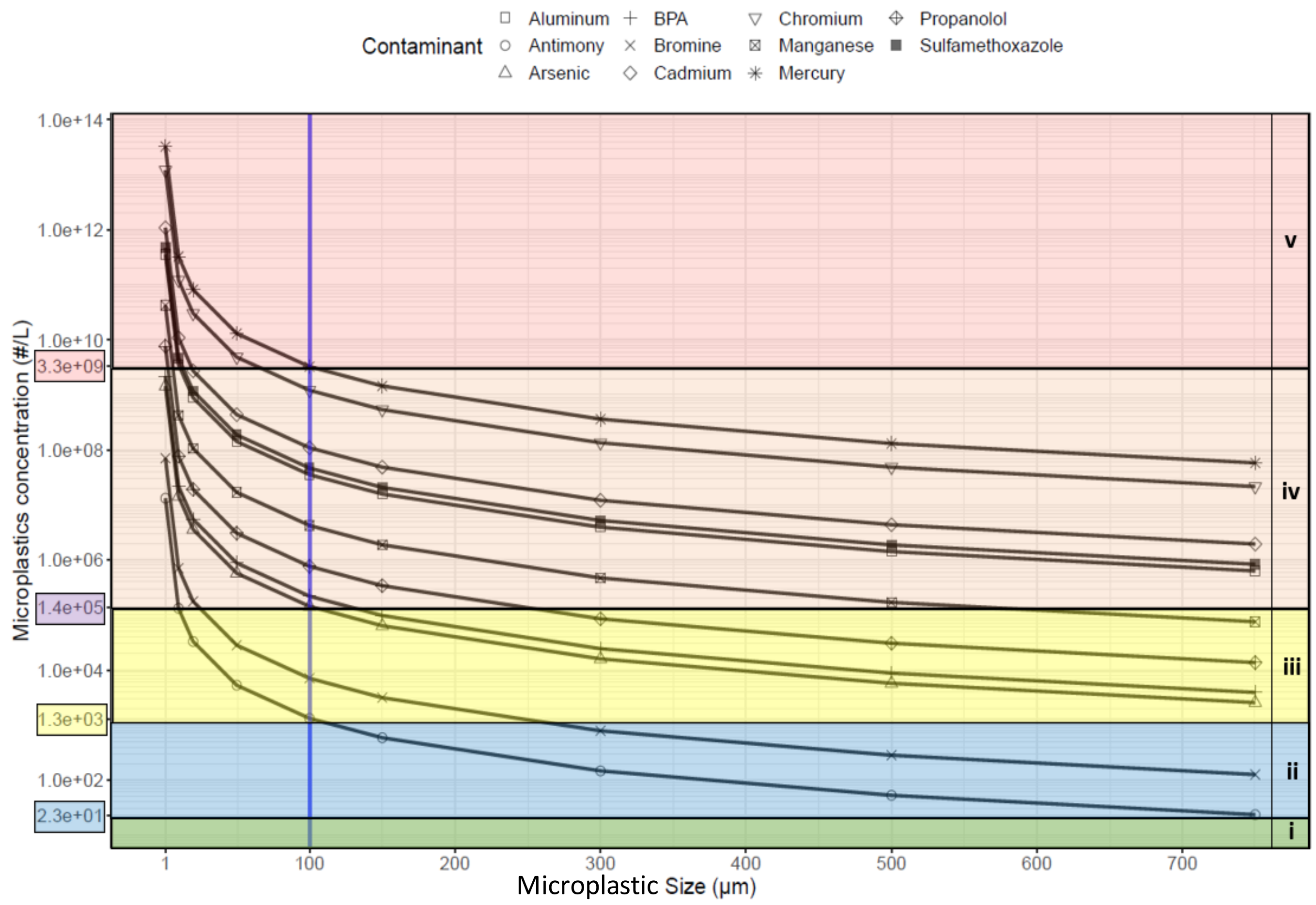


Figure 4.18: TMC zones identified considering a well operated treatment system (3-log particle removal).

The TMC curves developed can be divided into five zones as shown in Figure 4.18. The portion of the graph left of the vertical line at a microplastics size of 100 µm indicates TMCs with respect to the size of particles that are concerning in the context of drinking water. For microplastics that are greater than 1 µm in size, the particles of smaller size are more likely to transport further distances into filter media or even pass through filters and other drinking water treatment processes (Amirtharajah, 1988). Furthermore, the change in TMCs is highest between sizes 1 and 100 µm (Figure 4.18) compared to the remaining sizes which makes a size cut-off at 100 µm reasonable when discussing TMC.

The zones divided with respect to the TMC's at 100 µm distinguish relative health concern which increases as the TMCs increase from zone I (green) to zone IV (red). Zone I (TMC < 23 microplastics/L) correspond to safe operating conditions because microplastics concentrations in this zone are lower than the overall TMC calculated for all combinations of microplastics size, type, shape, and adsorbed contaminants. For microplastics concentration higher than the range of zone I, contamination of source water by antimony and bromine should be evaluated and analysis of the microplastics particles for sorption of these contaminants should be conducted. Leslie et al (2017) reported plastic particle concentration of 187 particles/L of water collected from surface water which falls in the TMC range defined by zone II. In zone III the TMCs calculated using available contaminant data are greater than one order of magnitude compared to zone II. Additional contaminants of concern in zone II are arsenic, bisphenol A, propranolol, and manganese. Microplastics concentration of 6,292 particles/L (Oßmann et al., 2018) and 4464 particles/L (Pivokonsky et al., 2018) found in bottled water and drinking water sources respectively fall in this zone. Zone IV has a TMC between $1.4 \times 10^5$ and $3.3 \times 10^9$ microplastics/L and microplastics concentrations falling in this zone has not been reported in sources relevant to drinking water. Contaminants of concern in this zone are aluminum, sulfamethoxazole, chromium, and mercury. Zone V comprises of TMCs greater than $3.3 \times 10^9$ microplastics/L and it is the most concerning zone. The microplastics concentration in zones II to V are expected impart a turbidity that exceeds the levels expected in well-maintained and treated surface water supplies (Skaf et al., 2020), and in most groundwater supplies (WHO, 2017). Drinking water sources having a TMC in zone V would warrant an investigation of water quality and adsorbed chemicals on microplastics in all the zones (I to V).

WHO (2019) review states that microplastics concentration as high as 10,000 microplastics/L has been detected in drinking water environments. However, the studies report total particle counts which include any particle that 'looks' like microplastics and further investigation confirmed as low as 3% of these reported numbers to be actually microplastics. This indicates exaggerated particle counts in literature that may occur due to improper sampling, errors during quantification which stems from the lack of a standardized measurement, and reporting procedure for microplastics.

For drinking water treatment, microplastics concentration in source water falling in zones II to V is not an absolute indicator of acute health risks of microplastics consumption. The TMCs are calculated using health standard concentrations which assume a constant exposure of a concentration of a contaminant through drinking water. For instance, a TMC of 23 particles/L means that a lifetime exposure of 23 microplastics per liter of water consumed might have health implications if they are associated with the specific contaminant of concern. Furthermore, a part of the worst-case-scenario approach in the assessment is a conservative assumption that all adsorbed contaminants are transferred to the human body. While the interactions of microplastics with digestive processes could impact the desorption of contaminants from their surface (Rochman et al., 2013), 100% transfer is unlikely (Hartmann et al., 2017; Sun et al., 2019).

The figure represents TMCs which were calculated using the assumption of a well-operated treatment utility having a 3-log removal of particles. This can be modified in the microplastics calculator for systems having higher, lower or no log removals (subsurface systems).

There were several key considerations and limitations in calculating the TMC. They are outlined as follows:

1. In this research, TMCs were calculated using literature-acquired data and its accuracy depends on the quality and availability of such information. The conceptual model revealed here for TMC calculations can be refined as more as more information becomes available.

2. The analysis is limited by the availability of combinations of data. Values for five parameters are required to be able to perform the calculation. Some parameters can be estimated or assumed but others cannot be. Until such time that the more integral parameters are quantified/published this will limit the overall accuracy of the concept.

3. The $AC_{LA}$ of a given contaminant was assumed to be similar across different types of microplastics which can lead to overestimation or underestimation of TMC since sorption capacities will vary depending on surface properties of different materials.

4. Greater numbers of sorption sites may be available on microplastics surfaces due to surface roughness associated with cracking or pores, as discussed previously.

### 4.5 Surface charge assessments

As expected, high concentrations of suspended microplastics (measured from the concentrated stock solutions) impacted net surface charge (i.e., evaluated by zeta potential analysis) of the particle in suspension. The microplastics concentrations in the stock suspensions are summarized in Table 3.1 and shown in Figure 4.19.

Figure 4.19: Stock suspensions of PE, PEEK, PS and ACR microplastics in MilliQ$^{TM}$ water, electrolyte solution, Grand River water, and Lake Ontario water.

The mean surface charge of microplastics as measured by zeta potential ranged from -71.7 mV to +28.3 mV in MilliQ$^{TM}$ water with PS and ACR respectively reflecting the endpoints of this range. The lower negative zeta potential of PS is consistent with expectations given the deprotonated carboxyl groups on their surface; this result is consistent with the findings (-7.4 to -50.2 mV) of Dai and Hozalski (2003), who also investigated PS transport in porous media. In another investigation, ACR paint was found to have a positive zeta potential at solution pH less than 4, which is believed to have been impacted by the addition of a tourmaline powder coating (Lameiras et al., 2008). The use of additives on these particles were shown to influence their zeta potential in suspension. However, as can be seen in Table 4.9, for the majority of the prepared samples that were suspended in the study water matrices investigated herein at concentrations of 500 microplastic particles/mL, the addition of these microplastics to the water matrices did not significantly impact the net zeta potential of the particles in suspension (Welch's t-test, $\alpha$ = 0.05). This result was consistently observed for the Grand River and Lake Ontario matrices (Table 4.9). In contrast, the addition of the two more negatively charged microplastics (PEEK and PS) did impact the net zeta potential of the particles respectively in suspension in the Lake Ontario and electrolyte solution water matrices (Table 4.9). Moreover, the addition of microplastics to MilliQ$^{TM}$ water impacted the net zeta potential of the particles in suspension in all cases, as would be expected (Table 4.9). It should be noted that the 500 particles/mL concentration of microplastics used in these experiments is elevated relative to microplastics concentrations that have been typically reported in surface waters (Table 2.4). These concentrations were used to represent an extreme potential treatment challenge.

Table 4.9: Impact of microplastics addition (at concentrations of 500 microplastics particles/L) on surface charge evaluated by the net zeta potential of particles suspended in the study water matrices.

| Microplastic | Water | P value |
|---|---|---|
| PE | MilliQ$^{TM}$ | 0.033 |
| | Electrolyte solution | 0.110 |
| | Lake Ontario | 0.553 |
| | Grand River | 0.717 |
| PEEK | MilliQ$^{TM}$ | 0.001 |
| | Electrolyte solution | 0.124 |
| | Lake Ontario | 0.008 |
| | Grand River | 0.356 |
| PS | MilliQ$^{TM}$ | 0.0005 |
| | Electrolyte solution | 0.003 |
| | Grand River | 0.414 |
| | Lake Ontario | 0.165 |
| ACR | MilliQ$^{TM}$ | 0.0006 |
| | Electrolyte solution | 0.811 |
| | Lake Ontario | 0.428 |
| | Grand River | 0.454 |

Coagulant was added to the water matrices (with and without microplastics addition) to achieve particle destabilization (i.e., zeta potential within 4 mV of the PZC) for optimal particle removal by physico-chemical filtration. The results of the zeta potential analyses are presented in Figure 4.20. Each of the raw water matrices required a different coagulant dose to achieve optimal particle destabilization; of course, this result was expected because of differences in water quality between the water matrices. Importantly, for each water matrix, the addition of a high concentration of microplastics did preclude effective coagulation and particle destabilization. Specifically, the coagulant dose required to destabilize particles in the various water matrices (without microplastics) was sufficient for achieving the same extent of particle destabilization (indicated by zeta potential of coagulated water reaching PZC ± 4 mV) when the water matrices contained 500 microplastics particles/mL—this was observed for all of the water matrices investigated (Figure 4.20), implying that the presence of microplastics did not increase coagulant demand. Notably, this was observed even in the cases in which microplastics addition to the water matrices impacted the net zeta potential of the particles suspended in those matrices prior to coagulation (e.g., microplastics in MilliQ$^{TM}$ water, PEEK in Lake Ontario water, and PS in the electrolyte solution). Thus, it is reasonable to conclude the microplastics were reasonably destabilized by coagulant addition—this result is consistent with the many reported studies of microplastics removal by filtration that were summarized in Table 2.8. Thus, while this investigation does not directly demonstrate microplastics removal by conventional treatment, it provides importance evidence that suggests that microplastics will be removed like any other particles by conventional "chemically-assisted" filtration processes (i.e., physico-chemical filtration processes preceded by coagulation).

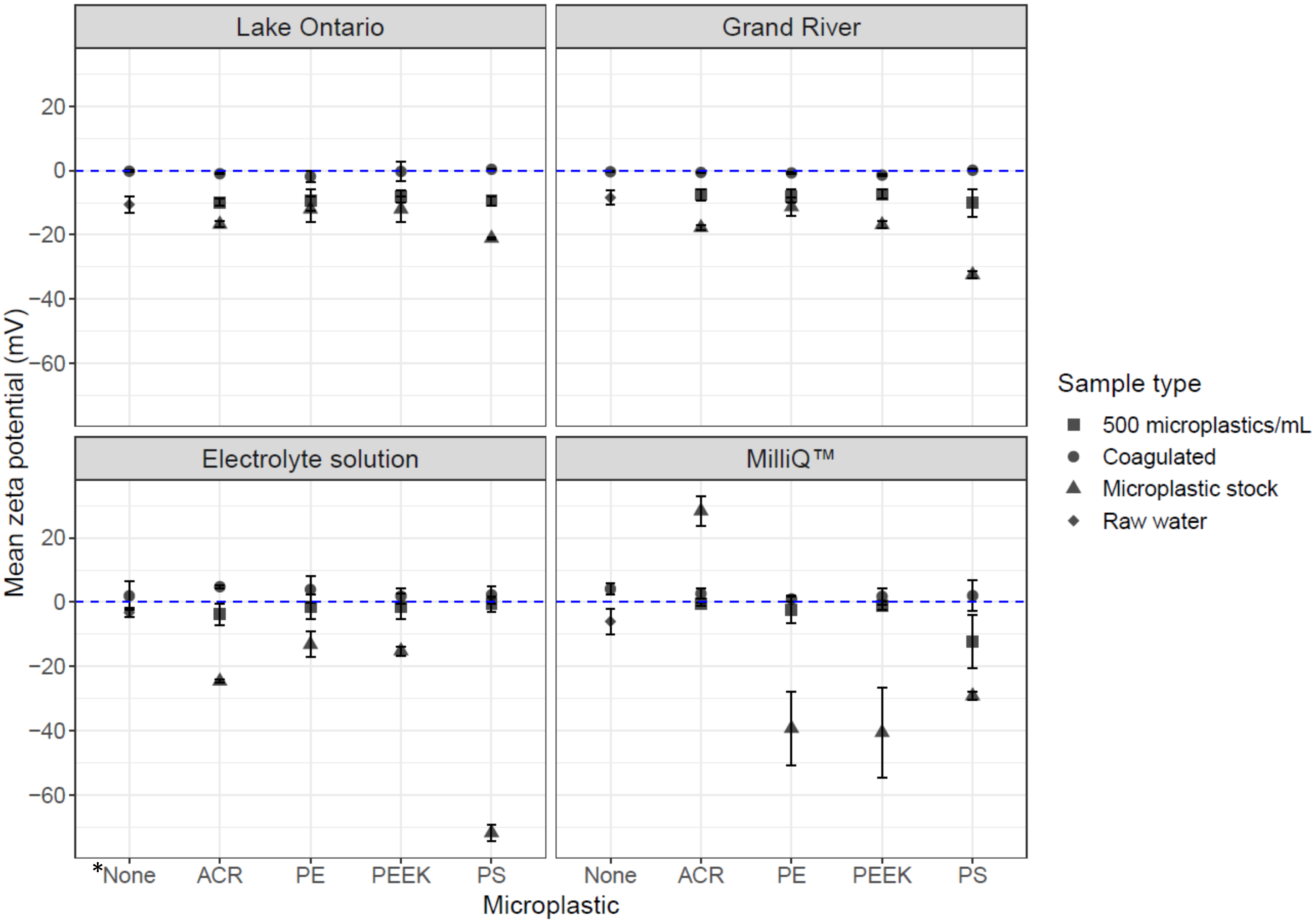


Figure 4.20: Comparison of mean zeta potentials of highly concentrated microplastics stock suspension, raw water, raw water spiked with 500 particles/mL and coagulated water. *None indicates raw water without added microplastics.

### 4.6 Confirmatory column studies

The objective of these confirmatory column studies was to confirm the consistencies of microplastics particles transport with existing predictive particle transport models. Microplastics transport and retention during passage through porous media is discussed for 1, 10, and 45 µm sized particles. Neither the porous material nor the particles were exposed to coagulant. The average percentage and $\log_{10}$ removals obtained from the experiments are shown in Table 4.10**.**

Table 4.10: Removal of 1 µm, 10 µm, and 45 µm polystyrene microspheres by bench-scale physico-chemical filtration (not preceded by coagulation).

| **Size** | **1 µm** | | **10 µm** | | **45 µm** | |
|---|---|---|---|---|---|---|
| Run number | % Removal | Log Removal | % Removal | Log Removal | % Removal | Log Removal |
| 1 | 38 | 0.2 | 94 | 1.2 | 95 | 1.3 |
| 2 | 42 | 0.2 | 89 | 1.0 | * | * |
| 3 | 44 | 0.3 | 89 | 1.0 | 100 | 2.8 |
| 4 | * | * | 89 | 1.0 | 97 | 1.5 |
| Average % removal | 41 | | 90 | | 97 | |
| SD (n = 3 or 4) | 2.0 | | 2.1 | | 1.8 | |
| Mean Log Removal | 0.2 | | 1.0 | | 1.9 | |

*results not available

As would be expected, the 45 µm microplastics were the most well removed compared to the microplastics of smaller sizes (1 and 10 µm) used in the experiment. Figure 4.21 shows that the transport of microplastics particles decreased with increasing size from 1 µm to 45 µm. On average, approximately 97% of the 45 µm sized microplastics were retained during passage through the porous media followed by 10 µm sized microplastics with an average retention of 90%. The lowest removal was found for 1 µm particles with an average removal of 43%. With increasing particle size, the percent removal also increased which is consistent with findings from other bench-scale filtration studies (in the absence of a coagulant). When interstitial spaces between pores are smaller than a critical size, larger particles are retained due to physical straining which explains the significant decrease in microplastics transport of 45 µm compared to the 1 µm and 10 µm spherical PS microplastics. This is consistent with the prediction of colloid filtration theory which states that colloidal retention increases with an increase in the ratio of the colloid diameter to the median grain size (Bradford et al., 2003). Findings from these confirmatory tests are consistent with the theory of particle removal during filtration. This is because microplastics are particles like any others in water and their removal by porous media filtration occurs by mechanisms that remove particles typically encountered in drinking water treatment systems. As reviewed in Emelko et al. (2005), particle removal by porous media filtration occurs by their transport close to collector particles which causes attachment. The dominant mechanisms for particle transport are diffusion and sedimentation and lead to minimum net transport efficiency of particles of approximately 1 µm in size. The attachment of particles on collectors is driven by the charge on collector surface and the particles themselves. A neutral net charge is desirable to prevent repulsion and facilitate particle attachment. The zeta potential varies with particle type and their surface properties as shown by (Dai and Hozalski, 2003b) where similar sized *Cryptosporidium parvum oocysts* and latex microspheres had zeta potentials that varied significantly. Microspheres were found to have a much more negative zeta potential due to the presence of deprotonated carboxyl groups on their surface.

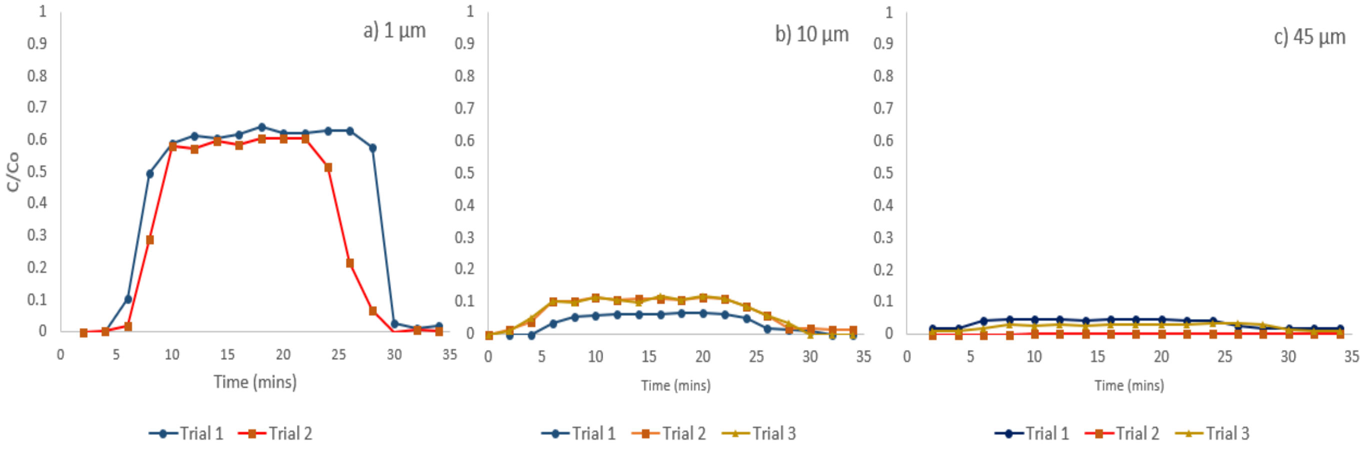


Figure 4.21: Comparison of the passage of three different microplastics particle sizes through porous media (0.2 mm effective size sand-no coagulant added).

Generally, water quality parameters such as pH, ionic strength, colloid surface charge, and physical factors such as hydrodynamics are known to effect zeta potential and subsequently the transport of microplastics through porous media. Chu et al. (2019) recorded the zeta potential of 1 µm sized polystyrene to vary between -75.7 mV to -34.1 mV for ionic strength of water in the range from 0.001 M to 0.2 M. Higher ionic strength was associated with less negative zeta potential creating suitable conditions for particle attachment. Similarly, nanoplastics exhibited a decrease in transport with increase in ionic strength (Dong et al., 2018). Surface charge on porous media can be influenced by pH which can affect its interaction with particles in water. With increasing pH, the negative surface potential of the media particles was found to increase which caused repulsion between media particles and polystyrene nanoplastics and resulted in increased transport (Wu et al., 2020). Multiple factors are known to influence particle transport through porous media and their effects are well documented in the literature.

# Chapter 5 Conclusions, Implications, and Recommendations

In the past decade, it has become increasingly evident that microplastics are present and often abundant in freshwater supplies; this, coupled with their high affinity for adsorbing chemical contaminants necessitates consideration regarding the potential health risks associated with their presence in drinking water.

## 5.1 Conclusions and implications

The findings from this study and key associated implications to the water industry are outlined below.

1. The Threshold Microplastics Concentration (TMC) indicates the total number of microplastics particles per liter of untreated (source) water, which if ingested, may lead to exposure to potentially harmful concentrations of chemical contaminants because of their desorption from microplastics. This concept is central to the framework for evaluating the indirect human health impacts attributable to the ingestion of microplastics in drinking water that was developed herein.

