

The Fate and Transport of Microplastics in Aquatic Ecosystems: Synthesis and Directions for Future Research

Dr. Shooka Karimpour (PI)

Assistant Professor, Department of Civil Engineering, Lassonde School of Engineering, York University

Dr. Satinder Brar (co-PI)

Professor, Department of Civil Engineering, Lassonde School of Engineering, York University

Dr. Hamidreza Shirkhani (Collaborator)

Research Officer, Civil Engineering Infrastructure group, National Research Council Canada

Team Members:

Arefeh Shamkhany, Preet Patel, Zhuoran Li

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Executive Summary

Background: Plastics are durable, lightweight, and cheap to manufacture, making them suitable candidates for use in a wide spectrum of products. Modern life would be significantly different without plastics and, as a result, global plastic production dramatically increased by 620% between 1975 and 2012. Despite their benefits, challenges related to the end-of-life of these materials remain to be addressed. It is estimated that 4.8 to 12.7 million tonnes of plastic waste entered the ocean in 2010. In the past decade, small plastic particles known as “microplastics”, sized smaller than 5mm, have emerged as a hazardous pollutant due to their impact on aquatic animals and human health. Plastics are considered relatively recalcitrant in aquatic systems as their decomposition and degradation can take up to several centuries, if not millennia. Even in the event of a very radical and unlikely response to this environmental crisis, in which plastics’ global production comes to a full halt, plastics will remain prevalent, and their adverse impacts will persist in aquatic systems for centuries.

MPs are spread and found globally, even in the deepest sea sediments and remote arctic areas. The distribution of MPs in such environments is closely associated with hydrodynamic conditions. Some of the physical processes responsible for the mobilization of nutrients, oxygen, and sediments - vital to aquatic ecosystems - are also capable of transporting MPs. Hydrodynamic processes play significant roles in the dispersal and deposition of aquatic MPs. However, our knowledge of the geographical and temporal distribution of MPs and their accumulation is limited, and in particular, the distribution in deep-water and deep sediments is largely unknown.

Objectives: Our objectives are to identify: i) The primary hydrodynamic parameters reported that impact microplastic transport; ii) The physical and chemical changes MPs undergo in aquatic ecosystems and their relevant hydrodynamic parametrization; iii) identify the impact of hydrodynamic processes on MP accumulation and presence.

Findings: Plastic generation has steadily increased in the past decades. An increase in plastic production leads to more release and emission to aquatic systems. Plastics are emitted through various pathways including, rivers, stormwater runoff, wastewater discharge, and windage. Plastics are found with multiple inherent properties: densities from 0.008 to 2.2 g/cm³ and by design have variable flexibility, rigidity, and chemical resistance.

Microplastic found in freshwater and marine environments also possess unique properties: Primary microplastics are manufactured as micro-size plastics. Secondary microplastics are the byproduct of fragmentation and degradation of larger size plastics in the aquatic environment. The majority of MPs found in the aquatic systems are secondary MPs. Therefore, one large plastic debris can break down over years, decades, and centuries into thousands of smaller sized plastics. This leads to far more reaching adverse impacts on the environment and ecosystem health.

The inherent plastic properties listed above impacts the fragmentation, breakdown process, and ultimate shape of the microplastics. Microplastic shape is a critical classification, as it

directly affects forces from the ambient fluid, interactions of fluid and particles, and changes to particle density. For instance, the particle volume affects its buoyance and weight, while its area affects fluid forces. The net of these forces governs the trajectory of MP particles. The distribution and accumulation are also dominated by the ambient fresh or seawater's kinematics and the properties listed in the report. The particle's apparent density is an important parameter: as particles with densities smaller than the density of the ambient fluid (light plastics such as LDPE, PP) tend to float, whereas heavier particles with densities greater than the density of the ambient fluid tend to sink. This, however, is not the sole parameter shaping fate and distribution. There is evidence linking microplastic distribution and presence to other factors such as biofouling (accumulation of biofilm on microplastic's surface), in-depth and surface currents, windage, density currents, among other factors. Furthermore, a comprehensive literature review on MP presence and distribution points out that MP distribution is size-, density-, and shape-selective. Studies mainly focus on identifying the impact of shape and density on dispersal; however, authors believe that MP size significantly affects distribution, especially distribution patterns linked to long-distance and in-depth transport.

Key Messages: Source plastic emission control is essential in plastic pollution control. Once emitted into marine and freshwater environments, plastics break into smaller pieces. These pieces can migrate thousands of kilometers affecting ecosystems and environments far from the source of the emission. Furthermore, tackling the problem of aquatic MP pollution stretches beyond any one discipline and understanding MP fate and transport requires an integrated and interdisciplinary approach.

1. Background: Microplastic pollution, a global and a national environmental threat

The widespread application of plastic material has brought far-reaching societal benefits; however, improper management of plastic waste has caused negative impacts on the environment, especially on aquatic ecosystems. Different clean-up technologies have emerged in the past decade, aiming to collect floating large plastic debris from ocean surfaces and, more recently, from the Great Lakes. However, multiple recent studies suggest that floating plastic debris on the surface of aquatic systems accounts for only about 1% of the estimated aquatic plastic budget and the remaining 99% of such plastics are *hidden* and end up in deep water and sediment.

In the past decade, small plastic particles known as “microplastics” (sized smaller than 5mm) have emerged as a hazardous pollutant due to their impacts on aquatic animals and human health. As will be highlighted in this report, in marine environments, microplastics (MPs) have been reported around the world, in the deepest sediments of the Pacific Ocean (Van Cauwenberghe et al., 2013) and in remote Arctic areas (Bergmann et al., 2017). Fewer studies are available on the spread of MPs in freshwater systems, especially in Canada. A recently published study by Huntington et al. (2020) have assessed MP presence in Hudson Bay. Authors have reported MPs in sediment and water samples and with a small population in the vicinity of the sites, they have concluded that MP presence was due to the long-term transport of plastic debris. Across the Great Lakes, MPs have been reported along shorelines [11,12,13], in offshore lake sediments [14, 15], and subsurface nearshore sediments [16]. In the sparsely populated Lake Winnipeg, MPs were also found in samples collected from surface (Anderson et al., 2017). Studies along Canadian coastal areas have also suggested notable concentration, specially close to urban areas. For instance, Desforges et al. (2014) have reported the concentration of MPs, presence of fibre, and distribution in the seawater of the Pacific Ocean around Vancouver Island. They have reported that in stations closer to the island with great a population concentration was generally higher fibres accounted for a higher percentage in nearshore samples.

While there is evidence of global aquatic MP widespread, research projects and publications in the national scale also have identified MP pollution across various seawater and freshwater environments in Canada. Based on population distribution, industrial activities, and other factors, part of freshwater and marine MP pollution has been attributed to regional and watershed activities, while others have been linked to long-distance transport of macro and micro-plastics. It is undoubtedly clear that the transport, deposition, and dispersal of aquatic plastics depend on 2 major factors: i) plastic and microplastic characteristic and ii) hydrodynamic patterns.

In the Environmental HydroDynamics lab (EHDLab) at Lassonde School of Engineering, we have conducted a comprehensive review of the existing scholarly publications in the area of MP transport. This project’s **overall objective** has been to describe the current state-of-art knowledge of physical processes that shape the transport and accumulation of aquatic MP debris. This project has identified:

- I) The primary hydrodynamic parameters reported (e.g., windage, terminal velocity, diffusivity, critical shear stress) that impact microplastic transport.
- II) The physical and chemical changes MPs undergo in aquatic ecosystems and their relevant hydrodynamic parametrization.
- III) The hotspot of MPs' accumulation and bioavailability reported in Canada and globally and identify the underlying hydrodynamic processes.