   If the concentration of microplastics entering a well-operated drinking water treatment plant is below the TMC, treated water microplastics concentrations do not pose significant health risk. If the concentration of microplastics entering a well-operated drinking water treatment plant is above the TMC, this does not *necessarily* imply an acute or chronic threat to human health. Rather, it indicates that closer examination of the microplastics types/concentrations, adsorbed contaminants, and/or solids treatment processes present in the system is needed to better assess health risk.

2. The indirect human health impacts attributable to the ingestion of microplastics in drinking water can be evaluated using the TMC framework developed herein. This framework can be expanded as more information regarding toxicity and contaminant AC of various combinations of contaminants and microplastics becomes available.

3. TMC curves can be generated for either individual or combinations of contaminants based on microplastics sizes, types, and shapes. TMC values for specific combinations of contaminants and microplastics types (for which sorption has been described) spanned six orders of magnitude.

4. A TMC of 2,550 microplastics particles per liter of source water was identified to assist well operated utilities (3-log particle removal) in evaluating potential health risks attributable to contaminants adsorbed to microplastics in treated drinking water. If antimony is present, the TMC decreases to 24 microplastics particles per liter. The TMC value is relevant regardless of MP size, shape, type, and contaminant(s) adsorbed. It can be updated as new information regarding contaminant sorption to microplastics becomes available.

There are several implications of Conclusions 1 to 4 for the drinking water industry. They include: (1) although the toxicological implications of microplastics in drinking are not fully understood, a simple, spreadsheet-based tool is immediately available for use to conduct a preliminary assessment of whether or not microplastics in a given source or treated drinking water supply could possibly be linked to health risk attributable to adsorbed contaminants given the currently available scientific data, (2) an analogous simple approach to evaluating the potential health effects of the microplastics materials themselves is not currently available; thus, care must be taken in interpreting and communicating the implications of water quality analyses relative to TMC values, and (3) as daily ingestion of a specified volume of drinking water is integral to the analysis developed herein, utilities may consider modifying that volume to better reflect consumer practices and evaluate risk in their region; this would be especially important in arid regions where higher daily volumes of water may be ingested, and (4) proactive evaluation of the sorption characteristics of specific contaminants (for which data regarding sorption to plastics are not available) are relatively straightforward to conduct and can be integrated into the framework developed herein, if needed.

5. Microplastics surface area is a key driving factor in the calculation of TMCs. Lower TMCs are associated with larger surface area when all other factors remain unchanged. Hence, long cylindrical microplastics were shown to yield the lowest TMCs when adsorption/ desorption of contaminants was assessed individually and in combination—long cylinders have the largest surface area of the shapes investigated.

6. Higher risk of indirect health impacts attributable to consumption of waterborne microplastics is associated with lower TMC. The sequence of higher risk attributable to lower TMCs based on microplastics shape and normalized for microplastics mass was thus: long cylinder < sphere < oblate spheroid (e=0.2) < oblate spheroid (e=0.9) < short cylinder.

7. Higher risk of indirect health impacts attributable to consumption of waterborne microplastics is also associated with the microplastic type. The sequence of higher risk attributable to lower TMCs based on microplastic type and normalized for microplastics mass was thus: PVC < PET < PS < HDPE < PP < PE.

8. Smaller microplastics pose higher health risks than larger microplastics on an equivalent mass basis, but on an equivalent particle count basis, larger microplastics pose higher health risks because they have larger surface area; thus, TMC values are higher for smaller microplastics of a given type because they require a higher concentration to contribute an equivalent surface area from which contaminants can desorb to the water matrix. While this relationship is obvious, it is worth noting that the largest microplastics size used in developing the TMC curves required approximately three orders of magnitude more mass than the smallest size to pose the same level health risk attributable to desorption of toxic contaminants. Hence, the calculated TMC values that were established by considering all available contaminant and microplastics type data corresponds to the largest size (i.e., 750 µm) of microplastics that were evaluated in the presented

assessment. Notably, particles larger than this size are readily and consistently removed during conventional drinking water treatment.

There are a few key implications of Conclusion 5 to 8 for the drinking water industry. They include: (1) reporting of microplastics concentrations and types in water should be standardized because the types, shapes, sizes, and units of concentration are integral to health risk assessment and these details enable comparison and benchmarking between systems, (2) application of the framework developed herein may require modification if applied to situations in which there are adequately high concentrations of highly porous or rough materials and surfaces that may have significantly higher surface area than that of the range of smooth microplastics shapes investigated here, and (3) the mode of microplastics analysis in raw or treated waters must be considered in any analysis of potential health risks from microplastics because it will affect the surface area believed to be available for contaminant desorption. While enumeration of discrete microplastics particles can be combined with particle size analysis to extend risk analysis beyond the simple comparison of microplastics concentration relative to the TMC, the more rapid though much less informative analysis of microplastics volumes by filtration and subsequent dissolution in solvents requires assumptions regarding microplastics size distributions and therefore surface area—therefore, this is not recommended.

9. Microplastics are particles similar to those typically removed from water during the particle removal stages of drinking water treatment. This was confirmed by demonstrating that the presence of microplastics at environmentally relevant concentrations in the various source water matrices investigated did not (i) preclude optimal particle destabilization (which enables optimal particle removal by physico-chemical filtration) or (ii) alter the coagulant doses required to achieve optimal particle destabilization (i.e., PZC ± 4 mV) even though the addition of the microplastics significantly change the net zeta potential of the particles suspended in the water matrices in some cases. Therefore, well operated conventional treatment plants are

expected to achieve 3-log (i.e., 99.9%) reductions in influent microplastics concentrations in a manner that is expected by the suite of U.S. Surface Water Treatment Rules and analogous international regulations such as O. Reg. 170 in Ontario, Canada when optimal particle destabilization by coagulation is achieved. Bench-scale column studies simulating groundwater flow have also shown particle retention patterns that are consistent with previous reports of particle removal in these systems.

There are two key implications of Conclusion 9 for the drinking water industry. They are (1) coagulant dosing in surface water treatment plants must achieve adequate particle destabilization so that microplastics (like other particles and protozoan pathogens) are adequately removed by physico-chemical/chemically-assisted filtration processes, and (2) high concentrations of microplastics pose higher potential health risks in groundwater supplies that do not receive treatment beyond disinfection because relative to surface water supplies that are treated by conventional filtration or equivalent processes.

## 5.2 Recommendations

Building on the outcomes of this research that were discussed above, the following are (1) operational recommendations for drinking water utilities concerned about the potential health risks posed by microplastics in water and (2) recommendations for further research.

### 5.2.1 Utility operators and managers

1. Test source water for the presence of antimony when microplastics concentrations exceed 24 particles/liter and consider evaluating microplastics particle and antimony concentrations in treated water.

2. Evaluate typical sizes, shapes, and types of microplastics in the specific source water during a range of conditions that includes events (e.g., high runoff in the urban or peri-urban environment) during which an influx of microplastics may occur.

3. Evaluate microplastics removal by key processes such as physico-chemical/chemically-assisted filtration at pilot-scale if concentrations of microplastics in source water are especially high/above the TMC.

### 5.2.2 Research

1. Generate more adsorption/desorption data of regulated and unregulated contaminants on different types of microplastics under realistic conditions for the framework to generate a more comprehensive TMC dataset.

2. Modify the developed framework to evaluate more case specific scenarios by integrating additional factors such as physico-chemical properties of the surrounding water matrix (temperature, pH, ionic strength, etc.), preferential sorption, porosity of microplastics types, etc., into the developed model.

3. Investigate microplastics transport through porous media by physico-chemical/ chemically-assisted filtration to identify strategies for better informing coagulant dosing and optimizing microplastics particle removal by filtration if needed.

4. Investigate presence/relevance, transport, and potential human health implications of pathogens adsorbed on microplastics in the environment.

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# Appendix A：

# Detailed bench-scale filtration data

Loading rates

**Flow**

$$Q\,\frac{m^3}{day} = v\,\frac{mL}{minute} \times \frac{1L}{1000mL} \times \frac{1m^3}{1000L} \times \frac{60min}{hour} \times \frac{24hours}{day}$$

Where:

Q = influent flow rate ($m^3$/day)
v = pump rate (mL/min)

Hydraulic loading rate (m/h) = $\frac{Pump\ flow\ rate\ (\frac{m^3}{h})}{Cross\ sectional\ area\ (m^2)}$ = $\frac{0.15\times10^{-3}}{\pi\times(0.8\times10^{-2})}$ = 0.75 m/h

| | |
|---|---|
| Pump flow rate | 2.5 mL/min |
| Influent flow rate | 0.0036 $m^3$/day |
| Column diameter | 16 mm |
| Cross-sectional area | 2 x $10^{-4}$ $m^2$ |
| Linear velocity | 18 m/day |
| Loading rate | 0.75 m/day |

**Column experiments**. Influent concentration, $C_O = 5 \times 10^7$ particles/mL was used for all experiments.

### 1 µm PS microplastics - Trial 1

Table A1: Data for generating calibration curve of 1 µm PS microplastics (trial 1).

| Concentration (particles/mL) | Absorbance (404 nm) | | | Avg. absorbance (nm) |
|---:|---:|---:|---:|---:|
| 50,000,000 | 0.632 | 0.633 | 0.634 | 0.633 |
| 10,000,000 | 0.143 | 0.143 | 0.143 | 0.143 |
| 5,000,000 | 0.0810 | 0.081 | 0.081 | 0.081 |
| 1,000,000 | 0.0303 | 0.030 | 0.029 | 0.030 |
| 500,000 | 0.020 | 0.021 | 0.022 | 0.021 |
| 50,000 | 0.010 | 0.0103 | 0.014 | 0.011 |
| 5,000 | 0.008 | 0.009 | 0.009 | 0.008 |
| 500 | 0.008 | 0.010 | 0.008 | 0.008 |

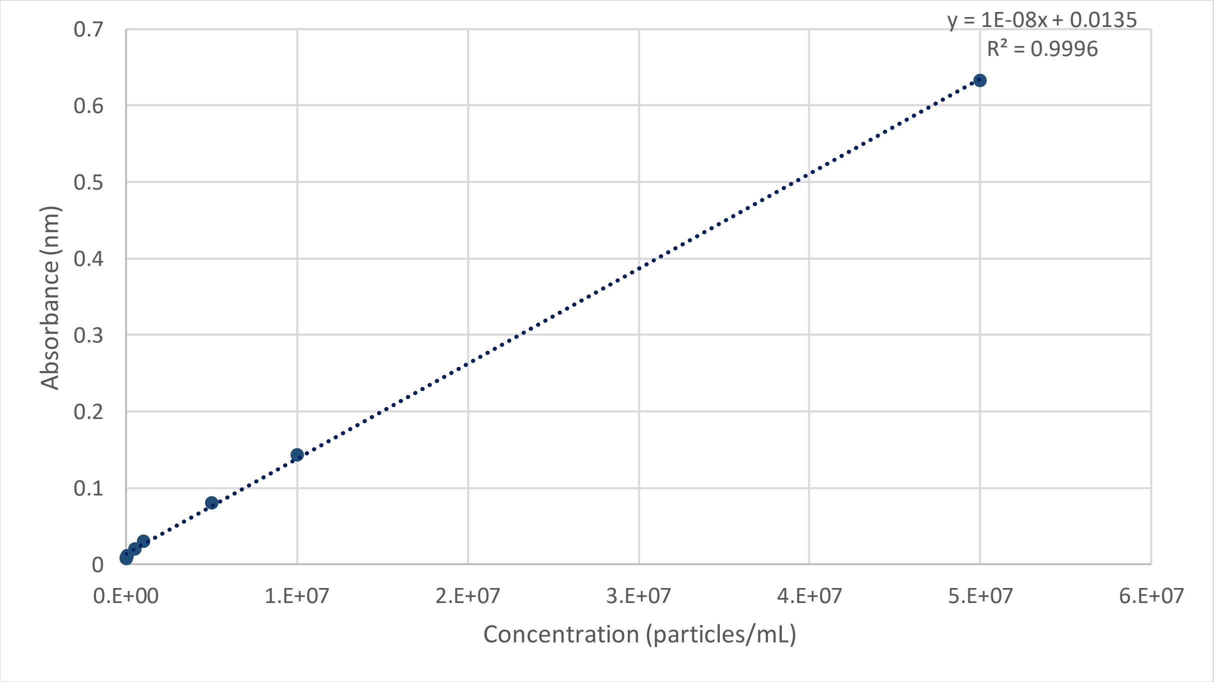

Figure A1: Calibration curve for 1 µm PS microplastics with absorbance measured at 404 nm (trial 1).

Table A2: Experimental data collected from column study with 1 µm PS microplastics (trial 1).

| Time (mins) | Absorbance (404 nm) | | | Avg. absorbance (nm) | Concentration (particles/mL) X $10^6$ | C/Co | Log $(C/C_O)$ | % Removal |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.012 | 0.013 | 0.012 | 0.013 | 0 | 0 | - | |
| 4 | 0.013 | 0.015 | 0.012 | 0.013 | 0 | 0 | - | |
| 6 | 0.066 | 0.066 | 0.065 | 0.066 | 5 | 0.10 | 0.98 | 90 |
| 8 | 0.259 | 0.262 | 0.260 | 0.261 | 24 | 0.49 | 0.30 | 51 |
| 10 | 0.309 | 0.304 | 0.313 | 0.309 | 29 | 0.59 | 0.23 | 41 |
| 12 | 0.324 | 0.314 | 0.320 | 0.319 | 30 | 0.61 | 0.21 | 39 |
| 14 | 0.317 | 0.317 | 0.317 | 0.317 | 30 | 0.61 | 0.22 | 39 |
| 16 | 0.326 | 0.321 | 0.321 | 0.323 | 31 | 0.62 | 0.21 | 38 |
| 18 | 0.330 | 0.336 | 0.338 | 0.335 | 32 | 0.64 | 0.19 | 36 |
| 20 | 0.324 | 0.323 | 0.324 | 0.324 | 31 | 0.62 | 0.21 | 38 |
| 22 | 0.325 | 0.325 | 0.324 | 0.325 | 31 | 0.62 | 0.21 | 38 |
| 24 | 0.331 | 0.326 | 0.327 | 0.328 | 31 | 0.63 | 0.20 | 37 |
| 26 | 0.333 | 0.324 | 0.327 | 0.328 | 31 | 0.63 | 0.20 | 37 |
| 28 | 0.301 | 0.301 | 0.306 | 0.303 | 29 | 0.58 | 0.24 | 42 |
| 30 | 0.027 | 0.026 | 0.028 | 0.027 | 1 | 0.03 | 1.58 | 97 |
| 32 | 0.017 | 0.020 | 0.022 | 0.019 | 0.6 | 0.01 | 1.90 | 99 |
| 34 | 0.023 | 0.022 | 0.022 | 0.022 | 0.9 | 0.02 | 1.75 | 98 |

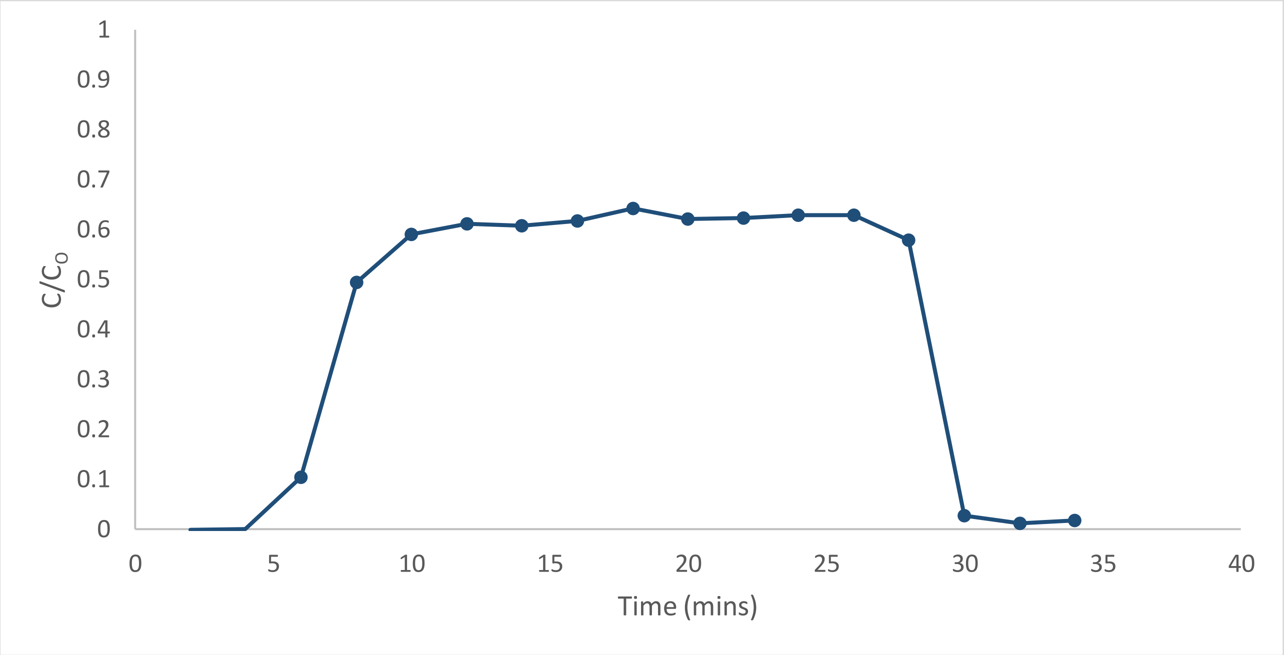

Figure A2: Breakthrough curve of 1 µm PS microplastics (trial 1).

**1 µm PS microplastics - Trial 2**

Table A3: Data for generating calibration curve of 1 µm PS microplastics (trial 2).

| Dilution | Absorbance (404 nm) | | | Avg. absorbance (nm) |
|---|---|---|---|---|
| 50,000,000 | 0.736 | 0.734 | 0.735 | 0.735 |
| 10,000,000 | 0.163 | 0.163 | 0.163 | 0.163 |
| 5,000,000 | 0.079 | 0.084 | 0.084 | 0.082 |
| 1,000,000 | 0.026 | 0.025 | 0.026 | 0.025 |
| 500,000 | 0.018 | 0.019 | 0.019 | 0.019 |
| 50,000 | 0.011 | 0.011 | 0.011 | 0.011 |
| 5,000 | 0.011 | 0.012 | 0.016 | 0.013 |
| 500 | 0.013 | 0.013 | 0.013 | 0.013 |

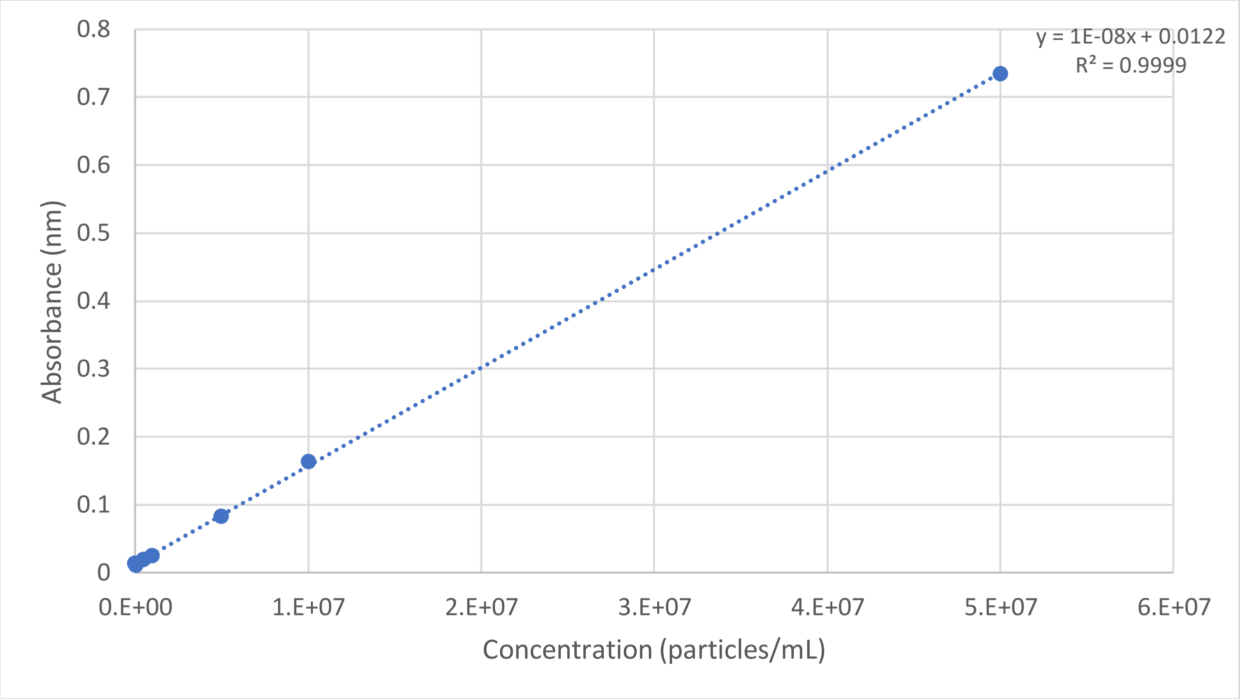

Figure A3: Calibration curve for 1 µm PS microplastics with absorbance measured at 404 nm (trial 2).

Table A4: Experimental data collected from column study with 1 µm PS microplastics (trial 2).

| **Time (mins)** | **Absorbance (404 nm)** | | | **Avg. absorbance (nm)** | **Concentration X $10^6$** | **C/Co** | **Log (C/Co)** | **% Removal** |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.014 | 0.012 | 0.011 | 0.012 | 0.001 | 0 | 4.68 | |
| 4 | 0.012 | 0.013 | 0.013 | 0.013 | 0.069 | 0 | 2.95 | |
| 6 | 0.022 | 0.021 | 0.022 | 0.022 | 0.945 | 0.02 | 1.72 | 98 |
| 8 | 0.159 | 0.155 | 0.155 | 0.157 | 14 | 0.29 | 0.54 | 71 |
| 10 | 0.318 | 0.301 | 0.282 | 0.303 | 29 | 0.58 | 0.24 | 42 |
| 12 | 0.292 | 0.299 | 0.306 | 0.299 | 29 | 0.57 | 0.24 | 43 |
| 14 | 0.301 | 0.316 | 0.314 | 0.310 | 30 | 0.60 | 0.22 | 40 |
| 16 | 0.304 | 0.310 | 0.299 | 0.305 | 29 | 0.58 | 0.23 | 43 |
| 18 | 0.312 | 0.309 | 0.321 | 0.314 | 30 | 0.60 | 0.22 | 40 |
| 20 | 0.316 | 0.307 | 0.323 | 0.316 | 30 | 0.61 | 0.22 | 39 |
| 22 | 0.319 | 0.316 | 0.307 | 0.314 | 30 | 0.60 | 0.22 | 40 |
| 24 | 0.279 | 0.270 | 0.265 | 0.271 | 26 | 0.52 | 0.29 | 48 |
| 26 | 0.109 | 0.122 | 0.129 | 0.120 | 11 | 0.22 | 0.67 | 78 |
| 28 | 0.047 | 0.046 | 0.046 | 0.046 | 3 | 0.07 | 1.17 | 93 |
| 30 | 0.013 | 0.012 | 0.011 | 0.012 | 0 | 0 | - | 100 |
| 32 | 0.013 | 0.018 | 0.014 | 0.016 | 0.348 | 0.01 | 2.16 | 99 |
| 34 | 0.012 | 0.011 | 0.014 | 0.013 | 0.041 | 0 | 3.09 | 99 |

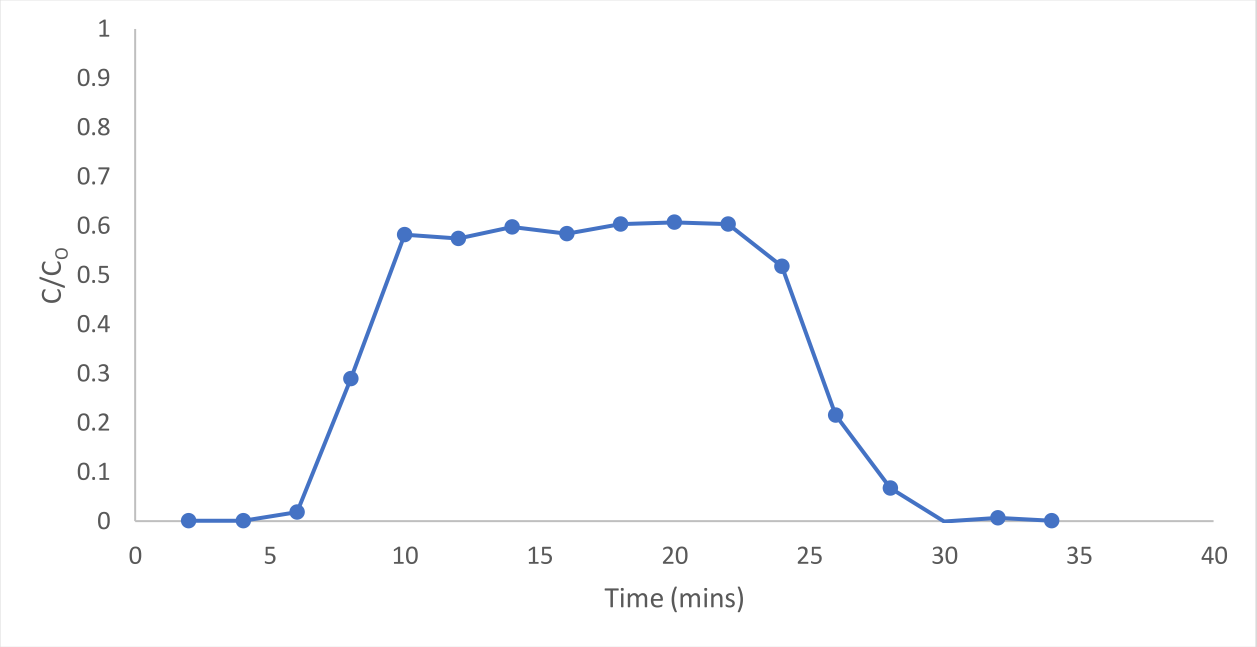

Figure A4: Breakthrough curve of 1 µm PS microplastics (trial 2).

**10 µm PS microplastics - Trial 1**

Table A5: Data for generating calibration curve of 10 µm PS microplastics (trial 1).

| Concentration | Absorbance (343 nm) | | | Avg. absorbance (nm) |
|---|---|---|---|---|
| 50,000,000 | 0.06554 | 0.07855 | 0.05877 | 0.06762 |
| 20,000,000 | 0.02340 | 0.03220 | 0.02027 | 0.02529 |
| 8,000,000 | 0.00753 | 0.00808 | 0.00757 | 0.00773 |
| 2,000,000 | 0.00335 | 0.00365 | 0.00357 | 0.00352 |
| 800,000 | 0.00034 | 0.00043 | 0.00046 | 0.00041 |
| 200,000 | 0.00035 | 0.00040 | 0.00037 | 0.00038 |
| 80,000 | 0.00003 | 0.00004 | 0.00004 | 0.00003 |

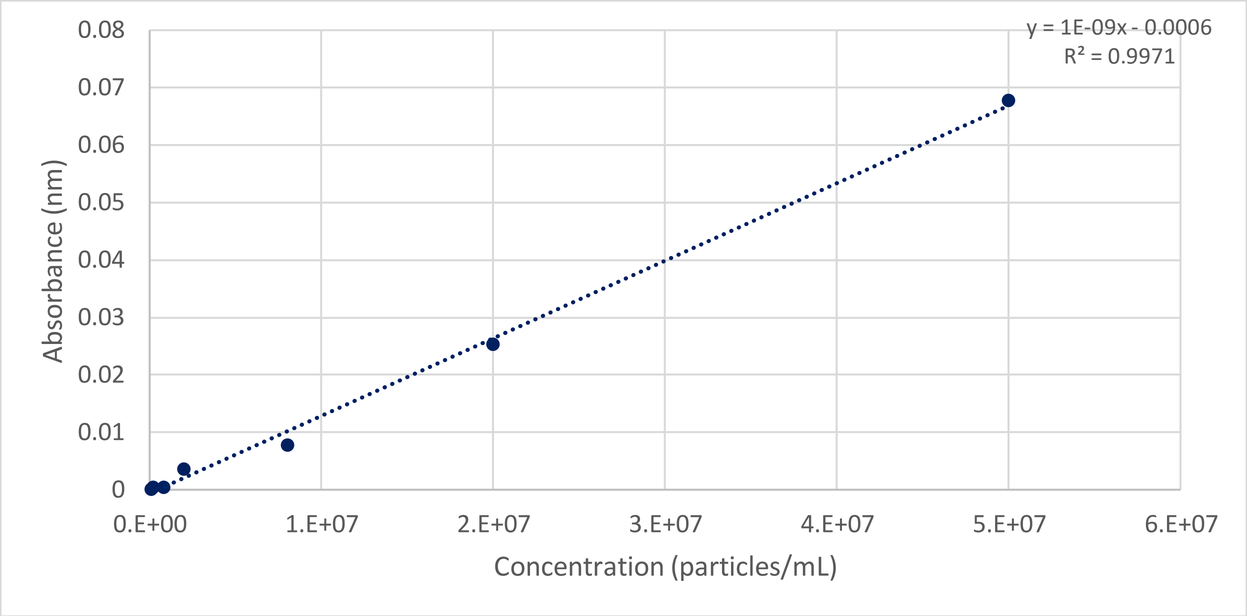

Figure A5: Calibration curve for 10 µm PS microplastics with absorbance measured at 343 nm (trial 1).

Table A6: Experimental data collected from column study with 10 µm PS microplastics (trial 1).

| Time (mins) | Absorbance (343 nm) | | | Avg. absorbance (nm) | Concentration (C) x $10^6$ | C/Co | Log Removal | % Removal |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | | 0.000 | - | 100 |
| 2 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.72 | 0.014 | 1.84 | 99 |
| 4 | 0.0011 | 0.0013 | 0.0016 | 0.0013 | 1.94 | 0.039 | 1.41 | 96 |
| 6 | 0.0041 | 0.0032 | 0.0063 | 0.0045 | 5.13 | 0.103 | 0.99 | 90 |
| 8 | 0.0045 | 0.0052 | 0.0041 | 0.0046 | 5.18 | 0.104 | 0.98 | 90 |
| 10 | 0.0047 | 0.0055 | 0.0051 | 0.0051 | 5.71 | 0.114 | 0.94 | 89 |
| 12 | 0.0058 | 0.0042 | 0.0043 | 0.0048 | 5.36 | 0.107 | 0.97 | 89 |
| 14 | 0.0054 | 0.0040 | 0.0054 | 0.0049 | 5.52 | 0.110 | 0.96 | 89 |
| 16 | 0.0056 | 0.0042 | 0.0053 | 0.0050 | 5.64 | 0.113 | 0.95 | 89 |
| 18 | 0.0044 | 0.0057 | 0.0041 | 0.0047 | 5.33 | 0.107 | 0.97 | 89 |
| 20 | 0.0051 | 0.0052 | 0.0051 | 0.0051 | 5.74 | 0.115 | 0.94 | 89 |
| 22 | 0.0053 | 0.0049 | 0.0047 | 0.0050 | 5.57 | 0.111 | 0.95 | 89 |
| 24 | 0.0056 | 0.0023 | 0.0032 | 0.0037 | 4.29 | 0.086 | 1.07 | 91 |
| 26 | 0.0011 | 0.0027 | 0.0030 | 0.0023 | 2.85 | 0.057 | 1.24 | 94 |
| 28 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 9.11 | 0.018 | 1.74 | 98 |
| 30 | 0.0002 | 0.0003 | 0.0002 | 0.0002 | 8.37 | 0.017 | 1.78 | 98 |
| 32 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 7.29 | 0.015 | 1.84 | 99 |
| 34 | 0.0001 | 0.0003 | 0.0001 | 0.0002 | 7.83 | 0.016 | 1.81 | 98 |

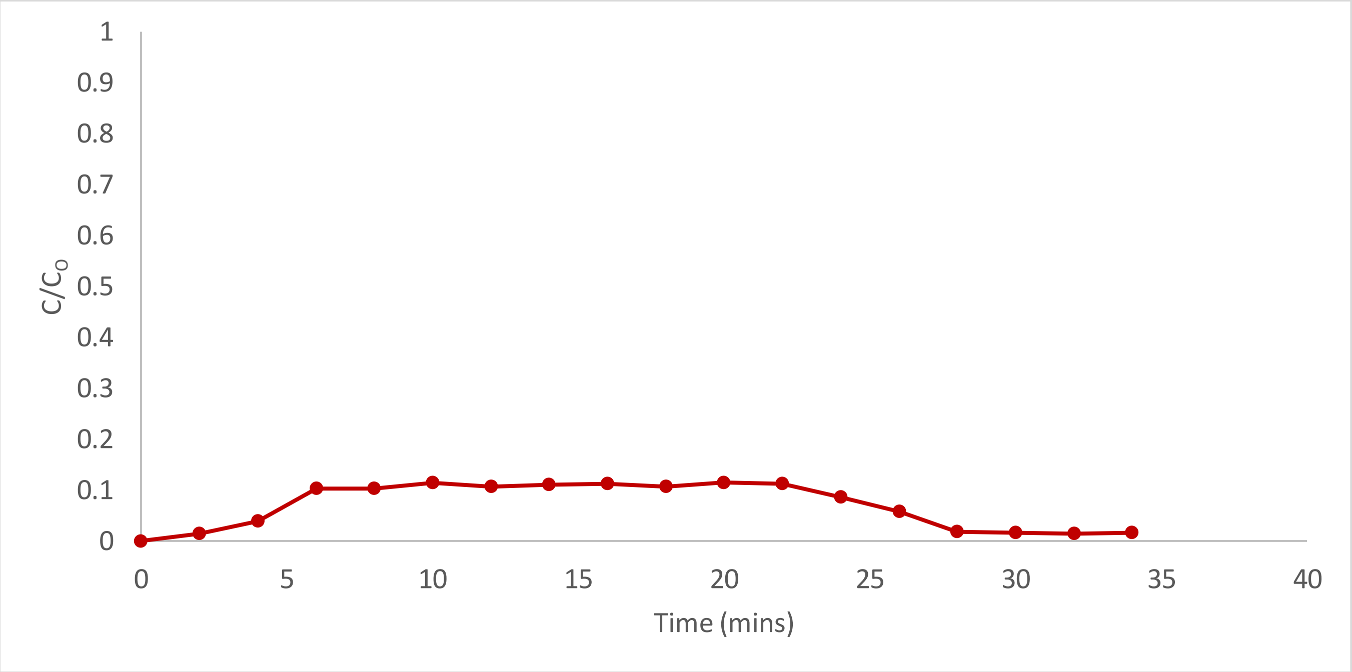

Figure A6: Breakthrough curve of 10 µm PS microplastics (trial 1).

**10 µm PS microplastics - Trial 2**

Table A7: Data for generating calibration curve of 10 µm PS microplastics (trial 2).

| Dilution | Absorbance (343 nm) | | | Avg. absorbance (nm) |
|---:|---:|---:|---:|---:|
| 50,000,000 | 0.0869 | 0.0861 | 0.0881 | 0.0871 |
| 30,000,000 | 0.0553 | 0.0552 | 0.0525 | 0.0544 |
| 10,000,000 | 0.0141 | 0.0145 | 0.0138 | 0.0142 |
| 5,000,000 | 0.0113 | 0.0114 | 0.0114 | 0.0114 |
| 3,000,000 | 0.0072 | 0.0085 | 0.0075 | 0.0077 |
| 1,000,000 | 0.0051 | 0.0053 | 0.0051 | 0.0052 |
| 100,000 | 0.0052 | 0.0050 | 0.0067 | 0.0056 |
| 50,000 | 0.0011 | 0.0023 | 0.0014 | 0.0016 |
| 30,000 | 0.0009 | 0.0009 | 0.0009 | 0.0009 |
| 10,000 | 0.0007 | 0.0009 | 0.0008 | 0.0008 |
| 50 | 0.0000 | 0.0001 | 0.0000 | 0.0000 |

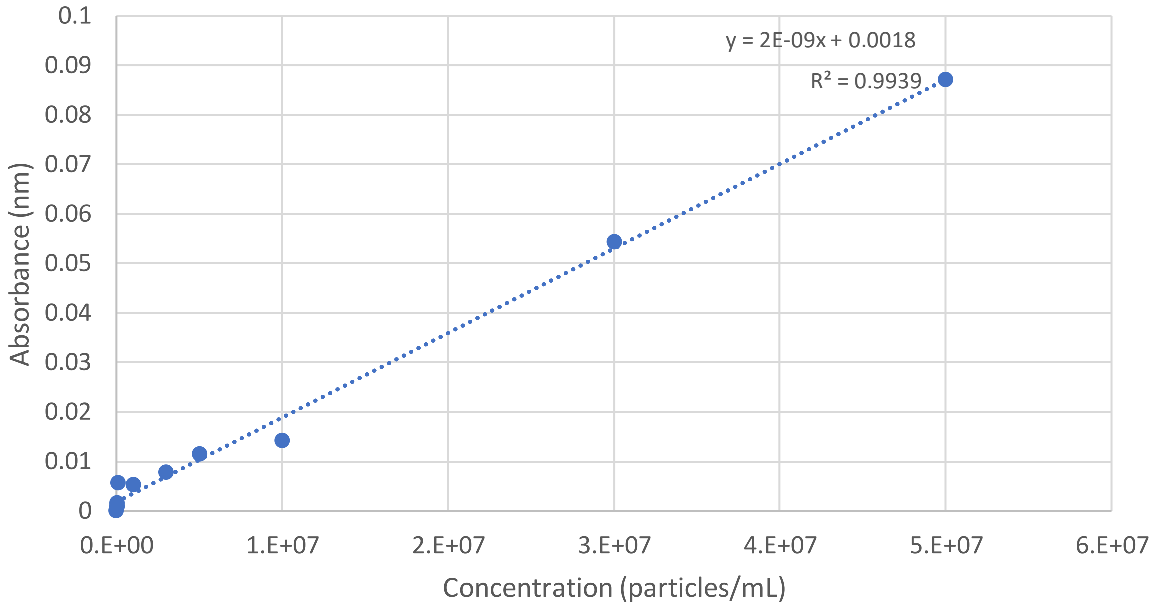

Figure A7: Calibration curve for 10 µm PS microplastics with absorbance measured at 343 nm (trial 2).

Table A8: Experimental data collected from column study with 10 µm PS microplastics (trial 2).

| Time (mins) | Absorbance (363 nm) | | | Avg. absorbance (nm) | Concentration (C) X $10^6$ | C/Co | Log (C/Co) | % removal |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.0013 | 0.0012 | 0.0014 | 0.0013 | 0 | 0.000 | - | |
| 4 | 0.0011 | 0.0019 | 0.0021 | 0.0017 | 0 | 0.000 | - | |
| 6 | 0.0029 | 0.0025 | 0.0025 | 0.0026 | 1.68 | 0.034 | 1.47 | 97 |
| 8 | 0.0031 | 0.0032 | 0.0030 | 0.0031 | 2.67 | 0.053 | 1.27 | 95 |
| 10 | 0.0033 | 0.0031 | 0.0032 | 0.0032 | 2.84 | 0.057 | 1.25 | 94 |
| 12 | 0.0034 | 0.0034 | 0.0035 | 0.0034 | 3.21 | 0.064 | 1.19 | 94 |
| 14 | 0.0034 | 0.0032 | 0.0033 | 0.0033 | 3.04 | 0.061 | 1.22 | 94 |
| 16 | 0.0033 | 0.0032 | 0.0037 | 0.0034 | 3.21 | 0.064 | 1.19 | 94 |
| 18 | 0.0033 | 0.0034 | 0.0036 | 0.0035 | 3.30 | 0.066 | 1.18 | 93 |
| 20 | 0.0035 | 0.0035 | 0.0033 | 0.0034 | 3.29 | 0.066 | 1.18 | 93 |
| 22 | 0.0034 | 0.0034 | 0.0034 | 0.0034 | 3.21 | 0.064 | 1.19 | 94 |
| 24 | 0.0032 | 0.0031 | 0.0031 | 0.0031 | 2.61 | 0.052 | 1.28 | 95 |
| 26 | 0.0021 | 0.0023 | 0.0023 | 0.0022 | 8.44 | 0.017 | 1.77 | 98 |
| 28 | 0.0022 | 0.0022 | 0.0022 | 0.0022 | 7.54 | 0.015 | 1.82 | 98 |
| 30 | 0.0020 | 0.0020 | 0.0021 | 0.0020 | 4.74 | 0.009 | 2.02 | 99 |
| 32 | 0.0012 | 0.0016 | 0.0019 | 0.0016 | 0 | 0.000 | - | |
| 34 | 0.0011 | 0.0015 | 0.0015 | 0.0014 | 0 | 0.000 | - | |

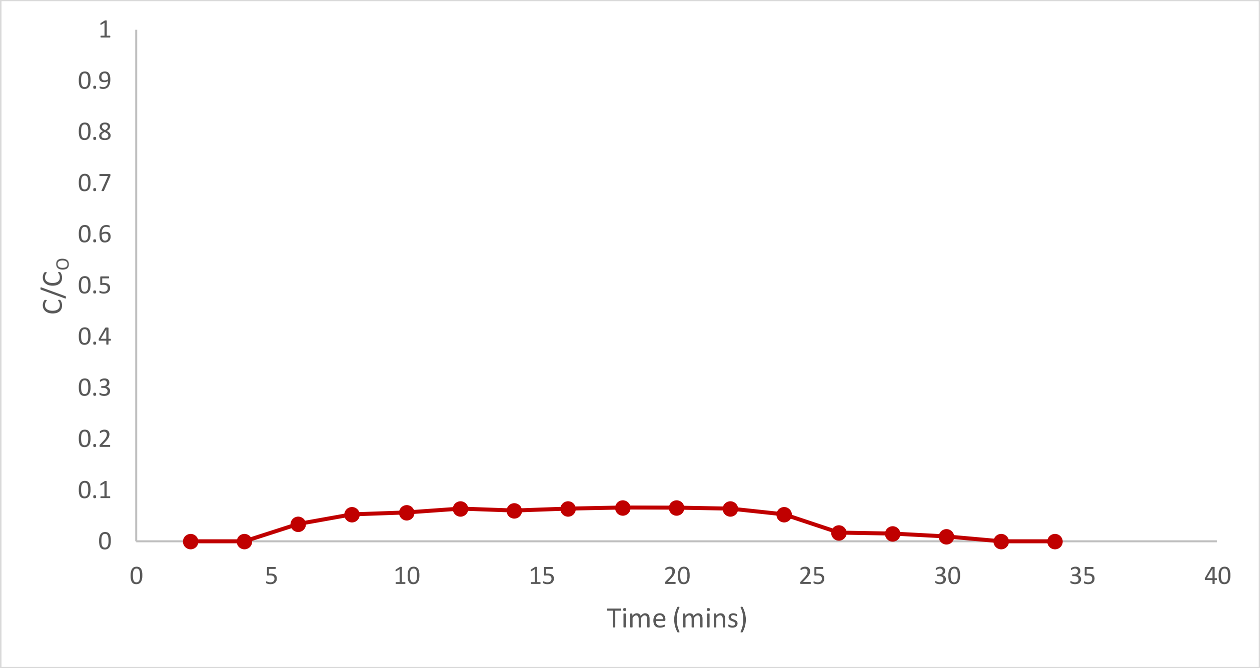

Figure A8: Breakthrough curve of 10 µm PS microplastics (trial 1).

### 45 µm PS microplastics – Trial 1

Table A9: Data for generating calibration curve of 45 µm PS microplastics (trial 1).

| Dilution | Absorbance (364 nm) | | | Avg. absorbance (nm) |
|---:|---:|---:|---:|---:|
| 50,000,000 | 1.2530 | 1.1097 | 1.1096 | 1.1574 |
| 30,000,000 | 0.6989 | 0.7124 | 0.6657 | 0.6923 |
| 500,000 | 0.0203 | 0.0303 | 0.0398 | 0.0302 |
| 5,000 | 0.0009 | 0.0008 | 0.0010 | 0.0009 |
| 50 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

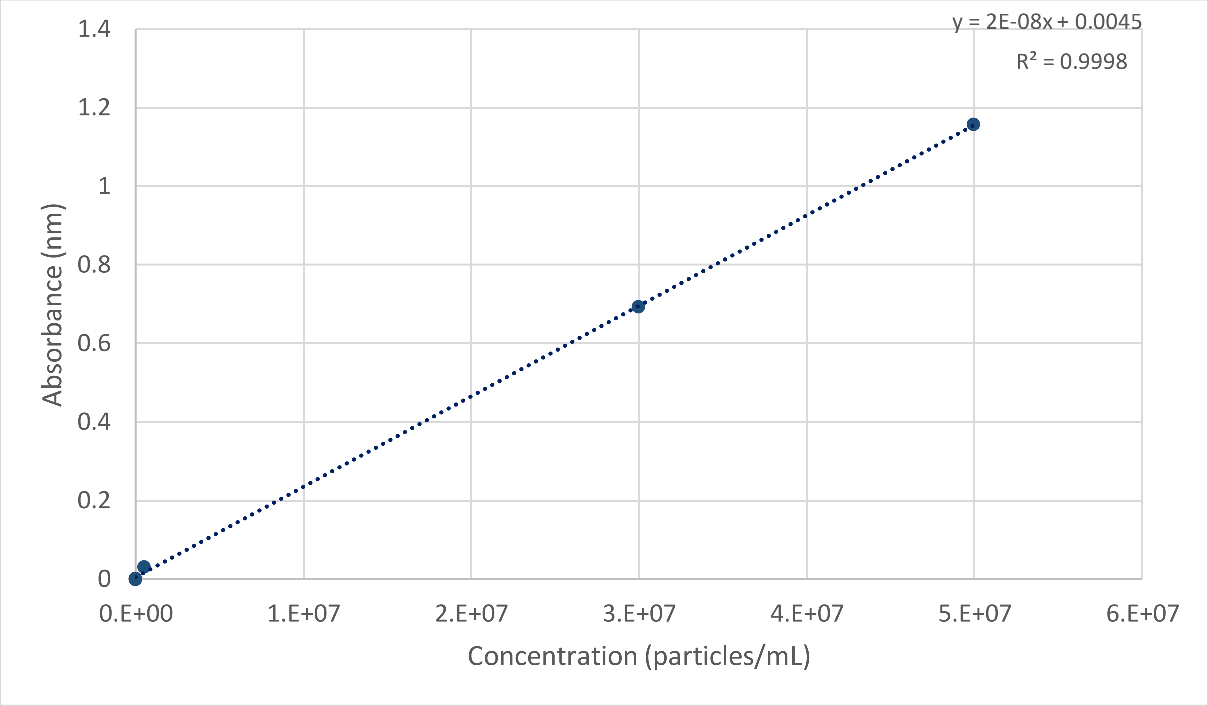

Figure A9: Calibration curve for 45 µm PS microplastics with absorbance measured at 364 nm (trial 1).