This report has several sections. Sections 2 to 5 address Objectives I, II, and III. In section 6 to 9 we will discuss research gaps, knowledge mobilization activities thus far, and implications on policy and recommendations.

2. Plastic production and emission

2.1 Plastic production and composition:

Plastics are durable, lightweight, and cheap to manufacture, and these properties make them suitable candidates for use in a broad spectrum of products. Modern life would be significantly different without plastics, and global plastic production has dramatically increased by 620% between 1975 and 2012 (Plastics Europe & EPRO, 2019). Plastic production has steadily increased globally since 2008. With the present trends, annual plastic production is expected to reach 1,124 million tonnes by 2050 (Ellen MacArthur Foundation 2016).

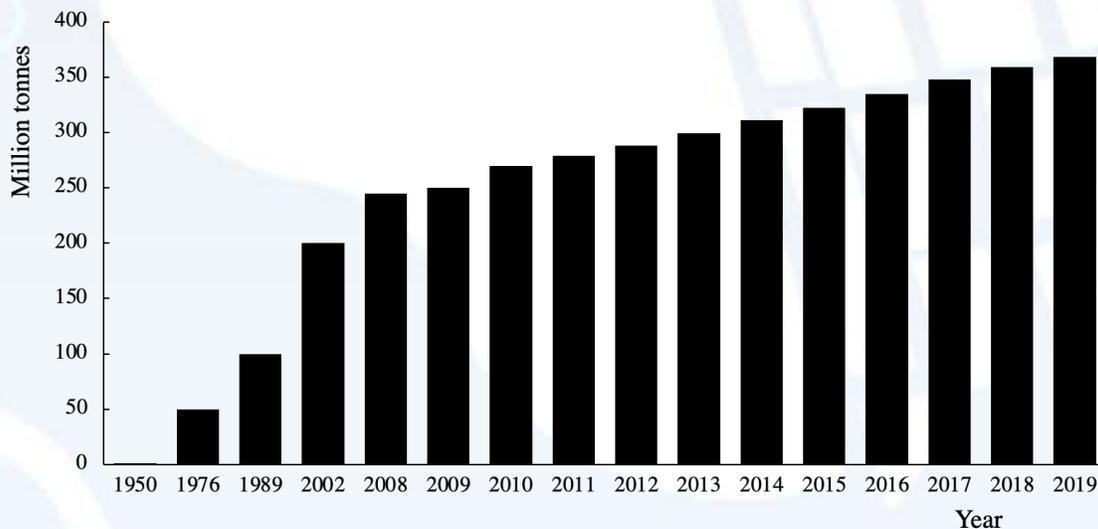


Figure 1: Global per annum plastic production since 1950.

Globally, 50% of produced plastics comprises polyethylene (LDPE, HDPE, LLDPE and MDPE) and polypropylene (Plastics Europe & EPRO, 2019). Packaging and building and construction industries account for about 60% of the total plastic use worldwide, where packaging alone accounts for the use of about 40% of plastic production. In this sector, a wide variety of polymer types are used. LDPE, HDPE, PE, and PET are used in different

packaging and services. Plastic classification by the Society of the Plastics Industry (SPI) divides all plastics into 7 categories and describes the properties of each polymer types. The purpose of the number is to identify the type of plastic used for the product, and not all plastics are recyclable or even reusable. Table 2 summarizes the range of densities, an important polymer property, reported by Schwartz et al. (2019).

Plastic debris is found in beaches, surface water, water column and deep-sea sediment. Plastic properties, including polymer density, govern the vertical distribution. As will be highlighted later in sections 3 and 5, polymer density is among many parameters that impact plastic distribution and transport. Plastic density is not the sole factor affecting the presence of macroplastics and MPs in aquatic systems. Therefore, despite misconception about marine or freshwater plastic pollution, not all light plastics are found in water's surface layer. This will be discussed thoroughly in this section and sections 3, 4, and 5.

Polymer type	Min (g/cm³)	Max (g/cm³)	Global plastic demand and distribution, 2018 (Plastics Europe & EPRO, 2019)
Polyethylene (PE – LDPE, HDPE, LLDPE, MDPE)	0.880	0.970	29.7%
Polypropylene (PP)	0.900	0.920	19.3%
Polyvinyl Chloride (PVC)	1.150	1.700	10%
Polyurethane (PUR)	0.008	1.121	7.9%
Polyethylene Terephthalate (PET/PETE)	1.370	1.450	7.7%
Polystyrene (PS/EPS)	0.960	1.050	6.4%
Others	0.016	2.200	19%
Fresh water	1.000	-	
Seawater	1.025	-	

Table 1 - Polymer density and global demand (adopted from various sources).

2.2 Aquatic plastic transport pathways

The release of plastics into the aquatic environment occurs through various pathways, including rivers, atmospheric transport, beach littering, and directly at sea via aquaculture, shipping and fishing activities. Figure 3 summarizes important pathways for aquatic plastic emission both land- and marine-based. Quantifying aquatic plastic input is an important step to develop a domestic and global budget of marine plastic. This means quantifying when and where plastic emission occurs to marine and freshwater environments.

Jambeck et al. (2015) estimated that approximately 11% (275 million tonnes) of the total waste generated is plastic. Given the total plastic production of 270 million tonnes in 2010, higher annual plastic waste with attributed to the time lag in the disposal of durable plastic goods, years to decades after production. Scaling by the population living within 50 km of

the coast (those likely to generate most of the waste becoming marine debris), they estimated that 99.5 million tonnes of plastic waste were generated in coastal regions in 2010, out of which, 31.9 million tonnes were classified as mismanaged.

By correlating the waste produced globally with watershed properties across the globe, Lebreton et al. (2017) have identified the plastic influx from rivers to oceans. They have also identified the top 20 polluting rivers in the world. A considerably high-population density combined with relatively large, mismanaged plastic waste production rates and episodes of heavy rainfalls, resulted in this dominant contribution from the Asian continent, with an estimated annual input of 1.21 (range 1.00–2.06) million tonnes per year. The top 20 polluting rivers were primarily located in Asia and accounted for more than two thirds (67%) of the global annual input while covering 2.2% of the continental surface area and representing 21% of the global population.

Furthermore, Tsunamis historically carry vast quantities of debris, including plastics, into the marine environment. In 2011, 9.0 magnitude Tohoku earthquake near Japan's coast triggered an extremely powerful tsunami with a runup height of 40 meters. There were more than 16,000 deaths and an estimated \$220 billion in damage (Dunbar et al., 2011). Tohoku tsunami washed approximately 5 million tons of debris into the oceans, 3.5 million tons were deposited along Japan's coast and the rest 1.5 million tons are afloat at sea (Ministry of the Environment, Government of Japan, 2012). Past tsunami events and numerical models (e.g., Matsuba et al., 2020; Park & Cox, 2019) have demonstrated that such events lead to a large influx of debris pushed into the oceans. Of this, a significant portion of debris comprises plastic waste, which can degrade into tiny particles due to weathering and can be consumed by marine organism. These pathways transport land-based plastics into marine and freshwater systems, and these terrestrial plastics account for 80% of the aquatic plastic waste (Jambeck, et al., 2015).