Table A10: Experimental data collected from column study with 45 µm PS microplastics (trial 1).

| Time (mins) | Absorbance (364 nm) | | | Avg. absorbance (nm) | Concentration (C) x $10^4$ | C/Co | Log (C/Co) |
|---|---|---|---|---|---|---|---|
| 0 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0 | 0.0000 | 0.00 |
| 2 | 0.0033 | 0.0034 | 0.0034 | 0.0033 | 0 | 0.0000 | 0.00 |
| 4 | 0.0035 | 0.0035 | 0.0035 | 0.0035 | 0 | 0.0000 | 0.00 |
| 6 | 0.0047 | 0.0047 | 0.0047 | 0.0047 | 0.87 | 0.0002 | 3.76 |
| 8 | 0.0059 | 0.0059 | 0.0059 | 0.0059 | 7.08 | 0.0014 | 2.85 |
| 10 | 0.0053 | 0.0057 | 0.0058 | 0.0056 | 5.54 | 0.0011 | 2.96 |
| 12 | 0.0060 | 0.0061 | 0.0062 | 0.0061 | 7.95E | 0.0016 | 2.80 |
| 14 | 0.0062 | 0.0061 | 0.0060 | 0.0061 | 7.96 | 0.0016 | 2.80 |
| 16 | 0.0062 | 0.0062 | 0.0062 | 0.0062 | 8.37 | 0.0017 | 2.78 |
| 18 | 0.0060 | 0.0061 | 0.0061 | 0.0060 | 7.70 | 0.0015 | 2.81 |
| 20 | 0.0059 | 0.0059 | 0.0060 | 0.0059 | 7.02 | 0.0014 | 2.85 |
| 22 | 0.0063 | 0.0059 | 0.0059 | 0.0060 | 7.48 | 0.0015 | 2.82 |
| 24 | 0.0058 | 0.0058 | 0.0058 | 0.0058 | 6.59 | 0.0013 | 2.88 |
| 26 | 0.0059 | 0.0059 | 0.0059 | 0.0059 | 6.94 | 0.0014 | 2.86 |
| 28 | 0.0059 | 0.0061 | 0.0061 | 0.0060 | 7.65 | 0.0015 | 2.82 |
| 30 | 0.0060 | 0.0060 | 0.0060 | 0.0060 | 7.33 | 0.0015 | 2.83 |
| 32 | 0.0061 | 0.0061 | 0.0062 | 0.0061 | 8.19 | 0.0016 | 2.79 |
| 34 | 0.0060 | 0.0062 | 0.0061 | 0.0061 | 8.06 | 0.0016 | 2.79 |
| 36 | 0.0049 | 0.0048 | 0.0048 | 0.0048 | 1.66 | 0.0003 | 3.48 |

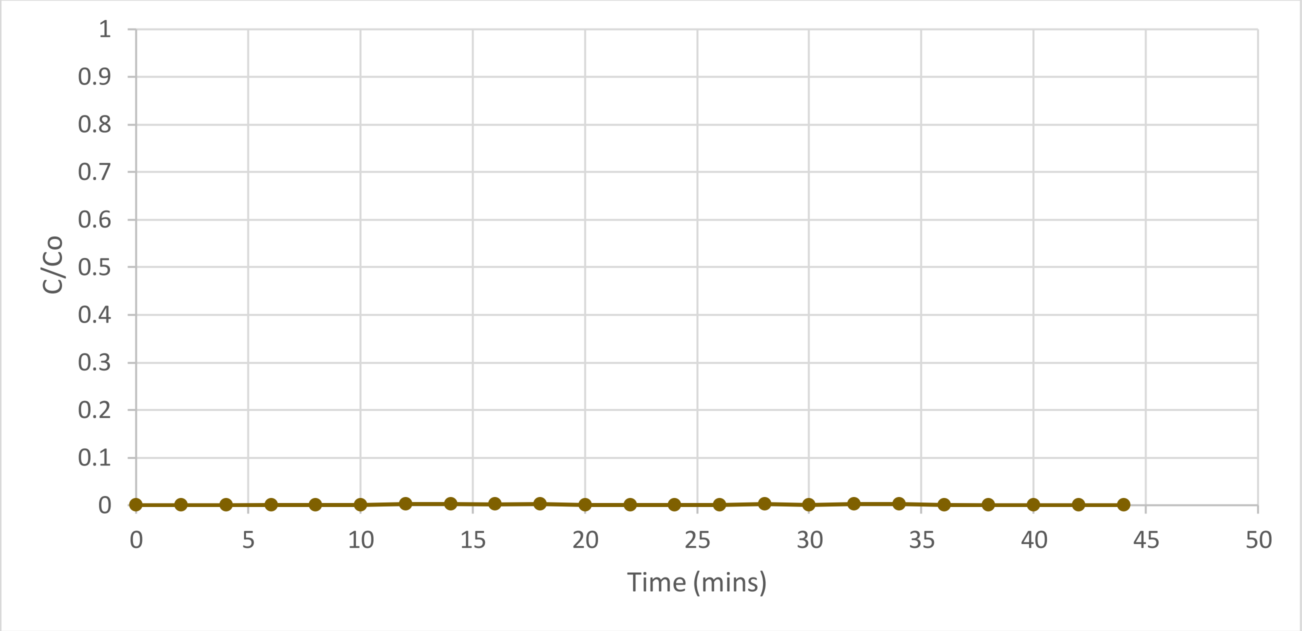

Figure A10: Breakthrough curve for 45 µm PS microplastics with absorbance measured at 364 nm (trial 1).

### 45 µm PS microplastics – Trial 2

Table A11: Data for generating calibration curve of 45 µm PS microplastics (trial 2).

| Dilution | Absorbance (364 nm) | | | Avg. absorbance (nm) |
|---|---|---|---|---|
| 50,000,000 | 1.253 | 1.110 | 1.110 | 1.157 |
| 30,000,000 | 0.699 | 0.712 | 0.666 | 0.692 |
| 500,000 | 0.020 | 0.030 | 0.040 | 0.030 |
| 5,000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 50 | 0.000 | 0.000 | 0.000 | 0.000 |

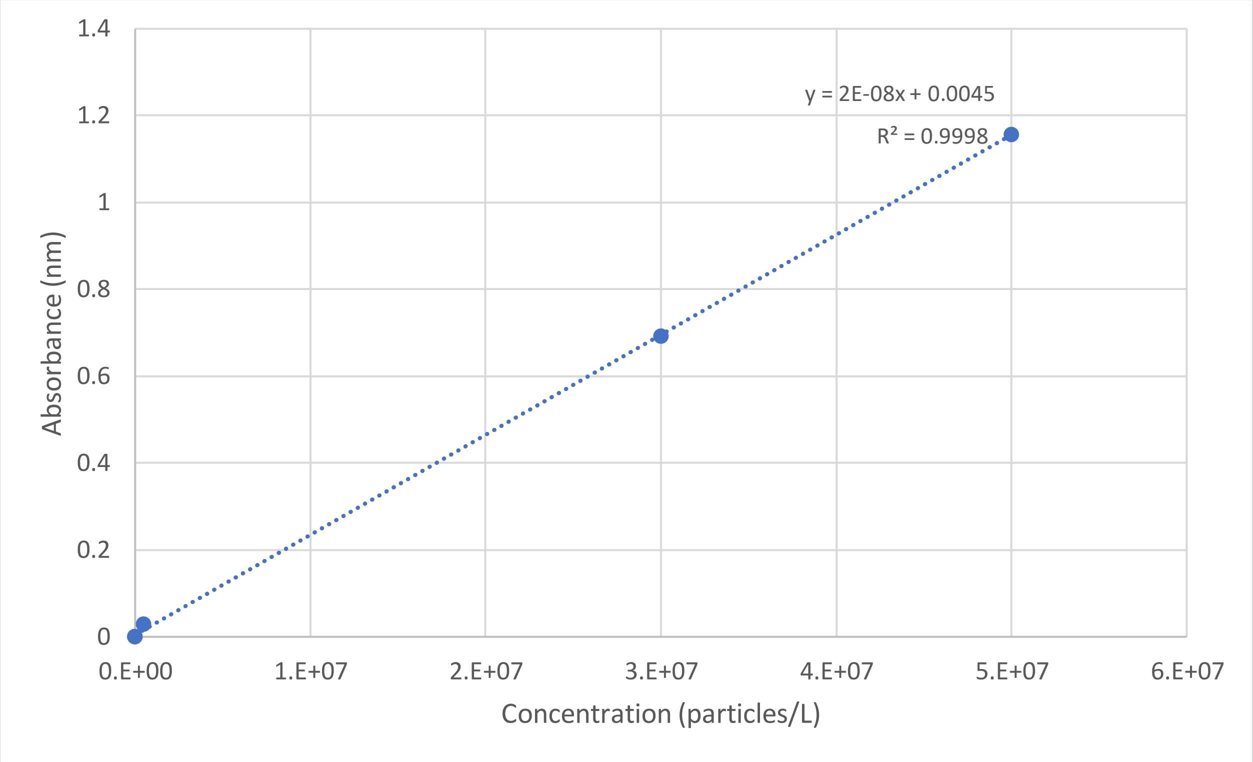

Figure A11: Calibration curve for 45 µm PS microplastics with absorbance measured at 364 nm (trial 2).

Table A12: Experimental data collected from column study with 45 µm PS microplastics (trial 2).

| Time | Absorbance (364 nm) | | | Avg. absorbance (nm) | Concentration (C) x $10^4$ | C/Co | Log (C/Co) |
|---|---|---|---|---|---|---|---|
| 0 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0 | 0.0000 | 0.00 |
| 2 | 0.0033 | 0.0034 | 0.0034 | 0.0033 | 0 | 0.0000 | 0.00 |
| 4 | 0.0035 | 0.0035 | 0.0035 | 0.0035 | 0 | 0.0000 | 0.00 |
| 6 | 0.0047 | 0.0047 | 0.0047 | 0.0047 | 0.90 | 0.0002 | 3.76 |
| 8 | 0.0059 | 0.0059 | 0.0059 | 0.0059 | 7.10 | 0.0014 | 2.85 |
| 10 | 0.0053 | 0.0057 | 0.0058 | 0.0056 | 5.70 | 0.0011 | 2.96 |
| 12 | 0.0060 | 0.0061 | 0.0062 | 0.0061 | 8.00 | 0.0016 | 2.80 |
| 14 | 0.0062 | 0.0061 | 0.0060 | 0.0061 | 8.00 | 0.0016 | 2.80 |
| 16 | 0.0062 | 0.0062 | 0.0062 | 0.0062 | 8.40 | 0.0017 | 2.78 |
| 18 | 0.0060 | 0.0061 | 0.0061 | 0.0060 | 8.00 | 0.0015 | 2.81 |
| 20 | 0.0059 | 0.0059 | 0.0060 | 0.0059 | 7.02 | 0.0014 | 2.85 |
| 22 | 0.0063 | 0.0059 | 0.0059 | 0.0060 | 7.50 | 0.0015 | 2.82 |
| 24 | 0.0058 | 0.0058 | 0.0058 | 0.0058 | 6.60 | 0.0013 | 2.88 |
| 26 | 0.0059 | 0.0059 | 0.0059 | 0.0059 | 6.94 | 0.0014 | 2.86 |
| 28 | 0.0059 | 0.0061 | 0.0061 | 0.0060 | 7.70 | 0.0015 | 2.82 |
| 30 | 0.0060 | 0.0060 | 0.0060 | 0.0060 | 7.33 | 0.0015 | 2.83 |
| 32 | 0.0061 | 0.0061 | 0.0062 | 0.0061 | 8.20 | 0.0016 | 2.79 |
| 34 | 0.0060 | 0.0062 | 0.0061 | 0.0061 | 8.06 | 0.0016 | 2.79 |
| 36 | 0.0049 | 0.0048 | 0.0048 | 0.0048 | 1.70 | 0.0003 | 3.48 |

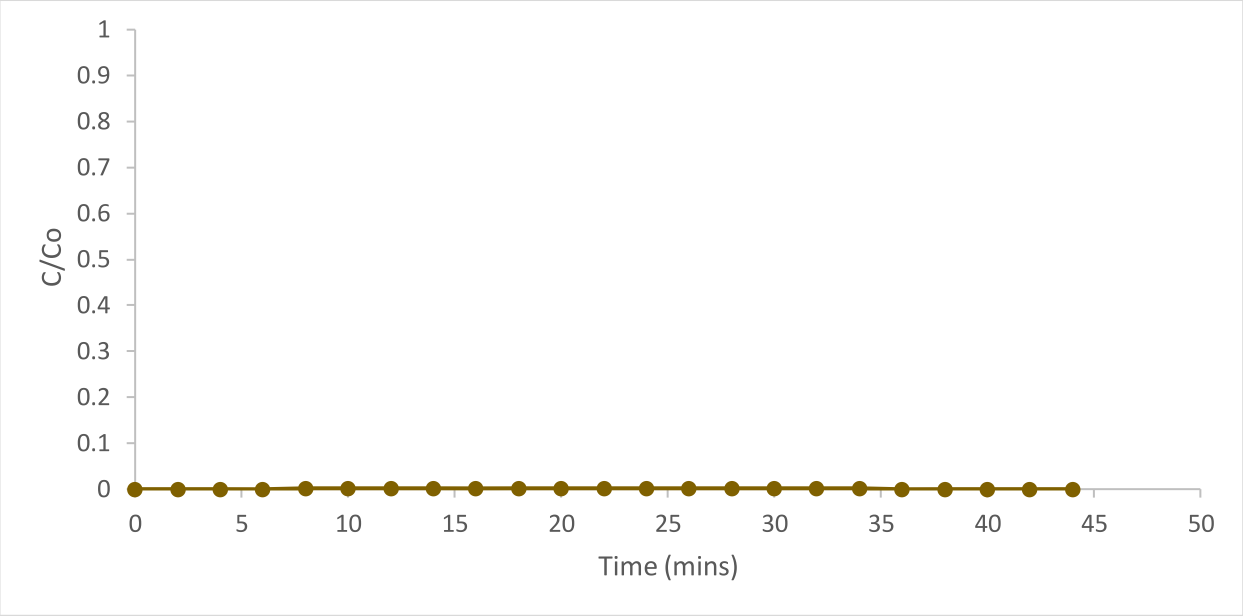

Figure A12: Calibration curve for 45 µm PS microplastics with absorbance measured at 364 nm (trial 2).

Grain size analysis

| | |
|---|---|
| **Start Weight** | 251.43 g |
| **End Weight** | 250.96 g |
| **Percent Loss** | 0.19% |

Table A13: Grain size analysis data for characterizing soil particles used in the column study.

| Sieve No. | Diameter (mm) | Mass Retained (g) | Percent Retained (%) | Cumulative Retained (%) | Cumulative Passing (%) |
|---|---|---|---|---|---|
| 4 | 4.75 | 0 | 0.00 | 0.00 | 100.00 |
| 5 | 4.00 | 0 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 0 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 0 | 0.00 | 0.00 | 100.00 |
| 30 | 0.60 | 0.1 | 0.04 | 0.04 | 99.96 |
| 50 | 0.30 | 90.4 | 35.95 | 35.99 | 64.01 |
| 70 | 0.210 | 159.12 | 63.29 | 99.28 | 0.72 |
| 100 | 0.150 | 1.31 | 0.52 | 99.80 | 0.20 |
| 270 | 0.053 | 0.03 | 0.01 | 99.81 | 0.19 |
| 400 | 0.038 | 0 | 0.00 | 99.81 | 0.19 |
| Pan | | 0 | 0.00 | 99.81 | 0.19 |
| | **Total** | **250.96** | **99.81** | | |

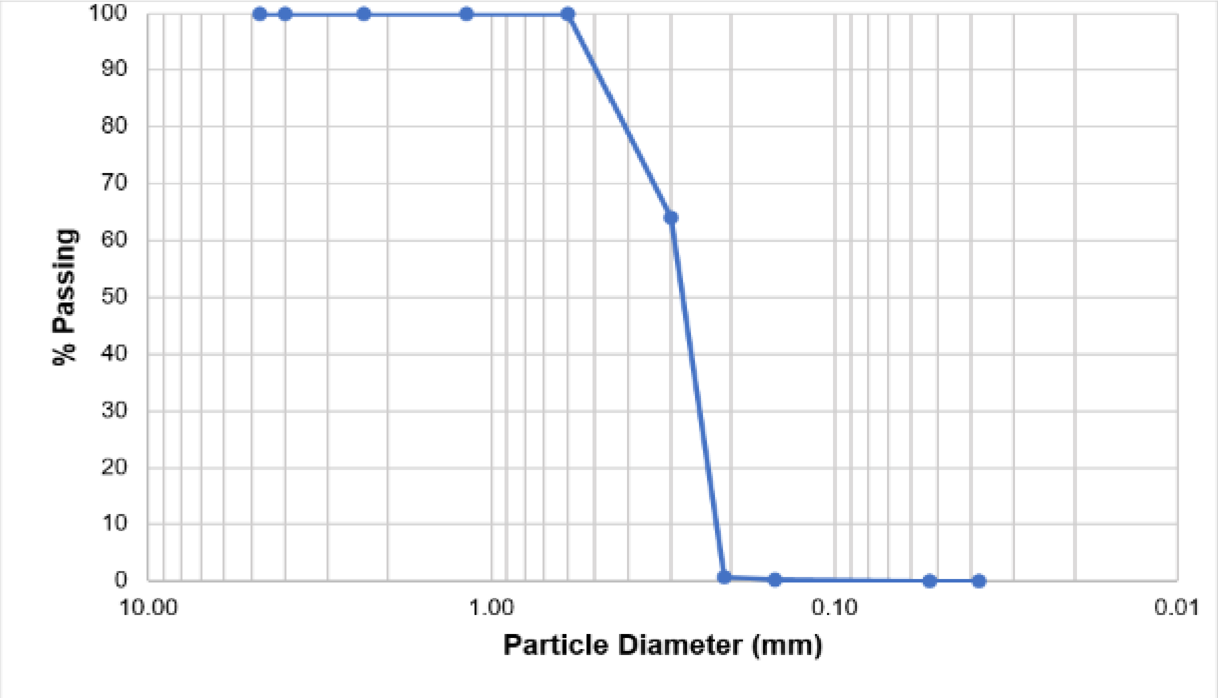

Figure A13: Soil grain size distribution curve.

# Appendix B:

## Detailed Microplastics Calculator data, example calculations, and outputs

*Sample calculation*

Calculating the threshold microplastics concentration (TMC) for spherical polyvinylchloride (PVC) microplastics of size 1 µm contaminated with antimony (Sb). For spheres, cylinders and oblate spheroids, the size refers to diameter, cross-sectional diameter, and equatorial diameter respectively

Density ($\rho$) of PVC = **1.39 g/cm$^3$**
Adsorption capacity ($AC_{LA}$) of Antimony = **27.8 mg/g**
The microplastics size used in the experiment from where the $AC_R$ was collected = **1000 µm**

Lowest health standard of antimony is an RfD (Reference dose) of **0.004 mg/day**. For a conservative estimation, the assessment was performed assuming consumption of this amount per liter of drinking water.

**Note:** The shape of microplastics particles was not reported and was assumed to be spheres, cylinders (long and short) or oblate spheroids (e= 0.2 and e = 0.9) when calculating TMC for spheres, cylinders, or oblate spheroids, respectively.

The total number of particles per gram ($N_{ijp}$) of 1 µm sized (i) spherical (sp) (j) PVC microplastics (p) is calculated:

$$\boldsymbol{N_{ijp} = \frac{1}{\rho_p \times V_{ij}}}$$

Here, $V_{ij}$ is the volume of a particle of a given size (i) and shape (j). The volume for 1 µm sized spherical particle is calculated as:

$$\mathbf{V_{1,\,sp}} = \frac{4}{3}\pi\times\left(\frac{d}{2}\right)^3 = \frac{4}{3}\pi\times\left(\frac{1}{2}\right)^3 = \mathbf{0.52360\ \mu m^3}$$

$$\boldsymbol{N_{1,sp,pvc}} = \frac{1}{\rho_{pvc}\times V_{1,sp}} = \frac{10^{12}}{1.39\times 0.5236}.\left(\frac{1}{\frac{g}{cm^3}\times cm^3}\right) = \mathbf{1.38\ x\ 10^{12}\ particles/g}$$

The total surface area per gram of 1 µm sized spherical PVC microplastics:

$$\boldsymbol{TSA_{1,sp,pvc} = N_{1,sp,pvc} \times A_{1,sp},}$$

where $A_{1,\,sp}$ is the surface area of one 1 µm sized spherical particle.

$$\boldsymbol{A_{1,sp}} = 4\pi\times\left(\frac{d}{2}\right)^2 = 4\pi\times\left(\frac{1}{2}\right)^2 = \mathbf{3.142\ \mu m^2}$$

$\boldsymbol{TSA_{1,sp,pvc}} = \frac{1.37\ x\ 10^{12}\ x\ 3.142}{10^{12}}.\left(\frac{particles}{g}\times m^2\right)$ = **4.32 m$^2$/g** of 1 µm sized spherical PVC microplastics.

The total surface area of microplastics as reported, $TSA_R$, here (i = 1000, j = sphere, p = pvc)

$$\boldsymbol{TSA_{R_{ijp}}} = \boldsymbol{N_{1000,sp,pvc}} \times \boldsymbol{A_{1000,sp}} = 1375 \left(\frac{particles}{g}\right) \text{ x } 3.14 \text{ x } 10^{6}\ (\mu\text{m}^2) \text{ x } \frac{1}{10^{12}} \cdot \left(\frac{m^2}{\mu\text{m}^2}\right) = \mathbf{0.00432\ m^2/g}$$

Normalized adsorption capacity concentration, $AC_M$ (mg/g):

$$\mathbf{AC_M = AC_{LA}} \times \frac{\boldsymbol{TSA_{1,sp,pvc}}}{\boldsymbol{TSA_{R_{1000,sp,pvc}}}} \mathbf{=} 27.8 \left(\frac{mg}{g}\right) \text{ x } \frac{4.32}{0.00432} \cdot \left(\frac{\frac{m^2}{g}}{\frac{m^2}{g}}\right) = \mathbf{27800\ mg/g}$$

The TMC is then calculated:

$$\mathbf{TMC} = \frac{\boldsymbol{H_x}}{\boldsymbol{AC_M}} \times \boldsymbol{N_{1,sp,pvc}} \times \mathbf{1000} = \frac{0.004}{27800} \cdot \left(\frac{\frac{mg}{L}}{\frac{mg}{g}}\right) \text{ x } 1.38 \text{ x } 10^{12} \left(\frac{particles}{g}\right) = \mathbf{1.986 \text{ x } 10^{8}\ particles/L}$$

The calculation assumes a well operated drinking water treatment with a 3 Log particle removal from its source water which is accounted for in the TMC equation by a multiplication factor of 1000.

The above was iterated through all combinations of microplastics type, shape, size and contaminants.