The remainder 20% are marine-based, where 10% is sourced from fishing gears and 10% is ship dominated (McLendon, 2019). The estimation of containers dropped from cargo ships is 1582 to 10000 every year (McLendon, 2019; World Shipping Council, 2017). One example of marine sourced plastics originated from shipping cargos is the accidental spill of plastic ducks in 1992 also known as Friendly Floatees. A cargo ship loaded with bath toys, including rubber ducks travelling from Hong Kong, China to the Seattle, USA encountered a strong storm, and caused total of twelve containers dropped into the ocean, which believes to have 29000 bath toys. Since the toys have no holes on them, their drifting journey on the ocean starts (Rachael, 2018). The study of travelling path for the rubber ducks is interesting as simulations and collection of these bath toys have demonstrated that the movement of the plastic ducks are continuous and these bath toys have the ability to pollute the oceans all over the world under the effect of ocean current.

3. Aquatic Microplastics: definition and properties

3.1 Defining Microplastics

Small pieces of floating plastics in the surface ocean were first reported in the scientific literature in the early 1970s (Carpenter et al. 1972), and later publications described studies identifying plastic fragments in birds in the 1960s (Harper and Fowler 1987). Small pieces

of plastic in the millimetre to sub-millimetre size range are recognized as Microplastics (MP). Microplastics are usually defined as polymer particles with a size smaller than 5mm (Arthur et al., 2009). On the other sides of the spectrum, plastics are also categorized as macroplastic (>200 mm), mesoplastic (between 5 to 200 mm) (e.g., Lee et al., 2013, Zhang 2017). Furthermore, nano-plastics are identified as microplastic particles further break down to smaller pieces (GESAMP, 2015). The study of nanoplastics falls beyond the scope of the current report. Although it is accepted in many studies that plastic particles sized smaller than 5 mm, with the rise of interest in studying MPs and their environmental impacts in recent years, new classifications are defined. Such classifications are often tailored to the scientific relevance to the area of study (e.g., Van Cauwendebrge et al. 2013) or the sampling and analysis method (Nerland et al, 2014). The European MSFD technical subgroup on marine litter (Galgani et al., 2013) proposed the classification that differentiates between small MPs (<1mm) and large MPs (1–5mm).

3.2 Primary and secondary Microplastics

Microplastic debris is broadly classified as either (i) primary or (ii) secondary microplastics. Primary MPs include production pellet nurdles and microbeads (abrasive particles incorporated into personal care products) and textile fibers, whereas secondary microplastics are formed by the natural mechanical and chemical breakdown of larger plastic debris after they have entered the aquatic environment.

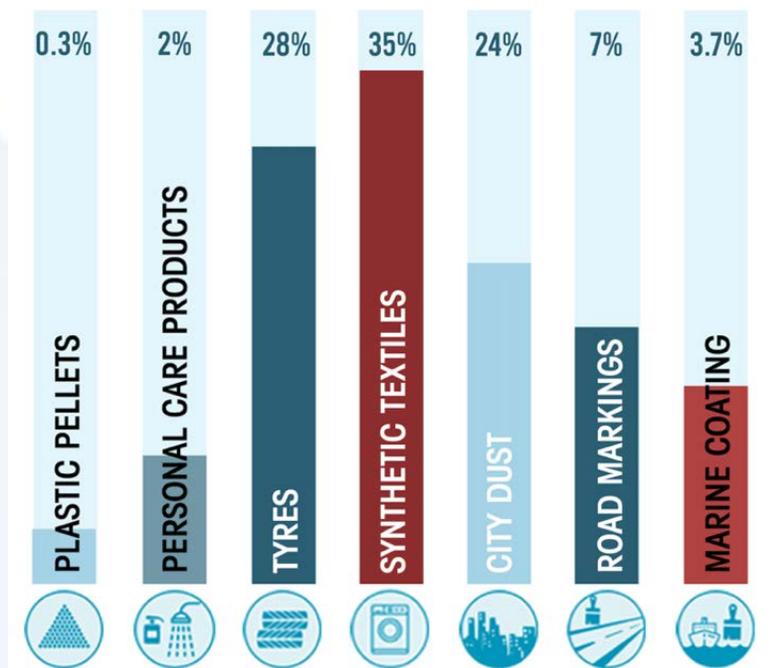


Figure 2: Source of global release of primary MPs.



Figure 3: Important pathways of aquatic plastic emission both land- and marine-based

3.3 Primary Microplastic sources

Boucher and Friot (2017) quantified the primary microplastics release sources and pathways. As noted by the paper, land-related sources such as tyre wear, city dust, and domestic wastewater contribute to the majority of primary microplastics in the ocean compare to marine-related sources such as pellets spillage and marine coatings. The authors have identified six sources for primary MPs: Synthetic textiles, tyres wear, road marking, marine coating, personal care, plastic pellets, and city dust. Table 2 summarizes their finding in terms of the estimated release of primary MPs in different regions across the world. In North America, Europe and Central Asia, the dominant primary MP is identified as tyre scrubs. The primary MP released from textile accounts for more than 35% of total primary MPs. These synthetic fibres comprise most primary MP release in India and South Asia, China, East Asia and Oceania, and Africa and the Middle east.

	Synthetic textiles	Tyre wear	Road marking	Marine coating	Personal care	Plastic pellets	City dust
India And South Asia	15.9	1.1	0.3	0.1	0.8	0	
North America	2.6	11.5	1.9	1	0.1	0.1	
Europe And Central Asia	4	8.6	2.4	0.6	0.2	0.1	
China	10.3	2.5	1.3	1.2	0.5	0	
East Asia And Oceania	6.3	5.3	1.6	1.5	0.3	0	
South America	2.9	5.1	0.9	0	0.2	0	
Africa And Middle East	4	3.2	0.6	0.4	0.5	0	

Table 2: Global release of primary MPs. Total among various sources and regions amount to 100%. From left to right: Synthetic textiles, tyres wear, road marking, marine coating, personal care, plastic pellets and city dust. Adopted from Boucher & Friot (2017).

As identified in Table 2, clothing fibres constitute a significant source of primary MPs. Textiles release fibres to the environment during production, use, and at end-of-life disposal. Approximately two-thirds of all textile items are now synthetic, dominated by petroleum-based organic polymers such as polyester, polyamide and acrylic. Plastic microfibrils (<5 mm) and nanofibrils (<100 nm) have been identified in ecosystems in all regions of the globe. They have been estimated to comprise up to 35% of primary microplastics in marine environments, a major proportion of microplastics on coastal shorelines, and persist for decades in soils treated with sludge from wastewater treatment plants.

Fibres are mainly emitted to aquatic systems through the effluent of WasteWater Treatment Plants (WWTPs). Talvitie et al. (2015) have indicated that fibres, including synthetic and natural fibres, are removed mainly by primary sedimentation rather than secondary and further. Several studies suggested that MPs' removal efficiency in conventional WWTPs is often higher than 97% (Carr et al., 2016; Xu et al., 2019; Wu et al. 2020). Nevertheless, as most MPs are retained in sewage sludge, a frequently used soil amendment, extracted MP in the sludge may also pose a threat to the terrestrial environment (Gherghel et al., 2019).

Conley et al. (2019) measured MP loading and removal efficiencies in 3 WWTPs in South Carolina and estimated that these WWTPs could reduce 99.9% of plastic debris input into the environment. Despite high removal rates of microfibres in WWTPs, due to the effluent volume, the receiving water bodies downstream of WWTPs often report a high concentration of MPs and microfibres. Habib et al. (1998) and Murphy et al. (2016), among others, found more microplastics in downstream of the WWTP with fibres as the majority. Talvitie et al. (2015) also suggest that WWTP is a significant pathway for marine microplastics, especially fibres, as the WWTP's effluent contains 25 times more fibres than the nearby water body.