Table B1: Adsorption capacities microplastics and their health standard values used in TMC calculations.

| Contaminant | | | | One-day (mg/L) | Ten-day (mg/L) | RfD (mg/kg/day) | DWEL (mg/L) | Life-time (mg/L) | MCL (mg/L) | Lowest PNEC (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| BPA | PVC | 13.2 | 0.19 | | | | | | | 0.00006 |
| BPS | | | 0.15 | | | | | | | |
| BPF | | | 0.16 | | | | | | | |
| BPB | | | 0.22 | | | | | | | |
| BPAF | | | 0.24 | | | | | | | |
| Sulfamethoxazole | PE | 45-48 | 0.087 | | | | | | | 0.02 |
| Propanolol | | | 0.133 | | | | | | | 0.0005 |
| Sertraline | | | 0.33 | | | | | | | |
| Aluminum | PET | 2000 | 0.375 | | | | | | 2.9 | |
| Chromium | | | 0.000454 | 1 | 1 | 0.003 | 0.1 | | 0.1 | |
| Manganese | | | 0.13 | 1 | 1 | 0.14 | 1.6 | 0.3 | 0.12 | |
| Iron | HDPE | 3000 | 0.26 | | | | | | | |
| Cobalt | LDPE | 3000 | 0.000658 | | | | | | | |
| Nickel | PVC | 3000 | 0.000581 | | | | | | | |
| Zinc | PP | 3000 | 0.008384 | 6 | 6 | 0.3 | 10 | 2 | | |
| Cadmium | | | 0.00014 | 0.04 | 0.04 | 0.0005 | 0.02 | 0.005 | | |
| Lead | | | 0.001873 | | | | | | 0.015 | |
| Tributylacetylcitrate | | | 0.0005 | | | | | | | |
| Tris(2chloro propyl) phosphate | | | 0.0004 | | | | | | | |
| PAHs | | | 0.0000056 | | | | | | | |
| OCPs | | | 0.0000113 | | | | | | | |
| triazines | | | 0.0000109 | | | | | | | |
| OPPs | | | 0.0000179 | | | | | | | |
| PCPs | | | 0.000116 | | | | | | | |
| Copper | PET | | 0.055 | | | | | | 1.3 | |

| **Contaminant** | | | | **One-day (mg/L)** | **Ten-day (mg/L)** | **RfD (mg/kg/day)** | **DWEL (mg/L)** | **Life-time (mg/L)** | **MCL (mg/L)** | **Lowest PNEC (mg/L)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Zinc | | | 0.045 | | | | | | | |
| PCB | Resin pellet | | | | | | | | 0.0005 | |
| Pyrene | | | | | | 0.03 | | | | |
| Cadmium | PE | | 1 | 0.04 | 0.04 | 0.0005 | 0.02 | 0.005 | | |
| Lead | PP | | 1 | | | | | | 0.015 | |
| Bromine | PS | | 13 | 0.2 | | 0.004 | 0.14 | | 0.01 | |
| Benzene | PP, PS | | | 0.2 | 0.2 | 0.004 | 0.1 | 0.003 | 0.005 | |
| Toluene | | | | 20 | 2 | 0.08 | 3 | | 0.06 | |
| Ethylbenzene | | | | 30 | 3 | 0.1 | 3 | 0.7 | 0.7 | |
| Xylene | | | | 40 | 40 | 0.2 | 7 | | 0.09 | |
| Tertiarybutylethers | | | | | | | | | | |
| Mercury | HDPE | 4.5 | 0.00125 | 0.002 | 0.002 | 0.0003 | 0.01 | 0.002 | 0.002 | |
| Lead | PE | 500 | | | | | | | 0.015 | |
| Chromium | | | | | | | | | | |
| Cadmium<br>Antimony<br>Arsenic | PVC | 75 | 0.151 | 0.04 | 0.04 | 0.0005 | 0.02 | 0.005 | | |
| | PS | | 0.134 | | | | | | | |
| | PP | | 0.124 | | | | | | | |
| | PE | | 0.114 | | | | | | | |
| Antimony | PS | 1000 | 0.89 | 0.01 | 0.01 | 0.0004 | 0.01 | 0.006 | 0.006 | |
| | PC | | 27.8 | | | | | | | |
| | PE | | 2.17 | | | | | | | |
| | PET | | 0.37 | | | | | | | |
| | PVC | | 6.26 | | | | | | | |
| Arsenic | PS | 0.1 – 1 | 1.92 | | | 0.0003 | 0.01 | | 0.01 | |
| | | 1 to 10 | | | | | | | | |
| | | 10 - 100 | | | | | | | | |

Table B2: TMCs for all combinations of contaminants (11), microplastics type (7), shape (5) and size (9).

| | | | TMC (#/L) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Microplastic size ($\mu$m) | | | | | | | | |
| **Contaminant** | **MP** | **Shape** | **1** | **10** | **20** | **50** | **100** | **150** | **300** | **500** | **750** |
| Aluminum | HDPE | SP | 7.61E+12 | 7.61E+10 | 1.90E+10 | 3.04E+09 | 7.61E+08 | 3.38E+08 | 8.45E+07 | 3.04E+07 | 1.35E+07 |
| Aluminum | HDPE | LC | 5.07E+11 | 5.07E+09 | 1.27E+09 | 2.03E+08 | 5.07E+07 | 2.25E+07 | 5.63E+06 | 2.03E+06 | 9.01E+05 |
| Aluminum | HDPE | SC | 5.07E+13 | 5.07E+11 | 1.27E+11 | 2.03E+10 | 5.07E+09 | 2.25E+09 | 5.63E+08 | 2.03E+08 | 9.01E+07 |
| Aluminum | HDPE | OS_0.2 | 7.76E+12 | 7.76E+10 | 1.94E+10 | 3.11E+09 | 7.76E+08 | 3.45E+08 | 8.63E+07 | 3.11E+07 | 1.38E+07 |
| Aluminum | HDPE | OS_0.9 | 1.75E+13 | 1.75E+11 | 4.36E+10 | 6.98E+09 | 1.75E+09 | 7.76E+08 | 1.94E+08 | 6.98E+07 | 3.10E+07 |
| Aluminum | PC | SP | 5.98E+12 | 5.98E+10 | 1.50E+10 | 2.39E+09 | 5.98E+08 | 2.66E+08 | 6.65E+07 | 2.39E+07 | 1.06E+07 |
| Aluminum | PC | LC | 3.99E+11 | 3.99E+09 | 9.97E+08 | 1.60E+08 | 3.99E+07 | 1.77E+07 | 4.43E+06 | 1.60E+06 | 7.09E+05 |
| Aluminum | PC | SC | 3.99E+13 | 3.99E+11 | 9.97E+10 | 1.60E+10 | 3.99E+09 | 1.77E+09 | 4.43E+08 | 1.60E+08 | 7.09E+07 |
| Aluminum | PC | OS_0.2 | 6.11E+12 | 6.11E+10 | 1.53E+10 | 2.44E+09 | 6.11E+08 | 2.71E+08 | 6.78E+07 | 2.44E+07 | 1.09E+07 |
| Aluminum | PC | OS_0.9 | 1.37E+13 | 1.37E+11 | 3.43E+10 | 5.49E+09 | 1.37E+09 | 6.10E+08 | 1.52E+08 | 5.49E+07 | 2.44E+07 |
| Aluminum | PE | SP | 8.57E+12 | 8.57E+10 | 2.14E+10 | 3.43E+09 | 8.57E+08 | 3.81E+08 | 9.52E+07 | 3.43E+07 | 1.52E+07 |
| Aluminum | PE | LC | 5.71E+11 | 5.71E+09 | 1.43E+09 | 2.28E+08 | 5.71E+07 | 2.54E+07 | 6.35E+06 | 2.28E+06 | 1.02E+06 |
| Aluminum | PE | SC | 5.71E+13 | 5.71E+11 | 1.43E+11 | 2.28E+10 | 5.71E+09 | 2.54E+09 | 6.35E+08 | 2.28E+08 | 1.02E+08 |
| Aluminum | PE | OS_0.2 | 8.74E+12 | 8.74E+10 | 2.19E+10 | 3.50E+09 | 8.74E+08 | 3.89E+08 | 9.71E+07 | 3.50E+07 | 1.55E+07 |
| Aluminum | PE | OS_0.9 | 1.97E+13 | 1.97E+11 | 4.91E+10 | 7.86E+09 | 1.97E+09 | 8.73E+08 | 2.18E+08 | 7.86E+07 | 3.49E+07 |
| Aluminum | PET | SP | 5.39E+12 | 5.39E+10 | 1.35E+10 | 2.16E+09 | 5.39E+08 | 2.40E+08 | 5.99E+07 | 2.16E+07 | 9.58E+06 |
| Aluminum | PET | LC | 3.59E+11 | 3.59E+09 | 8.98E+08 | 1.44E+08 | 3.59E+07 | 1.60E+07 | 3.99E+06 | 1.44E+06 | 6.39E+05 |
| Aluminum | PET | SC | 3.59E+13 | 3.59E+11 | 8.98E+10 | 1.44E+10 | 3.59E+09 | 1.60E+09 | 3.99E+08 | 1.44E+08 | 6.39E+07 |
| Aluminum | PET | OS_0.2 | 5.50E+12 | 5.50E+10 | 1.38E+10 | 2.20E+09 | 5.50E+08 | 2.45E+08 | 6.11E+07 | 2.20E+07 | 9.78E+06 |
| Aluminum | PET | OS_0.9 | 1.24E+13 | 1.24E+11 | 3.09E+10 | 4.95E+09 | 1.24E+09 | 5.50E+08 | 1.37E+08 | 4.95E+07 | 2.20E+07 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | PP | SP | 8.71E+12 | 8.71E+10 | 2.18E+10 | 3.49E+09 | 8.71E+08 | 3.87E+08 | 9.68E+07 | 3.49E+07 | 1.55E+07 |
| Aluminum | PP | LC | 5.81E+11 | 5.81E+09 | 1.45E+09 | 2.32E+08 | 5.81E+07 | 2.58E+07 | 6.45E+06 | 2.32E+06 | 1.03E+06 |
| Aluminum | PP | SC | 5.81E+13 | 5.81E+11 | 1.45E+11 | 2.32E+10 | 5.81E+09 | 2.58E+09 | 6.45E+08 | 2.32E+08 | 1.03E+08 |
| Aluminum | PP | OS_0.2 | 8.89E+12 | 8.89E+10 | 2.22E+10 | 3.56E+09 | 8.89E+08 | 3.95E+08 | 9.88E+07 | 3.56E+07 | 1.58E+07 |
| Aluminum | PP | OS_0.9 | 2.00E+13 | 2.00E+11 | 5.00E+10 | 8.00E+09 | 2.00E+09 | 8.89E+08 | 2.22E+08 | 8.00E+07 | 3.55E+07 |
| Aluminum | PS | SP | 6.87E+12 | 6.87E+10 | 1.72E+10 | 2.75E+09 | 6.87E+08 | 3.05E+08 | 7.63E+07 | 2.75E+07 | 1.22E+07 |
| Aluminum | PS | LC | 4.58E+11 | 4.58E+09 | 1.14E+09 | 1.83E+08 | 4.58E+07 | 2.03E+07 | 5.09E+06 | 1.83E+06 | 8.14E+05 |
| Aluminum | PS | SC | 4.58E+13 | 4.58E+11 | 1.14E+11 | 1.83E+10 | 4.58E+09 | 2.03E+09 | 5.09E+08 | 1.83E+08 | 8.14E+07 |
| Aluminum | PS | OS_0.2 | 7.01E+12 | 7.01E+10 | 1.75E+10 | 2.80E+09 | 7.01E+08 | 3.12E+08 | 7.79E+07 | 2.80E+07 | 1.25E+07 |
| Aluminum | PS | OS_0.9 | 1.58E+13 | 1.58E+11 | 3.94E+10 | 6.30E+09 | 1.58E+09 | 7.00E+08 | 1.75E+08 | 6.30E+07 | 2.80E+07 |
| Aluminum | PVC | SP | 5.32E+12 | 5.32E+10 | 1.33E+10 | 2.13E+09 | 5.32E+08 | 2.36E+08 | 5.91E+07 | 2.13E+07 | 9.45E+06 |
| Aluminum | PVC | LC | 3.54E+11 | 3.54E+09 | 8.86E+08 | 1.42E+08 | 3.54E+07 | 1.58E+07 | 3.94E+06 | 1.42E+06 | 6.30E+05 |
| Aluminum | PVC | SC | 3.54E+13 | 3.54E+11 | 8.86E+10 | 1.42E+10 | 3.54E+09 | 1.58E+09 | 3.94E+08 | 1.42E+08 | 6.30E+07 |
| Aluminum | PVC | OS_0.2 | 5.43E+12 | 5.43E+10 | 1.36E+10 | 2.17E+09 | 5.43E+08 | 2.41E+08 | 6.03E+07 | 2.17E+07 | 9.65E+06 |
| Aluminum | PVC | OS_0.9 | 1.22E+13 | 1.22E+11 | 3.05E+10 | 4.88E+09 | 1.22E+09 | 5.42E+08 | 1.36E+08 | 4.88E+07 | 2.17E+07 |
| Antimony | HDPE | SP | 2.83E+08 | 2.83E+06 | 7.08E+05 | 1.13E+05 | 2.83E+04 | 1.26E+04 | 3.14E+03 | 1.13E+03 | 5.03E+02 |
| Antimony | HDPE | LC | 1.89E+07 | 1.89E+05 | 4.72E+04 | 7.55E+03 | 1.89E+03 | 8.39E+02 | 2.10E+02 | 7.55E+01 | 3.35E+01 |
| Antimony | HDPE | SC | 1.89E+09 | 1.89E+07 | 4.72E+06 | 7.55E+05 | 1.89E+05 | 8.39E+04 | 2.10E+04 | 7.55E+03 | 3.35E+03 |
| Antimony | HDPE | OS_0.2 | 2.89E+08 | 2.89E+06 | 7.22E+05 | 1.16E+05 | 2.89E+04 | 1.28E+04 | 3.21E+03 | 1.16E+03 | 5.14E+02 |
| Antimony | HDPE | OS_0.9 | 6.49E+08 | 6.49E+06 | 1.62E+06 | 2.60E+05 | 6.49E+04 | 2.89E+04 | 7.21E+03 | 2.60E+03 | 1.15E+03 |
| Antimony | PC | SP | 2.23E+08 | 2.23E+06 | 5.56E+05 | 8.90E+04 | 2.23E+04 | 9.89E+03 | 2.47E+03 | 8.90E+02 | 3.96E+02 |
| Antimony | PC | LC | 1.48E+07 | 1.48E+05 | 3.71E+04 | 5.94E+03 | 1.48E+03 | 6.60E+02 | 1.65E+02 | 5.94E+01 | 2.64E+01 |
| Antimony | PC | SC | 1.48E+09 | 1.48E+07 | 3.71E+06 | 5.94E+05 | 1.48E+05 | 6.60E+04 | 1.65E+04 | 5.94E+03 | 2.64E+03 |
| Antimony | PC | OS_0.2 | 2.27E+08 | 2.27E+06 | 5.68E+05 | 9.09E+04 | 2.27E+04 | 1.01E+04 | 2.52E+03 | 9.09E+02 | 4.04E+02 |
| Antimony | PC | OS_0.9 | 5.11E+08 | 5.11E+06 | 1.28E+06 | 2.04E+05 | 5.11E+04 | 2.27E+04 | 5.67E+03 | 2.04E+03 | 9.08E+02 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Antimony | PE | SP | 3.19E+08 | 3.19E+06 | 7.97E+05 | 1.28E+05 | 3.19E+04 | 1.42E+04 | 3.54E+03 | 1.28E+03 | 5.67E+02 |
| Antimony | PE | LC | 2.13E+07 | 2.13E+05 | 5.31E+04 | 8.50E+03 | 2.13E+03 | 9.44E+02 | 2.36E+02 | 8.50E+01 | 3.78E+01 |
| Antimony | PE | SC | 2.13E+09 | 2.13E+07 | 5.31E+06 | 8.50E+05 | 2.13E+05 | 9.44E+04 | 2.36E+04 | 8.50E+03 | 3.78E+03 |
| Antimony | PE | OS_0.2 | 3.25E+08 | 3.25E+06 | 8.13E+05 | 1.30E+05 | 3.25E+04 | 1.45E+04 | 3.61E+03 | 1.30E+03 | 5.78E+02 |
| Antimony | PE | OS_0.9 | 7.31E+08 | 7.31E+06 | 1.83E+06 | 2.93E+05 | 7.31E+04 | 3.25E+04 | 8.13E+03 | 2.93E+03 | 1.30E+03 |
| Antimony | PET | SP | 2.01E+08 | 2.01E+06 | 5.02E+05 | 8.02E+04 | 2.01E+04 | 8.92E+03 | 2.23E+03 | 8.02E+02 | 3.57E+02 |
| Antimony | PET | LC | 1.34E+07 | 1.34E+05 | 3.34E+04 | 5.35E+03 | 1.34E+03 | 5.94E+02 | 1.49E+02 | 5.35E+01 | 2.38E+01 |
| Antimony | PET | SC | 1.34E+09 | 1.34E+07 | 3.34E+06 | 5.35E+05 | 1.34E+05 | 5.94E+04 | 1.49E+04 | 5.35E+03 | 2.38E+03 |
| Antimony | PET | OS_0.2 | 2.05E+08 | 2.05E+06 | 5.12E+05 | 8.19E+04 | 2.05E+04 | 9.10E+03 | 2.27E+03 | 8.19E+02 | 3.64E+02 |
| Antimony | PET | OS_0.9 | 4.60E+08 | 4.60E+06 | 1.15E+06 | 1.84E+05 | 4.60E+04 | 2.05E+04 | 5.11E+03 | 1.84E+03 | 8.18E+02 |
| Antimony | PP | SP | 3.24E+08 | 3.24E+06 | 8.11E+05 | 1.30E+05 | 3.24E+04 | 1.44E+04 | 3.60E+03 | 1.30E+03 | 5.76E+02 |
| Antimony | PP | LC | 2.16E+07 | 2.16E+05 | 5.40E+04 | 8.65E+03 | 2.16E+03 | 9.61E+02 | 2.40E+02 | 8.65E+01 | 3.84E+01 |
| Antimony | PP | SC | 2.16E+09 | 2.16E+07 | 5.40E+06 | 8.65E+05 | 2.16E+05 | 9.61E+04 | 2.40E+04 | 8.65E+03 | 3.84E+03 |
| Antimony | PP | OS_0.2 | 3.31E+08 | 3.31E+06 | 8.27E+05 | 1.32E+05 | 3.31E+04 | 1.47E+04 | 3.68E+03 | 1.32E+03 | 5.88E+02 |
| Antimony | PP | OS_0.9 | 7.44E+08 | 7.44E+06 | 1.86E+06 | 2.98E+05 | 7.44E+04 | 3.31E+04 | 8.27E+03 | 2.98E+03 | 1.32E+03 |
| Antimony | PS | SP | 2.56E+08 | 2.56E+06 | 6.39E+05 | 1.02E+05 | 2.56E+04 | 1.14E+04 | 2.84E+03 | 1.02E+03 | 4.54E+02 |
| Antimony | PS | LC | 1.70E+07 | 1.70E+05 | 4.26E+04 | 6.82E+03 | 1.70E+03 | 7.57E+02 | 1.89E+02 | 6.82E+01 | 3.03E+01 |
| Antimony | PS | SC | 1.70E+09 | 1.70E+07 | 4.26E+06 | 6.82E+05 | 1.70E+05 | 7.57E+04 | 1.89E+04 | 6.82E+03 | 3.03E+03 |
| Antimony | PS | OS_0.2 | 2.61E+08 | 2.61E+06 | 6.52E+05 | 1.04E+05 | 2.61E+04 | 1.16E+04 | 2.90E+03 | 1.04E+03 | 4.64E+02 |
| Antimony | PS | OS_0.9 | 5.86E+08 | 5.86E+06 | 1.47E+06 | 2.35E+05 | 5.86E+04 | 2.61E+04 | 6.51E+03 | 2.35E+03 | 1.04E+03 |
| Antimony | PVC | SP | 1.98E+08 | 1.98E+06 | 4.95E+05 | 7.91E+04 | 1.98E+04 | 8.79E+03 | 2.20E+03 | 7.91E+02 | 3.52E+02 |
| Antimony | PVC | LC | 1.32E+07 | 1.32E+05 | 3.30E+04 | 5.28E+03 | 1.32E+03 | 5.86E+02 | 1.47E+02 | 5.28E+01 | 2.34E+01 |
| Antimony | PVC | SC | 1.32E+09 | 1.32E+07 | 3.30E+06 | 5.28E+05 | 1.32E+05 | 5.86E+04 | 1.47E+04 | 5.28E+03 | 2.34E+03 |
| Antimony | PVC | OS_0.2 | 2.02E+08 | 2.02E+06 | 5.05E+05 | 8.08E+04 | 2.02E+04 | 8.97E+03 | 2.24E+03 | 8.08E+02 | 3.59E+02 |
| Antimony | PVC | OS_0.9 | 4.54E+08 | 4.54E+06 | 1.13E+06 | 1.82E+05 | 4.54E+04 | 2.02E+04 | 5.04E+03 | 1.82E+03 | 8.07E+02 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Arsenic | HDPE | SP | 3.07E+10 | 3.07E+08 | 7.68E+07 | 1.23E+07 | 3.07E+06 | 1.37E+06 | 3.42E+05 | 1.23E+05 | 5.46E+04 |
| Arsenic | HDPE | LC | 2.05E+09 | 2.05E+07 | 5.12E+06 | 8.20E+05 | 2.05E+05 | 9.11E+04 | 2.28E+04 | 8.20E+03 | 3.64E+03 |
| Arsenic | HDPE | SC | 2.05E+11 | 2.05E+09 | 5.12E+08 | 8.20E+07 | 2.05E+07 | 9.11E+06 | 2.28E+06 | 8.20E+05 | 3.64E+05 |
| Arsenic | HDPE | OS_0.2 | 3.14E+10 | 3.14E+08 | 7.84E+07 | 1.25E+07 | 3.14E+06 | 1.39E+06 | 3.49E+05 | 1.25E+05 | 5.58E+04 |
| Arsenic | HDPE | OS_0.9 | 7.05E+10 | 7.05E+08 | 1.76E+08 | 2.82E+07 | 7.05E+06 | 3.13E+06 | 7.84E+05 | 2.82E+05 | 1.25E+05 |
| Arsenic | PC | SP | 2.42E+10 | 2.42E+08 | 6.04E+07 | 9.67E+06 | 2.42E+06 | 1.07E+06 | 2.69E+05 | 9.67E+04 | 4.30E+04 |
| Arsenic | PC | LC | 1.61E+09 | 1.61E+07 | 4.03E+06 | 6.45E+05 | 1.61E+05 | 7.16E+04 | 1.79E+04 | 6.45E+03 | 2.86E+03 |
| Arsenic | PC | SC | 1.61E+11 | 1.61E+09 | 4.03E+08 | 6.45E+07 | 1.61E+07 | 7.16E+06 | 1.79E+06 | 6.45E+05 | 2.86E+05 |
| Arsenic | PC | OS_0.2 | 2.47E+10 | 2.47E+08 | 6.17E+07 | 9.87E+06 | 2.47E+06 | 1.10E+06 | 2.74E+05 | 9.87E+04 | 4.39E+04 |
| Arsenic | PC | OS_0.9 | 5.55E+10 | 5.55E+08 | 1.39E+08 | 2.22E+07 | 5.55E+06 | 2.46E+06 | 6.16E+05 | 2.22E+05 | 9.86E+04 |
| Arsenic | PE | SP | 3.46E+10 | 3.46E+08 | 8.65E+07 | 1.38E+07 | 3.46E+06 | 1.54E+06 | 3.85E+05 | 1.38E+05 | 6.15E+04 |
| Arsenic | PE | LC | 2.31E+09 | 2.31E+07 | 5.77E+06 | 9.23E+05 | 2.31E+05 | 1.03E+05 | 2.56E+04 | 9.23E+03 | 4.10E+03 |
| Arsenic | PE | SC | 2.31E+11 | 2.31E+09 | 5.77E+08 | 9.23E+07 | 2.31E+07 | 1.03E+07 | 2.56E+06 | 9.23E+05 | 4.10E+05 |
| Arsenic | PE | OS_0.2 | 3.53E+10 | 3.53E+08 | 8.83E+07 | 1.41E+07 | 3.53E+06 | 1.57E+06 | 3.93E+05 | 1.41E+05 | 6.28E+04 |
| Arsenic | PE | OS_0.9 | 7.94E+10 | 7.94E+08 | 1.99E+08 | 3.18E+07 | 7.94E+06 | 3.53E+06 | 8.82E+05 | 3.18E+05 | 1.41E+05 |
| Arsenic | PET | SP | 2.18E+10 | 2.18E+08 | 5.45E+07 | 8.71E+06 | 2.18E+06 | 9.68E+05 | 2.42E+05 | 8.71E+04 | 3.87E+04 |
| Arsenic | PET | LC | 1.45E+09 | 1.45E+07 | 3.63E+06 | 5.81E+05 | 1.45E+05 | 6.45E+04 | 1.61E+04 | 5.81E+03 | 2.58E+03 |
| Arsenic | PET | SC | 1.45E+11 | 1.45E+09 | 3.63E+08 | 5.81E+07 | 1.45E+07 | 6.45E+06 | 1.61E+06 | 5.81E+05 | 2.58E+05 |
| Arsenic | PET | OS_0.2 | 2.22E+10 | 2.22E+08 | 5.56E+07 | 8.89E+06 | 2.22E+06 | 9.88E+05 | 2.47E+05 | 8.89E+04 | 3.95E+04 |
| Arsenic | PET | OS_0.9 | 5.00E+10 | 5.00E+08 | 1.25E+08 | 2.00E+07 | 5.00E+06 | 2.22E+06 | 5.55E+05 | 2.00E+05 | 8.88E+04 |
| Arsenic | PP | SP | 3.52E+10 | 3.52E+08 | 8.80E+07 | 1.41E+07 | 3.52E+06 | 1.57E+06 | 3.91E+05 | 1.41E+05 | 6.26E+04 |
| Arsenic | PP | LC | 2.35E+09 | 2.35E+07 | 5.87E+06 | 9.39E+05 | 2.35E+05 | 1.04E+05 | 2.61E+04 | 9.39E+03 | 4.17E+03 |
| Arsenic | PP | SC | 2.35E+11 | 2.35E+09 | 5.87E+08 | 9.39E+07 | 2.35E+07 | 1.04E+07 | 2.61E+06 | 9.39E+05 | 4.17E+05 |
| Arsenic | PP | OS_0.2 | 3.59E+10 | 3.59E+08 | 8.98E+07 | 1.44E+07 | 3.59E+06 | 1.60E+06 | 3.99E+05 | 1.44E+05 | 6.39E+04 |
| Arsenic | PP | OS_0.9 | 8.08E+10 | 8.08E+08 | 2.02E+08 | 3.23E+07 | 8.08E+06 | 3.59E+06 | 8.98E+05 | 3.23E+05 | 1.44E+05 |

| **Contaminant** | **MP** | **Shape** | **1** | **10** | **20** | **50** | **100** | **150** | **300** | **500** | **750** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Arsenic | PS | SP | 2.78E+10 | 2.78E+08 | 6.94E+07 | 1.11E+07 | 2.78E+06 | 1.23E+06 | 3.08E+05 | 1.11E+05 | 4.93E+04 |
| Arsenic | PS | LC | 1.85E+09 | 1.85E+07 | 4.63E+06 | 7.40E+05 | 1.85E+05 | 8.22E+04 | 2.06E+04 | 7.40E+03 | 3.29E+03 |
| Arsenic | PS | SC | 1.85E+11 | 1.85E+09 | 4.63E+08 | 7.40E+07 | 1.85E+07 | 8.22E+06 | 2.06E+06 | 7.40E+05 | 3.29E+05 |
| Arsenic | PS | OS_0.2 | 2.83E+10 | 2.83E+08 | 7.08E+07 | 1.13E+07 | 2.83E+06 | 1.26E+06 | 3.15E+05 | 1.13E+05 | 5.04E+04 |
| Arsenic | PS | OS_0.9 | 6.37E+10 | 6.37E+08 | 1.59E+08 | 2.55E+07 | 6.37E+06 | 2.83E+06 | 7.07E+05 | 2.55E+05 | 1.13E+05 |
| Arsenic | PVC | SP | 2.15E+10 | 2.15E+08 | 5.37E+07 | 8.59E+06 | 2.15E+06 | 9.55E+05 | 2.39E+05 | 8.59E+04 | 3.82E+04 |
| Arsenic | PVC | LC | 1.43E+09 | 1.43E+07 | 3.58E+06 | 5.73E+05 | 1.43E+05 | 6.37E+04 | 1.59E+04 | 5.73E+03 | 2.55E+03 |
| Arsenic | PVC | SC | 1.43E+11 | 1.43E+09 | 3.58E+08 | 5.73E+07 | 1.43E+07 | 6.37E+06 | 1.59E+06 | 5.73E+05 | 2.55E+05 |
| Arsenic | PVC | OS_0.2 | 2.19E+10 | 2.19E+08 | 5.48E+07 | 8.77E+06 | 2.19E+06 | 9.75E+05 | 2.44E+05 | 8.77E+04 | 3.90E+04 |
| Arsenic | PVC | OS_0.9 | 4.93E+10 | 4.93E+08 | 1.23E+08 | 1.97E+07 | 4.93E+06 | 2.19E+06 | 5.48E+05 | 1.97E+05 | 8.76E+04 |
| BPA | HDPE | SP | 4.71E+10 | 4.71E+08 | 1.18E+08 | 1.88E+07 | 4.71E+06 | 2.09E+06 | 5.23E+05 | 1.88E+05 | 8.37E+04 |
| BPA | HDPE | LC | 3.14E+09 | 3.14E+07 | 7.84E+06 | 1.25E+06 | 3.14E+05 | 1.39E+05 | 3.49E+04 | 1.25E+04 | 5.58E+03 |
| BPA | HDPE | SC | 3.14E+11 | 3.14E+09 | 7.84E+08 | 1.25E+08 | 3.14E+07 | 1.39E+07 | 3.49E+06 | 1.25E+06 | 5.58E+05 |
| BPA | HDPE | OS_0.2 | 4.80E+10 | 4.80E+08 | 1.20E+08 | 1.92E+07 | 4.80E+06 | 2.13E+06 | 5.34E+05 | 1.92E+05 | 8.54E+04 |
| BPA | HDPE | OS_0.9 | 1.08E+11 | 1.08E+09 | 2.70E+08 | 4.32E+07 | 1.08E+07 | 4.80E+06 | 1.20E+06 | 4.32E+05 | 1.92E+05 |
| BPA | PC | SP | 3.70E+10 | 3.70E+08 | 9.25E+07 | 1.48E+07 | 3.70E+06 | 1.64E+06 | 4.11E+05 | 1.48E+05 | 6.58E+04 |
| BPA | PC | LC | 2.47E+09 | 2.47E+07 | 6.17E+06 | 9.87E+05 | 2.47E+05 | 1.10E+05 | 2.74E+04 | 9.87E+03 | 4.39E+03 |
| BPA | PC | SC | 2.47E+11 | 2.47E+09 | 6.17E+08 | 9.87E+07 | 2.47E+07 | 1.10E+07 | 2.74E+06 | 9.87E+05 | 4.39E+05 |
| BPA | PC | OS_0.2 | 3.78E+10 | 3.78E+08 | 9.44E+07 | 1.51E+07 | 3.78E+06 | 1.68E+06 | 4.20E+05 | 1.51E+05 | 6.72E+04 |
| BPA | PC | OS_0.9 | 8.49E+10 | 8.49E+08 | 2.12E+08 | 3.40E+07 | 8.49E+06 | 3.77E+06 | 9.43E+05 | 3.40E+05 | 1.51E+05 |
| BPA | PE | SP | 5.30E+10 | 5.30E+08 | 1.33E+08 | 2.12E+07 | 5.30E+06 | 2.36E+06 | 5.89E+05 | 2.12E+05 | 9.42E+04 |
| BPA | PE | LC | 3.53E+09 | 3.53E+07 | 8.83E+06 | 1.41E+06 | 3.53E+05 | 1.57E+05 | 3.93E+04 | 1.41E+04 | 6.28E+03 |
| BPA | PE | SC | 3.53E+11 | 3.53E+09 | 8.83E+08 | 1.41E+08 | 3.53E+07 | 1.57E+07 | 3.93E+06 | 1.41E+06 | 6.28E+05 |
| BPA | PE | OS_0.2 | 5.41E+10 | 5.41E+08 | 1.35E+08 | 2.16E+07 | 5.41E+06 | 2.40E+06 | 6.01E+05 | 2.16E+05 | 9.62E+04 |
| BPA | PE | OS_0.9 | 1.22E+11 | 1.22E+09 | 3.04E+08 | 4.86E+07 | 1.22E+07 | 5.40E+06 | 1.35E+06 | 4.86E+05 | 2.16E+05 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BPA | PET | SP | 3.34E+10 | 3.34E+08 | 8.34E+07 | 1.33E+07 | 3.34E+06 | 1.48E+06 | 3.71E+05 | 1.33E+05 | 5.93E+04 |
| BPA | PET | LC | 2.22E+09 | 2.22E+07 | 5.56E+06 | 8.89E+05 | 2.22E+05 | 9.88E+04 | 2.47E+04 | 8.89E+03 | 3.95E+03 |
| BPA | PET | SC | 2.22E+11 | 2.22E+09 | 5.56E+08 | 8.89E+07 | 2.22E+07 | 9.88E+06 | 2.47E+06 | 8.89E+05 | 3.95E+05 |
| BPA | PET | OS_0.2 | 3.40E+10 | 3.40E+08 | 8.51E+07 | 1.36E+07 | 3.40E+06 | 1.51E+06 | 3.78E+05 | 1.36E+05 | 6.05E+04 |
| BPA | PET | OS_0.9 | 7.65E+10 | 7.65E+08 | 1.91E+08 | 3.06E+07 | 7.65E+06 | 3.40E+06 | 8.50E+05 | 3.06E+05 | 1.36E+05 |
| BPA | PP | SP | 5.39E+10 | 5.39E+08 | 1.35E+08 | 2.16E+07 | 5.39E+06 | 2.40E+06 | 5.99E+05 | 2.16E+05 | 9.58E+04 |
| BPA | PP | LC | 3.59E+09 | 3.59E+07 | 8.99E+06 | 1.44E+06 | 3.59E+05 | 1.60E+05 | 3.99E+04 | 1.44E+04 | 6.39E+03 |
| BPA | PP | SC | 3.59E+11 | 3.59E+09 | 8.99E+08 | 1.44E+08 | 3.59E+07 | 1.60E+07 | 3.99E+06 | 1.44E+06 | 6.39E+05 |
| BPA | PP | OS_0.2 | 5.50E+10 | 5.50E+08 | 1.38E+08 | 2.20E+07 | 5.50E+06 | 2.45E+06 | 6.11E+05 | 2.20E+05 | 9.78E+04 |
| BPA | PP | OS_0.9 | 1.24E+11 | 1.24E+09 | 3.09E+08 | 4.95E+07 | 1.24E+07 | 5.50E+06 | 1.37E+06 | 4.95E+05 | 2.20E+05 |
| BPA | PS | SP | 4.25E+10 | 4.25E+08 | 1.06E+08 | 1.70E+07 | 4.25E+06 | 1.89E+06 | 4.72E+05 | 1.70E+05 | 7.55E+04 |
| BPA | PS | LC | 2.83E+09 | 2.83E+07 | 7.08E+06 | 1.13E+06 | 2.83E+05 | 1.26E+05 | 3.15E+04 | 1.13E+04 | 5.04E+03 |
| BPA | PS | SC | 2.83E+11 | 2.83E+09 | 7.08E+08 | 1.13E+08 | 2.83E+07 | 1.26E+07 | 3.15E+06 | 1.13E+06 | 5.04E+05 |
| BPA | PS | OS_0.2 | 4.34E+10 | 4.34E+08 | 1.08E+08 | 1.73E+07 | 4.34E+06 | 1.93E+06 | 4.82E+05 | 1.73E+05 | 7.71E+04 |
| BPA | PS | OS_0.9 | 9.75E+10 | 9.75E+08 | 2.44E+08 | 3.90E+07 | 9.75E+06 | 4.33E+06 | 1.08E+06 | 3.90E+05 | 1.73E+05 |
| BPA | PVC | SP | 3.29E+10 | 3.29E+08 | 8.22E+07 | 1.32E+07 | 3.29E+06 | 1.46E+06 | 3.66E+05 | 1.32E+05 | 5.85E+04 |
| BPA | PVC | LC | 2.19E+09 | 2.19E+07 | 5.48E+06 | 8.77E+05 | 2.19E+05 | 9.75E+04 | 2.44E+04 | 8.77E+03 | 3.90E+03 |
| BPA | PVC | SC | 2.19E+11 | 2.19E+09 | 5.48E+08 | 8.77E+07 | 2.19E+07 | 9.75E+06 | 2.44E+06 | 8.77E+05 | 3.90E+05 |
| BPA | PVC | OS_0.2 | 3.36E+10 | 3.36E+08 | 8.39E+07 | 1.34E+07 | 3.36E+06 | 1.49E+06 | 3.73E+05 | 1.34E+05 | 5.97E+04 |
| BPA | PVC | OS_0.9 | 7.55E+10 | 7.55E+08 | 1.89E+08 | 3.02E+07 | 7.55E+06 | 3.35E+06 | 8.39E+05 | 3.02E+05 | 1.34E+05 |
| Bromine | HDPE | SP | 6.05E+11 | 6.05E+09 | 1.51E+09 | 2.42E+08 | 6.05E+07 | 2.69E+07 | 6.73E+06 | 2.42E+06 | 1.08E+06 |
| Bromine | HDPE | LC | 4.04E+10 | 4.04E+08 | 1.01E+08 | 1.61E+07 | 4.04E+06 | 1.79E+06 | 4.48E+05 | 1.61E+05 | 7.17E+04 |
| Bromine | HDPE | SC | 4.04E+12 | 4.04E+10 | 1.01E+10 | 1.61E+09 | 4.04E+08 | 1.79E+08 | 4.48E+07 | 1.61E+07 | 7.17E+06 |
| Bromine | HDPE | OS_0.2 | 6.18E+11 | 6.18E+09 | 1.54E+09 | 2.47E+08 | 6.18E+07 | 2.75E+07 | 6.86E+06 | 2.47E+06 | 1.10E+06 |
| Bromine | HDPE | OS_0.9 | 1.39E+12 | 1.39E+10 | 3.47E+09 | 5.55E+08 | 1.39E+08 | 6.17E+07 | 1.54E+07 | 5.55E+06 | 2.47E+06 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bromine | PC | SP | 4.76E+11 | 4.76E+09 | 1.19E+09 | 1.90E+08 | 4.76E+07 | 2.12E+07 | 5.29E+06 | 1.90E+06 | 8.46E+05 |
| Bromine | PC | LC | 3.17E+10 | 3.17E+08 | 7.93E+07 | 1.27E+07 | 3.17E+06 | 1.41E+06 | 3.53E+05 | 1.27E+05 | 5.64E+04 |
| Bromine | PC | SC | 3.17E+12 | 3.17E+10 | 7.93E+09 | 1.27E+09 | 3.17E+08 | 1.41E+08 | 3.53E+07 | 1.27E+07 | 5.64E+06 |
| Bromine | PC | OS_0.2 | 4.86E+11 | 4.86E+09 | 1.21E+09 | 1.94E+08 | 4.86E+07 | 2.16E+07 | 5.40E+06 | 1.94E+06 | 8.64E+05 |
| Bromine | PC | OS_0.9 | 1.09E+12 | 1.09E+10 | 2.73E+09 | 4.37E+08 | 1.09E+08 | 4.85E+07 | 1.21E+07 | 4.37E+06 | 1.94E+06 |
| Bromine | PE | SP | 6.82E+11 | 6.82E+09 | 1.70E+09 | 2.73E+08 | 6.82E+07 | 3.03E+07 | 7.57E+06 | 2.73E+06 | 1.21E+06 |
| Bromine | PE | LC | 4.54E+10 | 4.54E+08 | 1.14E+08 | 1.82E+07 | 4.54E+06 | 2.02E+06 | 5.05E+05 | 1.82E+05 | 8.08E+04 |
| Bromine | PE | SC | 4.54E+12 | 4.54E+10 | 1.14E+10 | 1.82E+09 | 4.54E+08 | 2.02E+08 | 5.05E+07 | 1.82E+07 | 8.08E+06 |
| Bromine | PE | OS_0.2 | 6.96E+11 | 6.96E+09 | 1.74E+09 | 2.78E+08 | 6.96E+07 | 3.09E+07 | 7.73E+06 | 2.78E+06 | 1.24E+06 |
| Bromine | PE | OS_0.9 | 1.56E+12 | 1.56E+10 | 3.91E+09 | 6.26E+08 | 1.56E+08 | 6.95E+07 | 1.74E+07 | 6.26E+06 | 2.78E+06 |
| Bromine | PET | SP | 4.29E+11 | 4.29E+09 | 1.07E+09 | 1.72E+08 | 4.29E+07 | 1.91E+07 | 4.77E+06 | 1.72E+06 | 7.63E+05 |
| Bromine | PET | LC | 2.86E+10 | 2.86E+08 | 7.15E+07 | 1.14E+07 | 2.86E+06 | 1.27E+06 | 3.18E+05 | 1.14E+05 | 5.08E+04 |
| Bromine | PET | SC | 2.86E+12 | 2.86E+10 | 7.15E+09 | 1.14E+09 | 2.86E+08 | 1.27E+08 | 3.18E+07 | 1.14E+07 | 5.08E+06 |
| Bromine | PET | OS_0.2 | 4.38E+11 | 4.38E+09 | 1.09E+09 | 1.75E+08 | 4.38E+07 | 1.95E+07 | 4.86E+06 | 1.75E+06 | 7.78E+05 |
| Bromine | PET | OS_0.9 | 9.84E+11 | 9.84E+09 | 2.46E+09 | 3.94E+08 | 9.84E+07 | 4.37E+07 | 1.09E+07 | 3.94E+06 | 1.75E+06 |
| Bromine | PP | SP | 6.93E+11 | 6.93E+09 | 1.73E+09 | 2.77E+08 | 6.93E+07 | 3.08E+07 | 7.70E+06 | 2.77E+06 | 1.23E+06 |
| Bromine | PP | LC | 4.62E+10 | 4.62E+08 | 1.16E+08 | 1.85E+07 | 4.62E+06 | 2.05E+06 | 5.14E+05 | 1.85E+05 | 8.22E+04 |
| Bromine | PP | SC | 4.62E+12 | 4.62E+10 | 1.16E+10 | 1.85E+09 | 4.62E+08 | 2.05E+08 | 5.14E+07 | 1.85E+07 | 8.22E+06 |
| Bromine | PP | OS_0.2 | 7.08E+11 | 7.08E+09 | 1.77E+09 | 2.83E+08 | 7.08E+07 | 3.15E+07 | 7.86E+06 | 2.83E+06 | 1.26E+06 |
| Bromine | PP | OS_0.9 | 1.59E+12 | 1.59E+10 | 3.98E+09 | 6.36E+08 | 1.59E+08 | 7.07E+07 | 1.77E+07 | 6.36E+06 | 2.83E+06 |
| Bromine | PS | SP | 5.47E+11 | 5.47E+09 | 1.37E+09 | 2.19E+08 | 5.47E+07 | 2.43E+07 | 6.07E+06 | 2.19E+06 | 9.72E+05 |
| Bromine | PS | LC | 3.64E+10 | 3.64E+08 | 9.11E+07 | 1.46E+07 | 3.64E+06 | 1.62E+06 | 4.05E+05 | 1.46E+05 | 6.48E+04 |
| Bromine | PS | SC | 3.64E+12 | 3.64E+10 | 9.11E+09 | 1.46E+09 | 3.64E+08 | 1.62E+08 | 4.05E+07 | 1.46E+07 | 6.48E+06 |
| Bromine | PS | OS_0.2 | 5.58E+11 | 5.58E+09 | 1.39E+09 | 2.23E+08 | 5.58E+07 | 2.48E+07 | 6.20E+06 | 2.23E+06 | 9.92E+05 |
| Bromine | PS | OS_0.9 | 1.25E+12 | 1.25E+10 | 3.13E+09 | 5.02E+08 | 1.25E+08 | 5.57E+07 | 1.39E+07 | 5.02E+06 | 2.23E+06 |