Primary virgin MPs account for 15% to 31% of total microplastics found in aquatic systems. The majority of aquatic MPs are secondary MPs that are by-products of larger plastic pieces found in marine and freshwater systems (Boucher & Friot, 2017).

3.4 Secondary Microplastic generation

While primary or virgin MPs are manufactured to be small, secondary MPs result from larger-sized plastics' environmental breakdown. As they are transported in the environment, plastics and MPs are weathered through mechanical fragmentation, chemical degradation, and biofouling. The fragmentation of plastic debris into gradually smaller pieces is due to the combination of mechanical breakdown, photo-degradation, and possibly microbial degradation. These factors lead to continuous temporal changes in physical and chemical properties of plastics and fragmentation of larger plastics to meso- and eventually to microplastics.

These processes may lead to changes in plastic's surface texture. Photodegradation of the polymer matrix leads to bond cleavage and makes plastics brittle, causing them to disintegrate (e.g., Andrady, 2011; ter Halle et al., 2016). Among others, Cai et al. (2018) studied the impact of UV exposure for 3 polymers types of PP, PE, and PS. Their exposure studies have revealed that the pellet's surface's homogenous texture changed drastically over months of exposure, where cracks and flakes were common patterns of this degradation process.

Weathering, colonization of microorganisms (biofouling), mechanical abrasion, and shredding are other important parameters that can alter MPs' density, size, and shape and consequently affect their sinking velocity (Morét-Ferguson et al., 2010). The effects of environmental weathering on the transport behaviours of MP in the aquatic environment have not been comprehensively investigated (Waldman & Riling, 2020). Recent studies suggest that these processes do not impact the transport of MPs equally. Waldschläger et al. (2020), for instance, have demonstrated that the most dominant temporal change in plastic and microplastic physical characteristics is due to their exposure to (i) abrasion and fragmentation and (ii) biofouling on plastic and microplastic surface. As in this report, we are addressing the questions of MP migration and transport, this document only highlights these two processes.

3.5 Physical Fragmentation

On land, oxygen and sunlight are considered to be the most dominant process in the degradation and fragmentation of plastics. In aquatic systems, plastics are protected from high environmental temperatures and exposure to sunlight. Therefore, their degradation due to these conditions is prolonged (e.g., Corcoran et al., 2009; Ryan et al., 2009). In coastal environments, on the other hand, the physical forces of wind, waves, and tides cause the abrasion and mechanical degradation of plastics on the sea surface and beach sediments (Browne et al., 2010; Barnes et al., 2009; Lee et al., 2013; Fok et al., 2017). Furthermore, turbulent mixing with beach sediments may accelerate the fragmentation of plastic particles in these areas.

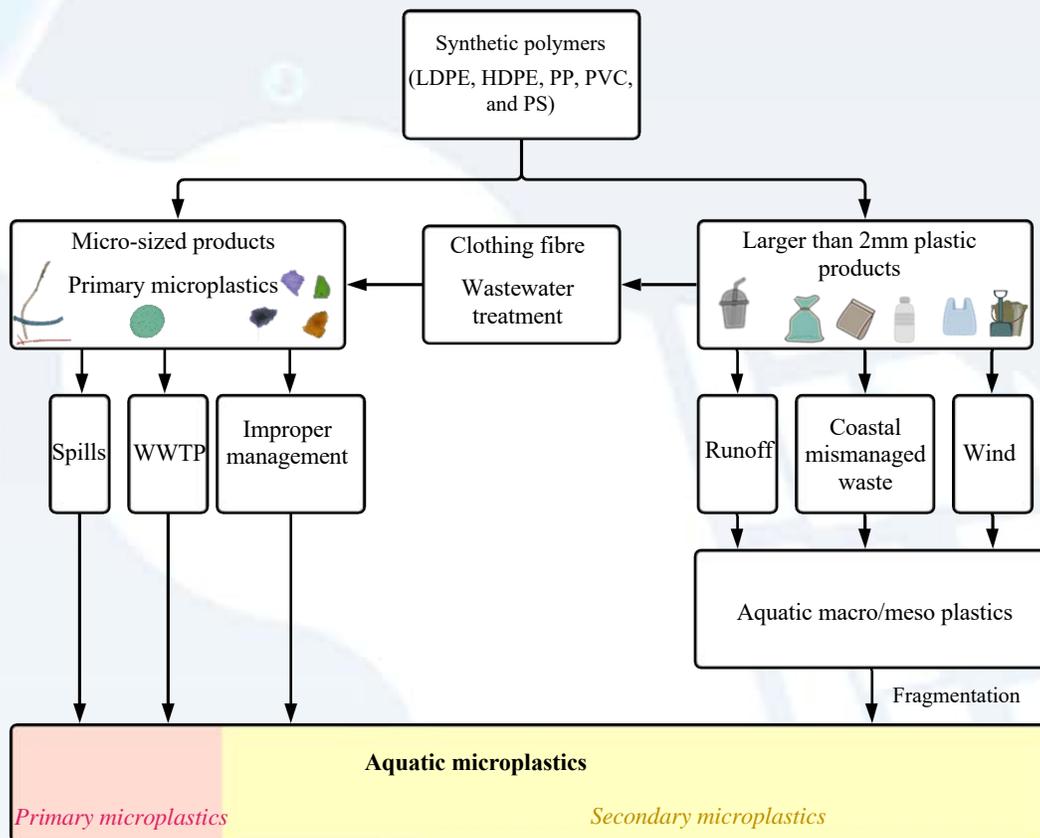


Figure 4: Flow diagram of sources and pathways of MPs

To establish and analyse the impact of coastal physical degradation on various plastic types, Efimova et al. (2018) have performed experiments using a laboratory mixer with an inclined rotation axis. In the experiment, natural marine pebbles collected on the Baltic Sea beach, tap water, and prepared samples of plastics were placed in the mixer. Single-use PP cups (material density 0.86 g/cm^3) and PS plates (1.05 g/cm^3) and LDPE garbage bags (0.92 g/cm^3) were used as the source of macroplastics for the experiments. They have considered MPs particles passing through a 5-mm sieve but remained within the nest of sieves with a minimum sieve size of 0.5mm. The observations by Efimova et al. (2018) followed, interestingly, the inherent properties of these polymers:

- Solid PS is a brittle, rigid material. Experiments showed a fast failure and fragmentation of this material. Very diverse secondary MPs were generated through this mechanical process, e.g., segments, flakes, strips, crumbs, etc. After 15 h of mixing, about 50% of macroplastics could still be identified visually in the original square shape. Three hours later, this number decreased to 20%. By 18h, about 80% of the initial plastic mass was observed in the range of 0.5 to 5.0 mm. After 21 h of mixing, the original shapes disappeared completely. The growth has significantly accelerated after 20hrs or experiment, manifesting material fatigue. The authors reported that PS has the fastest fragmentation among plastics tested.
- Light Density Polyethylene (LDPE) was chosen as a representative of flexible, elastic polymer material, prone to surface fatigue and tensile tearing. After 1 h of mixing with heavy pebbles, the films began bending two- or four-fold, but remained larger than 5mm. After 9h of mixing, a lot of particles were stretched and could be categorized into MPs. After 24 h, 31% of the total mass of the dried samples passed through the 5-mm sieve, thus falling into the class of MPs. The increase in mass of the samples of the MPs class with mixing time was nonlinear with a substantial jump after 20 h.
- The Society of the Plastics Industry describes • Polypropylene (PP) as hard but flexible material. This plastic type is associated with strong and resistant. Among the plastics examined in the experiments, PP appeared to have maximum longevity: after 24 h of energetic abrasion by pebbles, about 97.6% of initial large plastic pieces could still be visually identified as the original shape, although they were softer, more flexible, with smoother, and matte surface.
- The foamed PS was rigid and made of pre-expanded polystyrene beads. It has a very low density of 0.011 g/cm^3 , and hence during the mixing process, it mostly remained afloat on the water surface. This material is mostly floating and will be partly immune to the physical fragmentation process. However, the fragmentation rate to microplastics was linear, and this is the only material among those tested, which showed a linear trend. After 24h, only less than 10% were reported at a size range of 5mm and less.

All plastics are exposed to physical fragmentation processes. However, the same salient features that make these material suitable for various industries, also affect their fragmentation rate/speed and the shapes, roughness, and other physical properties of secondary MPs.

3.6 Biofouling

Plastics with densities smaller than the density of ambient water are positively buoyant that tend to float at the surface. Plastics with densities greater than the density of the ambient water tend to sink due to greater weight than buoyance. However, in numerous field-based studies, positively buoyant MPs were found, in great quantities, in sediments. Aquatic plastics, however, can undergo density changes due to biofouling that can lead to plastic sinking after some time. Biofouling is the most prominent factor in changing the apparent

density of plastics. The biofouling process occurs in two steps. First, a biofilm containing carbohydrate, proteins, exopolysaccharides, and microorganisms is formed on the MPs' surface and then macrofouling (barnacles, hydroids, algae bryozoans, mussels) will be attached to the biofilm (Muthukumar et al., 2011). Several parameters affect the biofilm formation and biofouling rate: depth profiles of light extinction, salinity, density, viscosity on the biofilm growth and settling of MPs (Kooi et al., 2017). Biofilm volume (number of algae) on MPs' surface is the main reason for these density differences and sinking of lighter microplastics. The total density of the biofouled microplastic is a function of attached biofilm growth, respiration, and mortality. Upon sinking, the biofouled particles encounter lower temperatures and limited light in greater depths, which provide poor environments for microorganisms, i.e. conditions that may negate the fouling and cause the plastics to re-emerge up into the surface layers (Ye & Andrady, 1991). In deeper waters, Ye & Andrady (1991) suggested that defouling occurs rather quickly. This leads to rather oscillating behavior of MP particles with the change of biofouling and defouling rate in depth. Kooi et al. (2017) simulated the change in vertical transport of small microplastic particles over time due to biofouling and defouling. Authors have suggested that the particles either float, sink to the ocean floor, or oscillate vertically, depending on the particle's size and density. Further discussion on the impact of biofouling on sinking patterns is available in section 3.1.

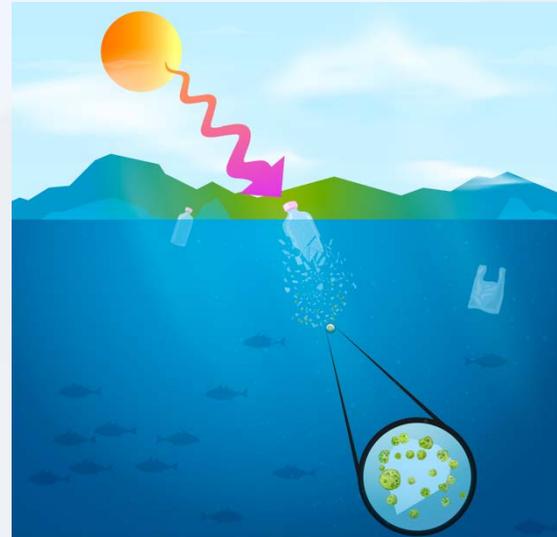


Figure 5: Biofouling on fragmented MPs

3.7 Microplastic shape classification

Different factors can be used for the classification of MP shape. Most shape factors are developed for sediment particles classifications. However, since MPs are also small-sized matters found in freshwater and marine systems, the same shape factors are often used for categorizing MP shapes. Each of the following factors describes different aspects of a particle's appearance. Therefore, they are often used in combination with other factors (Chubarenko et al., 2018). One of the most common factors for shape classification is the Equivalent Spherical Diameter (ESD) or the nominal diameter, which is defined as the diameter of a sphere with the same volume as the particle (Dietrich 1982). For an irregularly shaped MP particle, ESD can be calculated as (Kowalski et al., 2016):

$$ESD = (abc)^{1/3} \quad \text{Eq. 1}$$

where a , b , and c are the measured major, minor and intermediate dimensions of the best-fitted ellipse, respectively. Another parameter for shape classification is the Shape Factor

(SF), which is the deviation of a particle's shape from a sphere (Camenen, 2007). There are different equations for the calculation of SF. The most common equation for the SF calculation is developed by Corey et al. (1949), presented in Eq.2:

$$cfs = \left(\frac{D_s}{D_l \times D_i} \right)^{0.5} \quad \text{Eq. 2}$$

where *cfs* is the Corey shape factor, D_l , D_i , and D_s are the longest, intermediate, and the shortest dimensions of the particle, respectively. For a perfect sphere, *cfs* equals to 1. Smaller *cfs* values are associated with flat particles. The next shape classification factor is the particle roundness P, which is usually considered by analyzing naturally rounded and crushed particles and measuring the curvature variations along the grain surface. Particle roundness may be estimated using the scale of Briggs et al. (1962), varying from 0 for perfectly angular with all sharp edges to 6 perfectly round.

In addition to different shape classification factors, based on the general appearance, there are different categories for MPs' shapes. Tanaka and Takada (2016) presented a comprehensive classification for MPs shapes based on observations. This classification contains all different particles with regular and irregular shapes: (1) fragments: particles produced by fragmentation of larger materials with irregular or regular random shapes (secondary MP), (2) beads: particles manufactured as micro-sized products, either spherical or an aggregate of spheres (primary MP), (3) pellets: granules manufactured as a raw material of larger plastic products, with the shape of a cylinder or a disk with 2–5mm dimensions (primary MP), (4) foams: pieces of foams made from an aggregate of polymers (secondary MP), (5) films: soft fragments of thin polymers derived from plastic bags or wrapping paper and so on (secondary MP), (6) sheets: hard fragments of thin polymers (secondary MP), (7) filaments: threadlike polymers produced by fragmentation of ropes or lines used in fishing, >50µm (secondary MP), and (8) fibers: threadlike polymers derived from textiles, including clothing and furnishings, <50µm (secondary MP). Figure 6 illustrates MP particles belonging to different shape categories.



Figure 6: MPs shape classifications.

Moreover, MP shapes can be categorized into 3-D particles (all dimensions are in the same order), 2-D particles (one of the dimensions is significantly smaller than two others), and 1-D particles (one of the dimensions is significantly larger than two others) (Chubarenko et al. 2018). Based on this classification, beads, pellets, and fragments are categorized as 3-D, sheets, films, flakes, and flat fragments are classified as 2-D, and filaments and fibres are categorized as 1-D particles. This shape categorization is essential in MP transport and dispersal as they affect the drag force applied by the ambient fluid on MPs.

4. Aquatic plastic transport

Inputs of plastics from land, riverine, and marine sources go through beaching, drifting, and settling pathways until they reach temporary reservoirs on beaches, tidal wetlands, and marine sediments. A fraction of the plastics in the nearshore environment are carried by currents offshore and start their journey to the open ocean. Microplastics' trajectory and velocity are controlled by hydrodynamic processes, such as sinking, windage, in-depth and surface currents, and sediment gravity flow. In the following section, we will discuss the role of some of these parameters on MP transport, deposition, and entrainment.