| **Contaminant** | **MP** | **Shape** | **1** | **10** | **20** | **50** | **100** | **150** | **300** | **500** | **750** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bromine | PVC | SP | 4.23E+11 | 4.23E+09 | 1.06E+09 | 1.69E+08 | 4.23E+07 | 1.88E+07 | 4.70E+06 | 1.69E+06 | 7.52E+05 |
| Bromine | PVC | LC | 2.82E+10 | 2.82E+08 | 7.05E+07 | 1.13E+07 | 2.82E+06 | 1.25E+06 | 3.13E+05 | 1.13E+05 | 5.01E+04 |
| Bromine | PVC | SC | 2.82E+12 | 2.82E+10 | 7.05E+09 | 1.13E+09 | 2.82E+08 | 1.25E+08 | 3.13E+07 | 1.13E+07 | 5.01E+06 |
| Bromine | PVC | OS_0.2 | 4.32E+11 | 4.32E+09 | 1.08E+09 | 1.73E+08 | 4.32E+07 | 1.92E+07 | 4.80E+06 | 1.73E+06 | 7.68E+05 |
| Bromine | PVC | OS_0.9 | 9.71E+11 | 9.71E+09 | 2.43E+09 | 3.88E+08 | 9.71E+07 | 4.31E+07 | 1.08E+07 | 3.88E+06 | 1.73E+06 |
| Cadmium | HDPE | SP | 2.34E+13 | 2.34E+11 | 5.85E+10 | 9.37E+09 | 2.34E+09 | 1.04E+09 | 2.60E+08 | 9.37E+07 | 4.16E+07 |
| Cadmium | HDPE | LC | 1.56E+12 | 1.56E+10 | 3.90E+09 | 6.24E+08 | 1.56E+08 | 6.94E+07 | 1.73E+07 | 6.24E+06 | 2.78E+06 |
| Cadmium | HDPE | SC | 1.56E+14 | 1.56E+12 | 3.90E+11 | 6.24E+10 | 1.56E+10 | 6.94E+09 | 1.73E+09 | 6.24E+08 | 2.78E+08 |
| Cadmium | HDPE | OS_0.2 | 2.39E+13 | 2.39E+11 | 5.98E+10 | 9.56E+09 | 2.39E+09 | 1.06E+09 | 2.66E+08 | 9.56E+07 | 4.25E+07 |
| Cadmium | HDPE | OS_0.9 | 5.37E+13 | 5.37E+11 | 1.34E+11 | 2.15E+10 | 5.37E+09 | 2.39E+09 | 5.97E+08 | 2.15E+08 | 9.55E+07 |
| Cadmium | PC | SP | 1.84E+13 | 1.84E+11 | 4.60E+10 | 7.37E+09 | 1.84E+09 | 8.19E+08 | 2.05E+08 | 7.37E+07 | 3.27E+07 |
| Cadmium | PC | LC | 1.23E+12 | 1.23E+10 | 3.07E+09 | 4.91E+08 | 1.23E+08 | 5.46E+07 | 1.36E+07 | 4.91E+06 | 2.18E+06 |
| Cadmium | PC | SC | 1.23E+14 | 1.23E+12 | 3.07E+11 | 4.91E+10 | 1.23E+10 | 5.46E+09 | 1.36E+09 | 4.91E+08 | 2.18E+08 |
| Cadmium | PC | OS_0.2 | 1.88E+13 | 1.88E+11 | 4.70E+10 | 7.52E+09 | 1.88E+09 | 8.35E+08 | 2.09E+08 | 7.52E+07 | 3.34E+07 |
| Cadmium | PC | OS_0.9 | 4.23E+13 | 4.23E+11 | 1.06E+11 | 1.69E+10 | 4.23E+09 | 1.88E+09 | 4.69E+08 | 1.69E+08 | 7.51E+07 |
| Cadmium | PE | SP | 2.64E+13 | 2.64E+11 | 6.59E+10 | 1.05E+10 | 2.64E+09 | 1.17E+09 | 2.93E+08 | 1.05E+08 | 4.69E+07 |
| Cadmium | PE | LC | 1.76E+12 | 1.76E+10 | 4.40E+09 | 7.03E+08 | 1.76E+08 | 7.81E+07 | 1.95E+07 | 7.03E+06 | 3.13E+06 |
| Cadmium | PE | SC | 1.76E+14 | 1.76E+12 | 4.40E+11 | 7.03E+10 | 1.76E+10 | 7.81E+09 | 1.95E+09 | 7.03E+08 | 3.13E+08 |
| Cadmium | PE | OS_0.2 | 2.69E+13 | 2.69E+11 | 6.73E+10 | 1.08E+10 | 2.69E+09 | 1.20E+09 | 2.99E+08 | 1.08E+08 | 4.79E+07 |
| Cadmium | PE | OS_0.9 | 6.05E+13 | 6.05E+11 | 1.51E+11 | 2.42E+10 | 6.05E+09 | 2.69E+09 | 6.72E+08 | 2.42E+08 | 1.08E+08 |
| Cadmium | PET | SP | 1.66E+13 | 1.66E+11 | 4.15E+10 | 6.64E+09 | 1.66E+09 | 7.38E+08 | 1.84E+08 | 6.64E+07 | 2.95E+07 |
| Cadmium | PET | LC | 1.11E+12 | 1.11E+10 | 2.77E+09 | 4.43E+08 | 1.11E+08 | 4.92E+07 | 1.23E+07 | 4.43E+06 | 1.97E+06 |
| Cadmium | PET | SC | 1.11E+14 | 1.11E+12 | 2.77E+11 | 4.43E+10 | 1.11E+10 | 4.92E+09 | 1.23E+09 | 4.43E+08 | 1.97E+08 |
| Cadmium | PET | OS_0.2 | 1.69E+13 | 1.69E+11 | 4.23E+10 | 6.78E+09 | 1.69E+09 | 7.53E+08 | 1.88E+08 | 6.78E+07 | 3.01E+07 |
| Cadmium | PET | OS_0.9 | 3.81E+13 | 3.81E+11 | 9.52E+10 | 1.52E+10 | 3.81E+09 | 1.69E+09 | 4.23E+08 | 1.52E+08 | 6.77E+07 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | PP | SP | 2.68E+13 | 2.68E+11 | 6.71E+10 | 1.07E+10 | 2.68E+09 | 1.19E+09 | 2.98E+08 | 1.07E+08 | 4.77E+07 |
| Cadmium | PP | LC | 1.79E+12 | 1.79E+10 | 4.47E+09 | 7.15E+08 | 1.79E+08 | 7.95E+07 | 1.99E+07 | 7.15E+06 | 3.18E+06 |
| Cadmium | PP | SC | 1.79E+14 | 1.79E+12 | 4.47E+11 | 7.15E+10 | 1.79E+10 | 7.95E+09 | 1.99E+09 | 7.15E+08 | 3.18E+08 |
| Cadmium | PP | OS_0.2 | 2.74E+13 | 2.74E+11 | 6.85E+10 | 1.10E+10 | 2.74E+09 | 1.22E+09 | 3.04E+08 | 1.10E+08 | 4.87E+07 |
| Cadmium | PP | OS_0.9 | 6.15E+13 | 6.15E+11 | 1.54E+11 | 2.46E+10 | 6.15E+09 | 2.74E+09 | 6.84E+08 | 2.46E+08 | 1.09E+08 |
| Cadmium | PS | SP | 2.11E+13 | 2.11E+11 | 5.29E+10 | 8.46E+09 | 2.11E+09 | 9.40E+08 | 2.35E+08 | 8.46E+07 | 3.76E+07 |
| Cadmium | PS | LC | 1.41E+12 | 1.41E+10 | 3.52E+09 | 5.64E+08 | 1.41E+08 | 6.27E+07 | 1.57E+07 | 5.64E+06 | 2.51E+06 |
| Cadmium | PS | SC | 1.41E+14 | 1.41E+12 | 3.52E+11 | 5.64E+10 | 1.41E+10 | 6.27E+09 | 1.57E+09 | 5.64E+08 | 2.51E+08 |
| Cadmium | PS | OS_0.2 | 2.16E+13 | 2.16E+11 | 5.40E+10 | 8.63E+09 | 2.16E+09 | 9.59E+08 | 2.40E+08 | 8.63E+07 | 3.84E+07 |
| Cadmium | PS | OS_0.9 | 4.85E+13 | 4.85E+11 | 1.21E+11 | 1.94E+10 | 4.85E+09 | 2.16E+09 | 5.39E+08 | 1.94E+08 | 8.62E+07 |
| Cadmium | PVC | SP | 1.64E+13 | 1.64E+11 | 4.09E+10 | 6.55E+09 | 1.64E+09 | 7.28E+08 | 1.82E+08 | 6.55E+07 | 2.91E+07 |
| Cadmium | PVC | LC | 1.09E+12 | 1.09E+10 | 2.73E+09 | 4.37E+08 | 1.09E+08 | 4.85E+07 | 1.21E+07 | 4.37E+06 | 1.94E+06 |
| Cadmium | PVC | SC | 1.09E+14 | 1.09E+12 | 2.73E+11 | 4.37E+10 | 1.09E+10 | 4.85E+09 | 1.21E+09 | 4.37E+08 | 1.94E+08 |
| Cadmium | PVC | OS_0.2 | 1.67E+13 | 1.67E+11 | 4.18E+10 | 6.68E+09 | 1.67E+09 | 7.43E+08 | 1.86E+08 | 6.68E+07 | 2.97E+07 |
| Cadmium | PVC | OS_0.9 | 3.76E+13 | 3.76E+11 | 9.39E+10 | 1.50E+10 | 3.76E+09 | 1.67E+09 | 4.17E+08 | 1.50E+08 | 6.68E+07 |
| Chromium | HDPE | SP | 2.60E+14 | 2.60E+12 | 6.50E+11 | 1.04E+11 | 2.60E+10 | 1.16E+10 | 2.89E+09 | 1.04E+09 | 4.62E+08 |
| Chromium | HDPE | LC | 1.73E+13 | 1.73E+11 | 4.33E+10 | 6.93E+09 | 1.73E+09 | 7.70E+08 | 1.93E+08 | 6.93E+07 | 3.08E+07 |
| Chromium | HDPE | SC | 1.73E+15 | 1.73E+13 | 4.33E+12 | 6.93E+11 | 1.73E+11 | 7.70E+10 | 1.93E+10 | 6.93E+09 | 3.08E+09 |
| Chromium | HDPE | OS_0.2 | 2.65E+14 | 2.65E+12 | 6.63E+11 | 1.06E+11 | 2.65E+10 | 1.18E+10 | 2.95E+09 | 1.06E+09 | 4.72E+08 |
| Chromium | HDPE | OS_0.9 | 5.96E+14 | 5.96E+12 | 1.49E+12 | 2.39E+11 | 5.96E+10 | 2.65E+10 | 6.63E+09 | 2.39E+09 | 1.06E+09 |
| Chromium | PC | SP | 2.04E+14 | 2.04E+12 | 5.11E+11 | 8.18E+10 | 2.04E+10 | 9.09E+09 | 2.27E+09 | 8.18E+08 | 3.63E+08 |
| Chromium | PC | LC | 1.36E+13 | 1.36E+11 | 3.41E+10 | 5.45E+09 | 1.36E+09 | 6.06E+08 | 1.51E+08 | 5.45E+07 | 2.42E+07 |
| Chromium | PC | SC | 1.36E+15 | 1.36E+13 | 3.41E+12 | 5.45E+11 | 1.36E+11 | 6.06E+10 | 1.51E+10 | 5.45E+09 | 2.42E+09 |
| Chromium | PC | OS_0.2 | 2.09E+14 | 2.09E+12 | 5.22E+11 | 8.35E+10 | 2.09E+10 | 9.27E+09 | 2.32E+09 | 8.35E+08 | 3.71E+08 |
| Chromium | PC | OS_0.9 | 4.69E+14 | 4.69E+12 | 1.17E+12 | 1.88E+11 | 4.69E+10 | 2.08E+10 | 5.21E+09 | 1.88E+09 | 8.34E+08 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chromium | PE | SP | 2.93E+14 | 2.93E+12 | 7.32E+11 | 1.17E+11 | 2.93E+10 | 1.30E+10 | 3.25E+09 | 1.17E+09 | 5.21E+08 |
| Chromium | PE | LC | 1.95E+13 | 1.95E+11 | 4.88E+10 | 7.81E+09 | 1.95E+09 | 8.68E+08 | 2.17E+08 | 7.81E+07 | 3.47E+07 |
| Chromium | PE | SC | 1.95E+15 | 1.95E+13 | 4.88E+12 | 7.81E+11 | 1.95E+11 | 8.68E+10 | 2.17E+10 | 7.81E+09 | 3.47E+09 |
| Chromium | PE | OS_0.2 | 2.99E+14 | 2.99E+12 | 7.47E+11 | 1.20E+11 | 2.99E+10 | 1.33E+10 | 3.32E+09 | 1.20E+09 | 5.31E+08 |
| Chromium | PE | OS_0.9 | 6.72E+14 | 6.72E+12 | 1.68E+12 | 2.69E+11 | 6.72E+10 | 2.99E+10 | 7.46E+09 | 2.69E+09 | 1.19E+09 |
| Chromium | PET | SP | 1.84E+14 | 1.84E+12 | 4.61E+11 | 7.37E+10 | 1.84E+10 | 8.19E+09 | 2.05E+09 | 7.37E+08 | 3.28E+08 |
| Chromium | PET | LC | 1.23E+13 | 1.23E+11 | 3.07E+10 | 4.91E+09 | 1.23E+09 | 5.46E+08 | 1.36E+08 | 4.91E+07 | 2.18E+07 |
| Chromium | PET | SC | 1.23E+15 | 1.23E+13 | 3.07E+12 | 4.91E+11 | 1.23E+11 | 5.46E+10 | 1.36E+10 | 4.91E+09 | 2.18E+09 |
| Chromium | PET | OS_0.2 | 1.88E+14 | 1.88E+12 | 4.70E+11 | 7.52E+10 | 1.88E+10 | 8.36E+09 | 2.09E+09 | 7.52E+08 | 3.34E+08 |
| Chromium | PET | OS_0.9 | 4.23E+14 | 4.23E+12 | 1.06E+12 | 1.69E+11 | 4.23E+10 | 1.88E+10 | 4.70E+09 | 1.69E+09 | 7.51E+08 |
| Chromium | PP | SP | 2.98E+14 | 2.98E+12 | 7.45E+11 | 1.19E+11 | 2.98E+10 | 1.32E+10 | 3.31E+09 | 1.19E+09 | 5.29E+08 |
| Chromium | PP | LC | 1.99E+13 | 1.99E+11 | 4.96E+10 | 7.94E+09 | 1.99E+09 | 8.82E+08 | 2.21E+08 | 7.94E+07 | 3.53E+07 |
| Chromium | PP | SC | 1.99E+15 | 1.99E+13 | 4.96E+12 | 7.94E+11 | 1.99E+11 | 8.82E+10 | 2.21E+10 | 7.94E+09 | 3.53E+09 |
| Chromium | PP | OS_0.2 | 3.04E+14 | 3.04E+12 | 7.60E+11 | 1.22E+11 | 3.04E+10 | 1.35E+10 | 3.38E+09 | 1.22E+09 | 5.40E+08 |
| Chromium | PP | OS_0.9 | 6.83E+14 | 6.83E+12 | 1.71E+12 | 2.73E+11 | 6.83E+10 | 3.04E+10 | 7.59E+09 | 2.73E+09 | 1.21E+09 |
| Chromium | PS | SP | 2.35E+14 | 2.35E+12 | 5.87E+11 | 9.39E+10 | 2.35E+10 | 1.04E+10 | 2.61E+09 | 9.39E+08 | 4.17E+08 |
| Chromium | PS | LC | 1.56E+13 | 1.56E+11 | 3.91E+10 | 6.26E+09 | 1.56E+09 | 6.96E+08 | 1.74E+08 | 6.26E+07 | 2.78E+07 |
| Chromium | PS | SC | 1.56E+15 | 1.56E+13 | 3.91E+12 | 6.26E+11 | 1.56E+11 | 6.96E+10 | 1.74E+10 | 6.26E+09 | 2.78E+09 |
| Chromium | PS | OS_0.2 | 2.40E+14 | 2.40E+12 | 5.99E+11 | 9.58E+10 | 2.40E+10 | 1.06E+10 | 2.66E+09 | 9.58E+08 | 4.26E+08 |
| Chromium | PS | OS_0.9 | 5.39E+14 | 5.39E+12 | 1.35E+12 | 2.15E+11 | 5.39E+10 | 2.39E+10 | 5.98E+09 | 2.15E+09 | 9.57E+08 |
| Chromium | PVC | SP | 1.82E+14 | 1.82E+12 | 4.54E+11 | 7.27E+10 | 1.82E+10 | 8.08E+09 | 2.02E+09 | 7.27E+08 | 3.23E+08 |
| Chromium | PVC | LC | 1.21E+13 | 1.21E+11 | 3.03E+10 | 4.85E+09 | 1.21E+09 | 5.38E+08 | 1.35E+08 | 4.85E+07 | 2.15E+07 |
| Chromium | PVC | SC | 1.21E+15 | 1.21E+13 | 3.03E+12 | 4.85E+11 | 1.21E+11 | 5.38E+10 | 1.35E+10 | 4.85E+09 | 2.15E+09 |
| Chromium | PVC | OS_0.2 | 1.85E+14 | 1.85E+12 | 4.64E+11 | 7.42E+10 | 1.85E+10 | 8.24E+09 | 2.06E+09 | 7.42E+08 | 3.30E+08 |
| Chromium | PVC | OS_0.9 | 4.17E+14 | 4.17E+12 | 1.04E+12 | 1.67E+11 | 4.17E+10 | 1.85E+10 | 4.63E+09 | 1.67E+09 | 7.41E+08 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Manganese | HDPE | SP | 9.08E+11 | 9.08E+09 | 2.27E+09 | 3.63E+08 | 9.08E+07 | 4.04E+07 | 1.01E+07 | 3.63E+06 | 1.61E+06 |
| Manganese | HDPE | LC | 6.05E+10 | 6.05E+08 | 1.51E+08 | 2.42E+07 | 6.05E+06 | 2.69E+06 | 6.73E+05 | 2.42E+05 | 1.08E+05 |
| Manganese | HDPE | SC | 6.05E+12 | 6.05E+10 | 1.51E+10 | 2.42E+09 | 6.05E+08 | 2.69E+08 | 6.73E+07 | 2.42E+07 | 1.08E+07 |
| Manganese | HDPE | OS_0.2 | 9.27E+11 | 9.27E+09 | 2.32E+09 | 3.71E+08 | 9.27E+07 | 4.12E+07 | 1.03E+07 | 3.71E+06 | 1.65E+06 |
| Manganese | HDPE | OS_0.9 | 2.08E+12 | 2.08E+10 | 5.21E+09 | 8.33E+08 | 2.08E+08 | 9.26E+07 | 2.31E+07 | 8.33E+06 | 3.70E+06 |
| Manganese | PC | SP | 7.14E+11 | 7.14E+09 | 1.78E+09 | 2.86E+08 | 7.14E+07 | 3.17E+07 | 7.93E+06 | 2.86E+06 | 1.27E+06 |
| Manganese | PC | LC | 4.76E+10 | 4.76E+08 | 1.19E+08 | 1.90E+07 | 4.76E+06 | 2.12E+06 | 5.29E+05 | 1.90E+05 | 8.46E+04 |
| Manganese | PC | SC | 4.76E+12 | 4.76E+10 | 1.19E+10 | 1.90E+09 | 4.76E+08 | 2.12E+08 | 5.29E+07 | 1.90E+07 | 8.46E+06 |
| Manganese | PC | OS_0.2 | 7.29E+11 | 7.29E+09 | 1.82E+09 | 2.91E+08 | 7.29E+07 | 3.24E+07 | 8.10E+06 | 2.91E+06 | 1.30E+06 |
| Manganese | PC | OS_0.9 | 1.64E+12 | 1.64E+10 | 4.10E+09 | 6.55E+08 | 1.64E+08 | 7.28E+07 | 1.82E+07 | 6.55E+06 | 2.91E+06 |
| Manganese | PE | SP | 1.02E+12 | 1.02E+10 | 2.56E+09 | 4.09E+08 | 1.02E+08 | 4.54E+07 | 1.14E+07 | 4.09E+06 | 1.82E+06 |
| Manganese | PE | LC | 6.82E+10 | 6.82E+08 | 1.70E+08 | 2.73E+07 | 6.82E+06 | 3.03E+06 | 7.57E+05 | 2.73E+05 | 1.21E+05 |
| Manganese | PE | SC | 6.82E+12 | 6.82E+10 | 1.70E+10 | 2.73E+09 | 6.82E+08 | 3.03E+08 | 7.57E+07 | 2.73E+07 | 1.21E+07 |
| Manganese | PE | OS_0.2 | 1.04E+12 | 1.04E+10 | 2.61E+09 | 4.17E+08 | 1.04E+08 | 4.64E+07 | 1.16E+07 | 4.17E+06 | 1.86E+06 |
| Manganese | PE | OS_0.9 | 2.35E+12 | 2.35E+10 | 5.86E+09 | 9.38E+08 | 2.35E+08 | 1.04E+08 | 2.61E+07 | 9.38E+06 | 4.17E+06 |
| Manganese | PET | SP | 6.43E+11 | 6.43E+09 | 1.61E+09 | 2.57E+08 | 6.43E+07 | 2.86E+07 | 7.15E+06 | 2.57E+06 | 1.14E+06 |
| Manganese | PET | LC | 4.29E+10 | 4.29E+08 | 1.07E+08 | 1.72E+07 | 4.29E+06 | 1.91E+06 | 4.77E+05 | 1.72E+05 | 7.63E+04 |
| Manganese | PET | SC | 4.29E+12 | 4.29E+10 | 1.07E+10 | 1.72E+09 | 4.29E+08 | 1.91E+08 | 4.77E+07 | 1.72E+07 | 7.63E+06 |
| Manganese | PET | OS_0.2 | 6.57E+11 | 6.57E+09 | 1.64E+09 | 2.63E+08 | 6.57E+07 | 2.92E+07 | 7.30E+06 | 2.63E+06 | 1.17E+06 |
| Manganese | PET | OS_0.9 | 1.48E+12 | 1.48E+10 | 3.69E+09 | 5.90E+08 | 1.48E+08 | 6.56E+07 | 1.64E+07 | 5.90E+06 | 2.62E+06 |
| Manganese | PP | SP | 1.04E+12 | 1.04E+10 | 2.60E+09 | 4.16E+08 | 1.04E+08 | 4.62E+07 | 1.16E+07 | 4.16E+06 | 1.85E+06 |
| Manganese | PP | LC | 6.93E+10 | 6.93E+08 | 1.73E+08 | 2.77E+07 | 6.93E+06 | 3.08E+06 | 7.70E+05 | 2.77E+05 | 1.23E+05 |
| Manganese | PP | SC | 6.93E+12 | 6.93E+10 | 1.73E+10 | 2.77E+09 | 6.93E+08 | 3.08E+08 | 7.70E+07 | 2.77E+07 | 1.23E+07 |
| Manganese | PP | OS_0.2 | 1.06E+12 | 1.06E+10 | 2.65E+09 | 4.25E+08 | 1.06E+08 | 4.72E+07 | 1.18E+07 | 4.25E+06 | 1.89E+06 |
| Manganese | PP | OS_0.9 | 2.39E+12 | 2.39E+10 | 5.97E+09 | 9.54E+08 | 2.39E+08 | 1.06E+08 | 2.65E+07 | 9.54E+06 | 4.24E+06 |