4.1 Biofouling and sinking role in MP transport in aquatic environments

4.1.1 Settling and rise velocities

As shown in Figure 7, settling and rise velocities are the constant terminal velocity attained by a particle while falling or rising in a fluid column due to the equilibrium between gravitational, buoyance, and drag forces. Sinking patterns of natural sediment particles have been studied for several decades. Many primary investigations into the settling patterns of MPs, assume that MPs behave similarly to sediment particles. Most sediment particles being transported in fluvial flow have regular shapes such as spheres or ellipses as these particles are eroded over time. MPs have a diverse array of shapes from perfectly spherical microbeads, produced as virgin and primary MPs, to highly irregular shapes, such as fragments, and long disproportionate shapes, such as fibres. All the current literature on settling patterns of MPs, unanimously agree that the settling patterns are very sensitive to the shape of a particle. Furthermore, as listed in Table 1, MPs have diverse densities compared to natural sediments, ranging from 0.008 to 2.2 g/cm³. In recent years Khatmullina & Isachenko (2017) have looked at the settling patterns of cylinders and spheres MP, for MPs of regular shapes. Bagaev et al. (2017) have investigated the settling patterns of fibres. Despite these advances, the

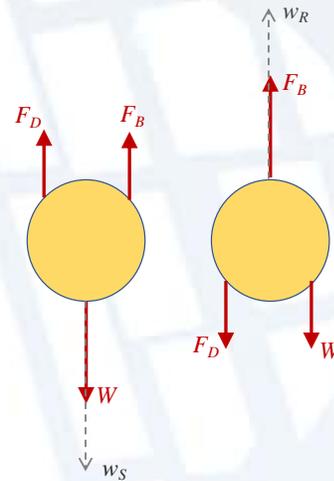


Figure 7: The force balance of a positively buoyant MP (right), and a negatively buoyant MP (left). W , F_D , and F_B represent particle weight, drag, and buoyant forces. w_R and w_S are the rising and sinking velocities.

settling patterns of weathered MPs are yet to be quantified. Secondary MPs possess random shapes due to exposure to various weathering processes. The sinking and rising velocities of MP particles are also entangled with biofouling and fragmentation. Biofouling has a notable impact on the sinking pattern, as described in the following section.

4.1.2 Biofouling and sinking

PE and PP plastic production comprise about 50% of total annual production. Both polymers are positively buoyant material which have densities below that of water (Schwarz et al., 2019). Therefore, it is expected that these positively buoyant plastics and MPs stay afloat in the surface layers. However, only a portion of MPs of these polymer types are found floating in surface layers. The global estimation of microplastic afloat in the ocean is only approximately 1% of annual global plastic inputs (Ter Halle et al., 2016). This is often attributed to the settling of biofouled MP particles as well as various in-depth circulation patterns (Kane & Clare, 2019).

Particle sinking and settling are directly linked to biofouling. Kooi et al. (2017) developed a framework to simulate MP's vertical transport, by only isolating biofouling and sinking. The growth of heavier micro- and macroorganisms on the surface of plastics leads to an increase in an apparent particle density. If the apparent density of biofouled particles exceeds that of the ambient fluid, particles sink. Biofouling, however, can be reversed when the sinking particle is exposed to limited light in greater depths. Defouling occurs quickly after particle submersion and can result from light limitation, grazing, or dissolution of carbonates in acid waters. Defouling makes MP particles lift to upper layers where they, once again, are exposed to sunlight and other favourable conditions for biofouling. Therefore, the defouled particles will sink again to deeper layers. Therefore, as a result, Kooi et al. (2017) concluded that MPs might fluctuate between different vertical layers in the water column.

4.1.3 Shape impact on biofouling

Biofouling affects small fragments faster than large ones due to their higher surface area to volume ratio. Although particle buoyancy and weight are proportional to its volume, particle's susceptibility to fouling is mainly dependent on its surface area (Ryan, 2015). Fazey and Ryan (2016) showed experimentally that small plastic items lost buoyancy much faster than larger ones and that there is a direct relationship between an item's volume (buoyancy) and the time to attain a 50% probability of sinking. Similar observations were reported for MPs of different shapes. Chubarenko et al. (2016) examined the process of biofouling of MPs of different shapes analytically. They have studied the dependence on the particle size and shape based on (i) its surface area and (ii) the time required for the particle's apparent density to reach the density of the ambient fluid. Biofouling rate of irregular MPs particles was also dependant on particle surface to volume ratio. Therefore, Chubarenko et al. (2016) concluded that biofouling affects the density of fibres faster than it does for fragments. A similar observation was made for 2D MPs. Compared to 3D

microbeads, they possess a larger surface to volume ratio, leading to higher biofouling rates.

4.2 Windage

4.2.1 Transport of microplastics in leeway drift

Microplastic particles of low density, such as polyethylene and polypropylene are highly susceptible to surface current, wind forces and waves. Transport of particles due to wind forces is known as windage, also referred as leeway drift. Wind forces may influence the trajectory and velocities of plastic particles, which are different from that of surface currents. The exact trajectory and velocity of plastic debris depend on particles properties (i.e., shape, size, and density). This leeway drift is shown to be independent of particle size. Instead, it is governed by the ratio of the unsubmerged volume to the submerged volume, which itself is a function of plastic density to the density of the ambient fluid (Chubarenko et al., 2016).

4.2.2 Transport of microplastics due to Ekman currents

Ekman transport results from two different phenomena: net water transport due to the Coriolis effect and frictional forces due to wind. There are five garbage patches: The North Pacific Gyre, the South Atlantic Gyre, the North Atlantic Gyre, the South Pacific Gyre, and the Indian Ocean Gyre. The largest garbage patch, North Pacific Gyre, holds approximately 1.8 trillion plastic pieces (Lebreton et al., 2018). A global simulation was carried out, and the model yielded that Ekman currents were to blame for the accumulation of plastic debris in five garbage patches. Simulations conducted with and without the Ekman currents demonstrated that plastic accumulation zones align well with these currents (Onink et al., 2019).

4.3 Turbulent Mixing

4.3.1 Transport of microplastics in thermohaline circulation

Bottom currents are a product of thermohaline circulation, and the driving factor is global density gradients, regulated by temperature and salinity variation. This process is initiated from extremely cold polar regions, where sea ice is formed. As sea ice melts, it leaves salt behind, leading to increased salinity and density of the surrounding water. Consecutively, the heavier fluid starts to sink to the ocean floor while pulling the surface water in. The process of ambient water freezing, heavier fluid sinking while surface water is pulled in, is the driving force behind thermohaline circulation, also known as the great ocean conveyor. Numerous field observations and computational research suggest that thermohaline circulation is among the physical processes responsible for the long-distance transport of MPs. In one instance, microplastics and fibres from the Kuril-Kamchatka Trench were located near Russia, and it was suggested that the transport mechanism was northwards deep-sea currents (Fischer et al., 2015; Peng et al., 2018).

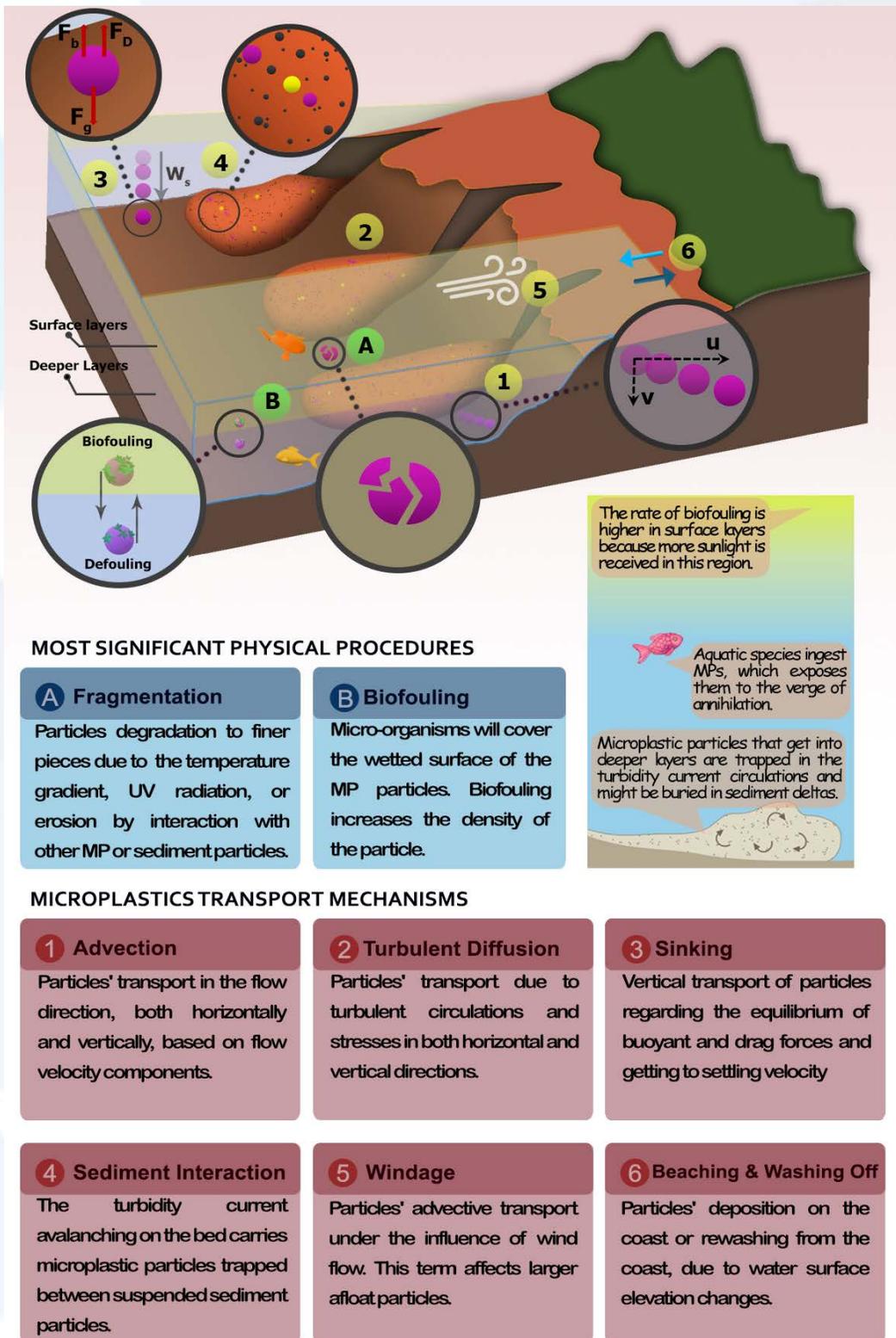


Figure 8: Summary of hydrodynamic processes

Evidence from MP accumulation in Arctic deep-sea sediments also suggests that a significant fraction of deep-sea debris was originated from Northern Europe and was transported to the North with the Thermohaline Circulation (Bergmann et al., 2017). Seafloor currents can promote lateral advection when shear stresses at the base of the flow are greater than the particles settling velocity (Kane et al., 2020; Kane & Clare, 2019). Numerical simulations performed in the Tyrrhenian Sea (part of the Mediterranean Sea) indicated that bottom currents were more pronounced in winter since seasonal variation led to a higher density gradient. Results showed that bed shear stress also influences MP mobility based on their shape (Kane et al., 2020).

4.3.2 Wind-induced mixing

Vertical mixing of plastics has been considered to be controlled by wind-induced turbulence, such as breaking waves and Langmuir circulations, and the mixing length is dependent on the mixed layer depth (Kukulka et al., 2012). Langmuir turbulence due to the interaction between the surface current and surface waves can facilitate deep submergence of positively buoyant particles. Recently, it was demonstrated that diurnal heating cycles in the surface boundary layer enhance turbulent downward mixing at night (Kukulka et al., 2016). Furthermore, vertical mixing can lead to deposition to the sea bottom and increase sediment retention of microplastic particles, which is particularly important in coastal seas where the surface mixing layer can reach the sea bottom (Zhang, 2017).

4.3.3 Density currents

In addition to settling and in-depth mixing, microplastics also arrive at the seafloor due to gravity currents. The concentration of plastic debris found in the sediments of the river's mouth is a magnitude greater than open waters, and direct fluvial inputs from river outflow contribute to gravity currents (Kane & Clare, 2019) also known as turbidity currents. Gravity currents deposit vast quantities of microplastics on the seabed, which can be transported due to deep-sea currents.

Submarine canyons are commonly occurring processes along the continental slope. These are large V-shaped channels along the continental slope; canyons can be tens to hundreds of kilometres across the continental shelf and tens to hundreds of kilometres along the slope. Kane and Clare (2019) suggested that gravity currents in canyons are able to transport microplastics that have the density of organic material. Pohl et al. (2020) carried out a laboratory experiment, which agrees that turbidity currents have the potential to transport and distribute large quantities of microplastics to deep-sea sediment. Turbidity currents would ultimately distribute microplastics on the basin floor, and deep-sea sediments. Thermohaline circulation would farther transport microplastic particles along the seafloor and deep-sea trenches.

5 Microplastic abundance and presence in aquatic systems

As described in section 3, the characteristics of plastic debris and MPs possess are diverse. Contrary to common misconception, plastics and MP debris are found in all water

compartments from surface to water column and deep ocean sediments. There is collective evidence, however, that such distribution greatly depends on MP properties. This section has consolidated and compiled literary data on the presence based on i) polymer type and ii) MP shape and size. Polymer and shape selectivity are suggested to affect MP accumulation and hotspot formation in marine and freshwater environments.

5.1 Observations based on polymer type

Plastic debris is found in high quantities along freshwater and saltwater beaches. A review study, which had consolidated data from 3 freshwater beaches and 5 oceanic beaches, concluded that PE and PP were predominant in beaches (Schwarz et al., 2019). Similarly, several other studies carried out on numerous beaches have noted that PE and PP were the most common polymer type (Corcoran et al., 2009; Zbyszewski & Corcoran, 2011; Zhao et al., 2015). Variation in the polymer composition is greatly influenced by the study site. For example, a study site closed to fishing activities could exhibit high quantities of PE and polyethylene terephthalate, since these polymers are widely used in the fishing industries (Cheang et al., 2018).

Recent estimates suggest that 200 million tons of plastic waste are currently circulating in the Atlantic Ocean (National Oceanography Centre, 2020). Seventy-four sampling sites in the Mediterranean surface water indicated that polyethylene (52%) and polypropylene (16%) were found in substantial quantities (Suaria et al., 2016). Comparable results were obtained from review studies by Erni-Cassola et al. (2019) and by Schwarz et al. (2019), where PE and PP were predominant in surface water followed by PS. Conversely, another study had pointed out that PS is the most abundant polymer (Di & Wang, 2018). This discrepancy in polymer composition was mainly due to regional effects and sampling methods. However, the overall data suggests that low-density polymers, PE, PP, and PS are predominant in surface water.