| **Contaminant** | **MP** | **Shape** | **1** | **10** | **20** | **50** | **100** | **150** | **300** | **500** | **750** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Manganese | PS | SP | 8.20E+11 | 8.20E+09 | 2.05E+09 | 3.28E+08 | 8.20E+07 | 3.64E+07 | 9.11E+06 | 3.28E+06 | 1.46E+06 |
| Manganese | PS | LC | 5.47E+10 | 5.47E+08 | 1.37E+08 | 2.19E+07 | 5.47E+06 | 2.43E+06 | 6.07E+05 | 2.19E+05 | 9.72E+04 |
| Manganese | PS | SC | 5.47E+12 | 5.47E+10 | 1.37E+10 | 2.19E+09 | 5.47E+08 | 2.43E+08 | 6.07E+07 | 2.19E+07 | 9.72E+06 |
| Manganese | PS | OS_0.2 | 8.37E+11 | 8.37E+09 | 2.09E+09 | 3.35E+08 | 8.37E+07 | 3.72E+07 | 9.30E+06 | 3.35E+06 | 1.49E+06 |
| Manganese | PS | OS_0.9 | 1.88E+12 | 1.88E+10 | 4.70E+09 | 7.52E+08 | 1.88E+08 | 8.36E+07 | 2.09E+07 | 7.52E+06 | 3.34E+06 |
| Manganese | PVC | SP | 6.35E+11 | 6.35E+09 | 1.59E+09 | 2.54E+08 | 6.35E+07 | 2.82E+07 | 7.05E+06 | 2.54E+06 | 1.13E+06 |
| Manganese | PVC | LC | 4.23E+10 | 4.23E+08 | 1.06E+08 | 1.69E+07 | 4.23E+06 | 1.88E+06 | 4.70E+05 | 1.69E+05 | 7.52E+04 |
| Manganese | PVC | SC | 4.23E+12 | 4.23E+10 | 1.06E+10 | 1.69E+09 | 4.23E+08 | 1.88E+08 | 4.70E+07 | 1.69E+07 | 7.52E+06 |
| Manganese | PVC | OS_0.2 | 6.48E+11 | 6.48E+09 | 1.62E+09 | 2.59E+08 | 6.48E+07 | 2.88E+07 | 7.20E+06 | 2.59E+06 | 1.15E+06 |
| Manganese | PVC | OS_0.9 | 1.46E+12 | 1.46E+10 | 3.64E+09 | 5.82E+08 | 1.46E+08 | 6.47E+07 | 1.62E+07 | 5.82E+06 | 2.59E+06 |
| Mercury | HDPE | SP | 6.99E+14 | 6.99E+12 | 1.75E+12 | 2.80E+11 | 6.99E+10 | 3.11E+10 | 7.77E+09 | 2.80E+09 | 1.24E+09 |
| Mercury | HDPE | LC | 4.66E+13 | 4.66E+11 | 1.17E+11 | 1.87E+10 | 4.66E+09 | 2.07E+09 | 5.18E+08 | 1.87E+08 | 8.29E+07 |
| Mercury | HDPE | SC | 4.66E+15 | 4.66E+13 | 1.17E+13 | 1.87E+12 | 4.66E+11 | 2.07E+11 | 5.18E+10 | 1.87E+10 | 8.29E+09 |
| Mercury | HDPE | OS_0.2 | 7.14E+14 | 7.14E+12 | 1.78E+12 | 2.86E+11 | 7.14E+10 | 3.17E+10 | 7.93E+09 | 2.86E+09 | 1.27E+09 |
| Mercury | HDPE | OS_0.9 | 1.60E+15 | 1.60E+13 | 4.01E+12 | 6.42E+11 | 1.60E+11 | 7.13E+10 | 1.78E+10 | 6.42E+09 | 2.85E+09 |
| Mercury | PC | SP | 5.50E+14 | 5.50E+12 | 1.38E+12 | 2.20E+11 | 5.50E+10 | 2.44E+10 | 6.11E+09 | 2.20E+09 | 9.78E+08 |
| Mercury | PC | LC | 3.67E+13 | 3.67E+11 | 9.17E+10 | 1.47E+10 | 3.67E+09 | 1.63E+09 | 4.07E+08 | 1.47E+08 | 6.52E+07 |
| Mercury | PC | SC | 3.67E+15 | 3.67E+13 | 9.17E+12 | 1.47E+12 | 3.67E+11 | 1.63E+11 | 4.07E+10 | 1.47E+10 | 6.52E+09 |
| Mercury | PC | OS_0.2 | 5.61E+14 | 5.61E+12 | 1.40E+12 | 2.25E+11 | 5.61E+10 | 2.50E+10 | 6.24E+09 | 2.25E+09 | 9.98E+08 |
| Mercury | PC | OS_0.9 | 1.26E+15 | 1.26E+13 | 3.15E+12 | 5.05E+11 | 1.26E+11 | 5.61E+10 | 1.40E+10 | 5.05E+09 | 2.24E+09 |
| Mercury | PE | SP | 7.88E+14 | 7.88E+12 | 1.97E+12 | 3.15E+11 | 7.88E+10 | 3.50E+10 | 8.75E+09 | 3.15E+09 | 1.40E+09 |
| Mercury | PE | LC | 5.25E+13 | 5.25E+11 | 1.31E+11 | 2.10E+10 | 5.25E+09 | 2.33E+09 | 5.83E+08 | 2.10E+08 | 9.34E+07 |
| Mercury | PE | SC | 5.25E+15 | 5.25E+13 | 1.31E+13 | 2.10E+12 | 5.25E+11 | 2.33E+11 | 5.83E+10 | 2.10E+10 | 9.34E+09 |
| Mercury | PE | OS_0.2 | 8.04E+14 | 8.04E+12 | 2.01E+12 | 3.22E+11 | 8.04E+10 | 3.57E+10 | 8.93E+09 | 3.22E+09 | 1.43E+09 |
| Mercury | PE | OS_0.9 | 1.81E+15 | 1.81E+13 | 4.52E+12 | 7.23E+11 | 1.81E+11 | 8.03E+10 | 2.01E+10 | 7.23E+09 | 3.21E+09 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mercury | PET | SP | 4.96E+14 | 4.96E+12 | 1.24E+12 | 1.98E+11 | 4.96E+10 | 2.20E+10 | 5.51E+09 | 1.98E+09 | 8.81E+08 |
| Mercury | PET | LC | 3.30E+13 | 3.30E+11 | 8.26E+10 | 1.32E+10 | 3.30E+09 | 1.47E+09 | 3.67E+08 | 1.32E+08 | 5.88E+07 |
| Mercury | PET | SC | 3.30E+15 | 3.30E+13 | 8.26E+12 | 1.32E+12 | 3.30E+11 | 1.47E+11 | 3.67E+10 | 1.32E+10 | 5.88E+09 |
| Mercury | PET | OS_0.2 | 5.06E+14 | 5.06E+12 | 1.26E+12 | 2.02E+11 | 5.06E+10 | 2.25E+10 | 5.62E+09 | 2.02E+09 | 8.99E+08 |
| Mercury | PET | OS_0.9 | 1.14E+15 | 1.14E+13 | 2.84E+12 | 4.55E+11 | 1.14E+11 | 5.05E+10 | 1.26E+10 | 4.55E+09 | 2.02E+09 |
| Mercury | PP | SP | 8.01E+14 | 8.01E+12 | 2.00E+12 | 3.21E+11 | 8.01E+10 | 3.56E+10 | 8.90E+09 | 3.21E+09 | 1.42E+09 |
| Mercury | PP | LC | 5.34E+13 | 5.34E+11 | 1.34E+11 | 2.14E+10 | 5.34E+09 | 2.37E+09 | 5.94E+08 | 2.14E+08 | 9.50E+07 |
| Mercury | PP | SC | 5.34E+15 | 5.34E+13 | 1.34E+13 | 2.14E+12 | 5.34E+11 | 2.37E+11 | 5.94E+10 | 2.14E+10 | 9.50E+09 |
| Mercury | PP | OS_0.2 | 8.18E+14 | 8.18E+12 | 2.04E+12 | 3.27E+11 | 8.18E+10 | 3.63E+10 | 9.09E+09 | 3.27E+09 | 1.45E+09 |
| Mercury | PP | OS_0.9 | 1.84E+15 | 1.84E+13 | 4.60E+12 | 7.35E+11 | 1.84E+11 | 8.17E+10 | 2.04E+10 | 7.35E+09 | 3.27E+09 |
| Mercury | PS | SP | 6.32E+14 | 6.32E+12 | 1.58E+12 | 2.53E+11 | 6.32E+10 | 2.81E+10 | 7.02E+09 | 2.53E+09 | 1.12E+09 |
| Mercury | PS | LC | 4.21E+13 | 4.21E+11 | 1.05E+11 | 1.68E+10 | 4.21E+09 | 1.87E+09 | 4.68E+08 | 1.68E+08 | 7.48E+07 |
| Mercury | PS | SC | 4.21E+15 | 4.21E+13 | 1.05E+13 | 1.68E+12 | 4.21E+11 | 1.87E+11 | 4.68E+10 | 1.68E+10 | 7.48E+09 |
| Mercury | PS | OS_0.2 | 6.45E+14 | 6.45E+12 | 1.61E+12 | 2.58E+11 | 6.45E+10 | 2.86E+10 | 7.16E+09 | 2.58E+09 | 1.15E+09 |
| Mercury | PS | OS_0.9 | 1.45E+15 | 1.45E+13 | 3.62E+12 | 5.80E+11 | 1.45E+11 | 6.44E+10 | 1.61E+10 | 5.80E+09 | 2.58E+09 |
| Mercury | PVC | SP | 4.89E+14 | 4.89E+12 | 1.22E+12 | 1.96E+11 | 4.89E+10 | 2.17E+10 | 5.43E+09 | 1.96E+09 | 8.69E+08 |
| Mercury | PVC | LC | 3.26E+13 | 3.26E+11 | 8.15E+10 | 1.30E+10 | 3.26E+09 | 1.45E+09 | 3.62E+08 | 1.30E+08 | 5.79E+07 |
| Mercury | PVC | SC | 3.26E+15 | 3.26E+13 | 8.15E+12 | 1.30E+12 | 3.26E+11 | 1.45E+11 | 3.62E+10 | 1.30E+10 | 5.79E+09 |
| Mercury | PVC | OS_0.2 | 4.99E+14 | 4.99E+12 | 1.25E+12 | 2.00E+11 | 4.99E+10 | 2.22E+10 | 5.54E+09 | 2.00E+09 | 8.87E+08 |
| Mercury | PVC | OS_0.9 | 1.12E+15 | 1.12E+13 | 2.80E+12 | 4.49E+11 | 1.12E+11 | 4.99E+10 | 1.25E+10 | 4.49E+09 | 1.99E+09 |
| Propanolol | HDPE | SP | 1.64E+11 | 1.64E+09 | 4.11E+08 | 6.57E+07 | 1.64E+07 | 7.30E+06 | 1.83E+06 | 6.57E+05 | 2.92E+05 |
| Propanolol | HDPE | LC | 1.10E+10 | 1.10E+08 | 2.74E+07 | 4.38E+06 | 1.10E+06 | 4.87E+05 | 1.22E+05 | 4.38E+04 | 1.95E+04 |
| Propanolol | HDPE | SC | 1.10E+12 | 1.10E+10 | 2.74E+09 | 4.38E+08 | 1.10E+08 | 4.87E+07 | 1.22E+07 | 4.38E+06 | 1.95E+06 |
| Propanolol | HDPE | OS_0.2 | 1.68E+11 | 1.68E+09 | 4.19E+08 | 6.71E+07 | 1.68E+07 | 7.45E+06 | 1.86E+06 | 6.71E+05 | 2.98E+05 |
| Propanolol | HDPE | OS_0.9 | 3.77E+11 | 3.77E+09 | 9.43E+08 | 1.51E+08 | 3.77E+07 | 1.68E+07 | 4.19E+06 | 1.51E+06 | 6.70E+05 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Propanolol | PC | SP | 1.29E+11 | 1.29E+09 | 3.23E+08 | 5.17E+07 | 1.29E+07 | 5.74E+06 | 1.44E+06 | 5.17E+05 | 2.30E+05 |
| Propanolol | PC | LC | 8.62E+09 | 8.62E+07 | 2.15E+07 | 3.45E+06 | 8.62E+05 | 3.83E+05 | 9.57E+04 | 3.45E+04 | 1.53E+04 |
| Propanolol | PC | SC | 8.62E+11 | 8.62E+09 | 2.15E+09 | 3.45E+08 | 8.62E+07 | 3.83E+07 | 9.57E+06 | 3.45E+06 | 1.53E+06 |
| Propanolol | PC | OS_0.2 | 1.32E+11 | 1.32E+09 | 3.30E+08 | 5.28E+07 | 1.32E+07 | 5.86E+06 | 1.47E+06 | 5.28E+05 | 2.34E+05 |
| Propanolol | PC | OS_0.9 | 2.96E+11 | 2.96E+09 | 7.41E+08 | 1.19E+08 | 2.96E+07 | 1.32E+07 | 3.29E+06 | 1.19E+06 | 5.27E+05 |
| Propanolol | PE | SP | 1.85E+11 | 1.85E+09 | 4.63E+08 | 7.40E+07 | 1.85E+07 | 8.23E+06 | 2.06E+06 | 7.40E+05 | 3.29E+05 |
| Propanolol | PE | LC | 1.23E+10 | 1.23E+08 | 3.08E+07 | 4.94E+06 | 1.23E+06 | 5.48E+05 | 1.37E+05 | 4.94E+04 | 2.19E+04 |
| Propanolol | PE | SC | 1.23E+12 | 1.23E+10 | 3.08E+09 | 4.94E+08 | 1.23E+08 | 5.48E+07 | 1.37E+07 | 4.94E+06 | 2.19E+06 |
| Propanolol | PE | OS_0.2 | 1.89E+11 | 1.89E+09 | 4.72E+08 | 7.56E+07 | 1.89E+07 | 8.40E+06 | 2.10E+06 | 7.56E+05 | 3.36E+05 |
| Propanolol | PE | OS_0.9 | 4.25E+11 | 4.25E+09 | 1.06E+09 | 1.70E+08 | 4.25E+07 | 1.89E+07 | 4.72E+06 | 1.70E+06 | 7.55E+05 |
| Propanolol | PET | SP | 1.16E+11 | 1.16E+09 | 2.91E+08 | 4.66E+07 | 1.16E+07 | 5.18E+06 | 1.29E+06 | 4.66E+05 | 2.07E+05 |
| Propanolol | PET | LC | 7.76E+09 | 7.76E+07 | 1.94E+07 | 3.11E+06 | 7.76E+05 | 3.45E+05 | 8.63E+04 | 3.11E+04 | 1.38E+04 |
| Propanolol | PET | SC | 7.76E+11 | 7.76E+09 | 1.94E+09 | 3.11E+08 | 7.76E+07 | 3.45E+07 | 8.63E+06 | 3.11E+06 | 1.38E+06 |
| Propanolol | PET | OS_0.2 | 1.19E+11 | 1.19E+09 | 2.97E+08 | 4.76E+07 | 1.19E+07 | 5.28E+06 | 1.32E+06 | 4.76E+05 | 2.11E+05 |
| Propanolol | PET | OS_0.9 | 2.67E+11 | 2.67E+09 | 6.68E+08 | 1.07E+08 | 2.67E+07 | 1.19E+07 | 2.97E+06 | 1.07E+06 | 4.75E+05 |
| Propanolol | PP | SP | 1.88E+11 | 1.88E+09 | 4.71E+08 | 7.53E+07 | 1.88E+07 | 8.37E+06 | 2.09E+06 | 7.53E+05 | 3.35E+05 |
| Propanolol | PP | LC | 1.26E+10 | 1.26E+08 | 3.14E+07 | 5.02E+06 | 1.26E+06 | 5.58E+05 | 1.39E+05 | 5.02E+04 | 2.23E+04 |
| Propanolol | PP | SC | 1.26E+12 | 1.26E+10 | 3.14E+09 | 5.02E+08 | 1.26E+08 | 5.58E+07 | 1.39E+07 | 5.02E+06 | 2.23E+06 |
| Propanolol | PP | OS_0.2 | 1.92E+11 | 1.92E+09 | 4.80E+08 | 7.69E+07 | 1.92E+07 | 8.54E+06 | 2.14E+06 | 7.69E+05 | 3.42E+05 |
| Propanolol | PP | OS_0.9 | 4.32E+11 | 4.32E+09 | 1.08E+09 | 1.73E+08 | 4.32E+07 | 1.92E+07 | 4.80E+06 | 1.73E+06 | 7.68E+05 |
| Propanolol | PS | SP | 1.48E+11 | 1.48E+09 | 3.71E+08 | 5.94E+07 | 1.48E+07 | 6.59E+06 | 1.65E+06 | 5.94E+05 | 2.64E+05 |
| Propanolol | PS | LC | 9.89E+09 | 9.89E+07 | 2.47E+07 | 3.96E+06 | 9.89E+05 | 4.40E+05 | 1.10E+05 | 3.96E+04 | 1.76E+04 |
| Propanolol | PS | SC | 9.89E+11 | 9.89E+09 | 2.47E+09 | 3.96E+08 | 9.89E+07 | 4.40E+07 | 1.10E+07 | 3.96E+06 | 1.76E+06 |
| Propanolol | PS | OS_0.2 | 1.51E+11 | 1.51E+09 | 3.79E+08 | 6.06E+07 | 1.51E+07 | 6.73E+06 | 1.68E+06 | 6.06E+05 | 2.69E+05 |
| Propanolol | PS | OS_0.9 | 3.40E+11 | 3.40E+09 | 8.51E+08 | 1.36E+08 | 3.40E+07 | 1.51E+07 | 3.78E+06 | 1.36E+06 | 6.05E+05 |

| **Contaminant** | **MP** | **Shape** | **1** | **10** | **20** | **50** | **100** | **150** | **300** | **500** | **750** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Propanolol | PVC | SP | 1.15E+11 | 1.15E+09 | 2.87E+08 | 4.60E+07 | 1.15E+07 | 5.11E+06 | 1.28E+06 | 4.60E+05 | 2.04E+05 |
| Propanolol | PVC | LC | 7.66E+09 | 7.66E+07 | 1.91E+07 | 3.06E+06 | 7.66E+05 | 3.40E+05 | 8.51E+04 | 3.06E+04 | 1.36E+04 |
| Propanolol | PVC | SC | 7.66E+11 | 7.66E+09 | 1.91E+09 | 3.06E+08 | 7.66E+07 | 3.40E+07 | 8.51E+06 | 3.06E+06 | 1.36E+06 |
| Propanolol | PVC | OS_0.2 | 1.17E+11 | 1.17E+09 | 2.93E+08 | 4.69E+07 | 1.17E+07 | 5.21E+06 | 1.30E+06 | 4.69E+05 | 2.08E+05 |
| Propanolol | PVC | OS_0.9 | 2.64E+11 | 2.64E+09 | 6.59E+08 | 1.05E+08 | 2.64E+07 | 1.17E+07 | 2.93E+06 | 1.05E+06 | 4.69E+05 |
| Sulfamethoxazole | HDPE | SP | 1.00E+13 | 1.00E+11 | 2.51E+10 | 4.02E+09 | 1.00E+09 | 4.47E+08 | 1.12E+08 | 4.02E+07 | 1.79E+07 |
| Sulfamethoxazole | HDPE | LC | 6.70E+11 | 6.70E+09 | 1.67E+09 | 2.68E+08 | 6.70E+07 | 2.98E+07 | 7.44E+06 | 2.68E+06 | 1.19E+06 |
| Sulfamethoxazole | HDPE | SC | 6.70E+13 | 6.70E+11 | 1.67E+11 | 2.68E+10 | 6.70E+09 | 2.98E+09 | 7.44E+08 | 2.68E+08 | 1.19E+08 |
| Sulfamethoxazole | HDPE | OS_0.2 | 1.03E+13 | 1.03E+11 | 2.56E+10 | 4.10E+09 | 1.03E+09 | 4.56E+08 | 1.14E+08 | 4.10E+07 | 1.82E+07 |
| Sulfamethoxazole | HDPE | OS_0.9 | 2.31E+13 | 2.31E+11 | 5.76E+10 | 9.22E+09 | 2.31E+09 | 1.02E+09 | 2.56E+08 | 9.22E+07 | 4.10E+07 |
| Sulfamethoxazole | PC | SP | 7.90E+12 | 7.90E+10 | 1.98E+10 | 3.16E+09 | 7.90E+08 | 3.51E+08 | 8.78E+07 | 3.16E+07 | 1.40E+07 |
| Sulfamethoxazole | PC | LC | 5.27E+11 | 5.27E+09 | 1.32E+09 | 2.11E+08 | 5.27E+07 | 2.34E+07 | 5.85E+06 | 2.11E+06 | 9.37E+05 |
| Sulfamethoxazole | PC | SC | 5.27E+13 | 5.27E+11 | 1.32E+11 | 2.11E+10 | 5.27E+09 | 2.34E+09 | 5.85E+08 | 2.11E+08 | 9.37E+07 |
| Sulfamethoxazole | PC | OS_0.2 | 8.07E+12 | 8.07E+10 | 2.02E+10 | 3.23E+09 | 8.07E+08 | 3.58E+08 | 8.96E+07 | 3.23E+07 | 1.43E+07 |
| Sulfamethoxazole | PC | OS_0.9 | 1.81E+13 | 1.81E+11 | 4.53E+10 | 7.25E+09 | 1.81E+09 | 8.06E+08 | 2.01E+08 | 7.25E+07 | 3.22E+07 |
| Sulfamethoxazole | PE | SP | 1.13E+13 | 1.13E+11 | 2.83E+10 | 4.53E+09 | 1.13E+09 | 5.03E+08 | 1.26E+08 | 4.53E+07 | 2.01E+07 |
| Sulfamethoxazole | PE | LC | 7.55E+11 | 7.55E+09 | 1.89E+09 | 3.02E+08 | 7.55E+07 | 3.35E+07 | 8.38E+06 | 3.02E+06 | 1.34E+06 |
| Sulfamethoxazole | PE | SC | 7.55E+13 | 7.55E+11 | 1.89E+11 | 3.02E+10 | 7.55E+09 | 3.35E+09 | 8.38E+08 | 3.02E+08 | 1.34E+08 |
| Sulfamethoxazole | PE | OS_0.2 | 1.16E+13 | 1.16E+11 | 2.89E+10 | 4.62E+09 | 1.16E+09 | 5.13E+08 | 1.28E+08 | 4.62E+07 | 2.05E+07 |
| Sulfamethoxazole | PE | OS_0.9 | 2.60E+13 | 2.60E+11 | 6.49E+10 | 1.04E+10 | 2.60E+09 | 1.15E+09 | 2.88E+08 | 1.04E+08 | 4.62E+07 |
| Sulfamethoxazole | PET | SP | 7.12E+12 | 7.12E+10 | 1.78E+10 | 2.85E+09 | 7.12E+08 | 3.17E+08 | 7.91E+07 | 2.85E+07 | 1.27E+07 |
| Sulfamethoxazole | PET | LC | 4.75E+11 | 4.75E+09 | 1.19E+09 | 1.90E+08 | 4.75E+07 | 2.11E+07 | 5.28E+06 | 1.90E+06 | 8.44E+05 |
| Sulfamethoxazole | PET | SC | 4.75E+13 | 4.75E+11 | 1.19E+11 | 1.90E+10 | 4.75E+09 | 2.11E+09 | 5.28E+08 | 1.90E+08 | 8.44E+07 |
| Sulfamethoxazole | PET | OS_0.2 | 7.27E+12 | 7.27E+10 | 1.82E+10 | 2.91E+09 | 7.27E+08 | 3.23E+08 | 8.08E+07 | 2.91E+07 | 1.29E+07 |
| Sulfamethoxazole | PET | OS_0.9 | 1.63E+13 | 1.63E+11 | 4.08E+10 | 6.54E+09 | 1.63E+09 | 7.26E+08 | 1.82E+08 | 6.54E+07 | 2.90E+07 |

| Contaminant | MP | Shape | 1 | 10 | 20 | 50 | 100 | 150 | 300 | 500 | 750 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sulfamethoxazole | PP | SP | 1.15E+13 | 1.15E+11 | 2.88E+10 | 4.61E+09 | 1.15E+09 | 5.12E+08 | 1.28E+08 | 4.61E+07 | 2.05E+07 |
| Sulfamethoxazole | PP | LC | 7.68E+11 | 7.68E+09 | 1.92E+09 | 3.07E+08 | 7.68E+07 | 3.41E+07 | 8.53E+06 | 3.07E+06 | 1.36E+06 |
| Sulfamethoxazole | PP | SC | 7.68E+13 | 7.68E+11 | 1.92E+11 | 3.07E+10 | 7.68E+09 | 3.41E+09 | 8.53E+08 | 3.07E+08 | 1.36E+08 |
| Sulfamethoxazole | PP | OS_0.2 | 1.18E+13 | 1.18E+11 | 2.94E+10 | 4.70E+09 | 1.18E+09 | 5.22E+08 | 1.31E+08 | 4.70E+07 | 2.09E+07 |
| Sulfamethoxazole | PP | OS_0.9 | 2.64E+13 | 2.64E+11 | 6.60E+10 | 1.06E+10 | 2.64E+09 | 1.17E+09 | 2.93E+08 | 1.06E+08 | 4.70E+07 |
| Sulfamethoxazole | PS | SP | 9.07E+12 | 9.07E+10 | 2.27E+10 | 3.63E+09 | 9.07E+08 | 4.03E+08 | 1.01E+08 | 3.63E+07 | 1.61E+07 |
| Sulfamethoxazole | PS | LC | 6.05E+11 | 6.05E+09 | 1.51E+09 | 2.42E+08 | 6.05E+07 | 2.69E+07 | 6.72E+06 | 2.42E+06 | 1.08E+06 |
| Sulfamethoxazole | PS | SC | 6.05E+13 | 6.05E+11 | 1.51E+11 | 2.42E+10 | 6.05E+09 | 2.69E+09 | 6.72E+08 | 2.42E+08 | 1.08E+08 |
| Sulfamethoxazole | PS | OS_0.2 | 9.26E+12 | 9.26E+10 | 2.32E+10 | 3.70E+09 | 9.26E+08 | 4.12E+08 | 1.03E+08 | 3.70E+07 | 1.65E+07 |
| Sulfamethoxazole | PS | OS_0.9 | 2.08E+13 | 2.08E+11 | 5.20E+10 | 8.33E+09 | 2.08E+09 | 9.25E+08 | 2.31E+08 | 8.33E+07 | 3.70E+07 |
| Sulfamethoxazole | PVC | SP | 7.02E+12 | 7.02E+10 | 1.76E+10 | 2.81E+09 | 7.02E+08 | 3.12E+08 | 7.81E+07 | 2.81E+07 | 1.25E+07 |
| Sulfamethoxazole | PVC | LC | 4.68E+11 | 4.68E+09 | 1.17E+09 | 1.87E+08 | 4.68E+07 | 2.08E+07 | 5.20E+06 | 1.87E+06 | 8.33E+05 |
| Sulfamethoxazole | PVC | SC | 4.68E+13 | 4.68E+11 | 1.17E+11 | 1.87E+10 | 4.68E+09 | 2.08E+09 | 5.20E+08 | 1.87E+08 | 8.33E+07 |
| Sulfamethoxazole | PVC | OS_0.2 | 7.17E+12 | 7.17E+10 | 1.79E+10 | 2.87E+09 | 7.17E+08 | 3.19E+08 | 7.97E+07 | 2.87E+07 | 1.27E+07 |
| Sulfamethoxazole | PVC | OS_0.9 | 1.61E+13 | 1.61E+11 | 4.03E+10 | 6.45E+09 | 1.61E+09 | 7.16E+08 | 1.79E+08 | 6.45E+07 | 2.87E+07 |