High-density polymers are commonly found in water column, however, low-density microplastics have also been spotted in the water column due to biofouling. Polyethylene terephthalate ($\approx 42\%$) and polyamide ($\approx 27\%$) were most common in water column, in the Monterey Bay, California (Choy et al., 2019). The abundance of polyethylene terephthalate was linked to single-use beverage bottles and packaging materials, whereas vast quantities of polyamide were linked with textiles and the automotive industry. Conversely, a study in the Atlantic Ocean at a depth of 3 meters, and PE represented 42% of the microplastics particles collected (Enders et al., 2015). A review study consolidated data from 4 water column studies obtained that polyesters, polyamide, acrylics, and PE were predominant in the water column (Erni-Cassola et al., 2019). Schwarz et al. (2019) review study pointed out that PE, PP and PS were the leading polymers in the water column. The inconsistent polymer distribution could be explained by the influence of local activities and sampling procedure (i.e., sampling period and sampling process). Several low-density polymers and high-density polymers dominate observations in the water column, and additional research is required to determine polymer composition.

Along with high-density polymers, buoyant low-density polymers are also found in sediments. Cheang et al. (2018) have collected twenty-four benthic sediment samples from four coral communities in Hong Kong, and have reported that polyethylene (51.9%) and polyethylene terephthalate (29.3%) were the most common polymer. Conversely, Schwarz et al. (2019) review study had suggested that PE and PS were the leading polymers in sediments, and Erni-Cassola et al. (2019) indicated that polyesters, polyamide, and acrylics were prevalent in sediments. High-density polymers were abundant in sediments, however, low-density polyethylene was also predominant. Other than local influence and sampling procedure, the number of microplastics particles analyzed may also be the reason behind this variation. Based on the current studies, it is difficult to obtain polymer composition in sediments, and further research is required to study the fate and transport of high and low density MPs in sediments.

5.2 Evidence of size and shape selectivity in aquatic systems

Based on field observations, residence time would also affect MPs shapes in the aquatic environment. MP particles present in the aquatic environment for a longer time have smooth polished shapes since they had more interaction with other MP particles or sediments. In contrast, sharp edges demonstrate that the particle was recently fragmented or introduced to the aquatic environment (Hidalgo-Ruz et al., 2012).

In terms of abundance based on shape categories, fragments with 0.5 to 2 mm size followed by films are the most abundant MP shapes in the surface layers (Browne et al., 2010; Cózar et al., 2017; Moore et al., 2001; Song et al., 2014; Doyle et al., 2011). In beach sediment samples, the most abundant particles are fragments (< 1 mm) followed by fibres (Ballent et al., 2016; Browne et al., 2010; Van Cauwenberghe et al., 2013). However, analyzing bed sediment samples in regions farther from the coastline demonstrates that fibres comprise the majority of MP particles in these regions (Browne et al., 2011; Woodall et al., 2014; Thompson et al., 2004; Naidoo et al., 2015). MPs in sediment samples are mainly sized smaller than 2 mm (Browne et al., 2010; Browne et al., 2011; Sagawa et al., 2018).

Based on field studies, as sediment samples get farther from the coast, MPs become finer (Browne et al., 2011; Naidoo et al., 2015). This evidence describes the entertainment of MPs based on particle size. Finer particles have a better chance of entertainment with ambient water and are transported farther in freshwater and marine environments. In addition, the presence of fine fragments and fibres in bed sediment samples shows that these particles also have significant in-depth motions. This further can be described with higher biofouling rates for smaller particles. This also explains why among different MP shape categories, those with a larger exterior surface ratio to the volume are expected in deeper layers (such as fibres and filaments). In contrast, particles with a smaller surface to volume ratio will be abundant in the upper layers (Ryan 2015).

6 Limitations, gaps, and possibility of new studies

Based on our observations reported here, we identified several knowledge gaps, important to the dispersal and distribution of aquatic plastics. Some of these are listed in Table 3:

Table 3: Knowledge gap identified

Knowledge Gap	Objective
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Standardized sampling methods and analysis	To understand the spread of aquatic plastic pollution, we should be able to identify the aquatic MP status quo and temporal trends in the environment. There are numerous challenges in sampling collection, storage, and analysis from various water compartments (surface, sediment, water column). For instance, in collecting MP samples from surface water, mesh sizes variable between 100µm to 30000µm are used. This mesh size selection will simply lead to size-selective collection, that would impact the interpretation and analysis. In environmental monitoring, harmonized procedures are necessary to establish comparable and reliable results.
Size selective accumulation	As described in section 5, most studies focus on shape and more importantly, polymer selectivity. However, evidence collected based on MP research in remote areas and deep-sea sediment also suggest that size selectively has a great impact on distribution. This is especially critical, given that smaller MPs are more likely to enter the food web.
Quantification of fundamental transport parameters, including: MP settling patterns; Impact of fragmentation and biofouling on sinking and settling	The variability of distribution patterns based on MP properties is due to the impact on water-particle interactions. Most simulations on MP particles are based on simplified assumptions. These include assumptions for sediment-like behaviours. Further research is required to quantify such fundamental transport aspects of MPs.
Transport of MPs from freshwater to marine environments	Most MPs are released into the marine environment via freshwater pathways. Understanding the fate and behaviour of microplastics is important when it comes to minimizing environmental impacts most effectively.
Understanding and quantifying temporal changes of plastics	The majority of aquatic microplastics are identified as secondary and released to the environment due to the breakdown of larger plastic debris. Better understating of degradation and rate will quantify the gradual release of secondary MPs into the environment.
A framework and platform to foresee MP distribution, dispersal, and accumulation	Environmental agencies in Canada commonly use hydrodynamic models to foresee water quantity and quality across Canada. A compatible model, paired with existing hydrodynamic models, is necessary to predict plastic and MP distribution. The status quo knowledge of plastic transport cannot accurately quantify distribution. However, the development of such modelling framework is necessary, and the framework evolves as our understanding of MP transport evolves.

7 Knowledge Mobilization activities

The knowledge mobilization table below illustrates our activities, so far, in research and development, listed in different categories.

Table 4: Summary of knowledge mobilization activities

Category and Target Audience	Activities
Researchers: International Hydrodynamic Research Community – Undergraduate / Graduate trainees	<ul style="list-style-type: none"> • 4 international conference presentations in various IAHR conferences, led by graduate students, in October 2020 and February 2021. • 3 national conference papers and presentations in CSCE, led by graduate students, scheduled for May 2021. • 2 journal manuscript under preparation entitled: “The impact of Microplastic size on deep-sea intrusion and distant transport: A review and synthesis of recent research” “Biofouling parametrization and impact on in-depth transport” • 2 undergraduate recruitment in summer 2021 and 3 graduate students so far.
Communications with government environmental agencies	<ul style="list-style-type: none"> • Identified representatives in Environment and Climate Change Canada and Ontario Ministry of the Environment and Climate Change. • Presented findings on two occasions to agency representatives. • Have established new collaborations and submitted 3 collaborative grant applications.
Consumer and general population	<ul style="list-style-type: none"> • Development of infographics on the state of plastic and MP pollution (2 samples are included in the report). • Creating social media activities as outreach platforms.

8 Implications on policy and recommendations

Canada’s domestic approach to plastic wastes has been built on a vast array of government programs and regulations, as well as initiatives by industry, community, and environmental organisations. This includes regulations to ban cosmetic microbeads by 2019 and plastic bags and other single-use plastics by 2021. Despite the awareness and ongoing actions to tackle plastic pollution, plastic pollution is a growing environmental threat. Some of the policies and recommendations in the Canadian context are:

- Theme A: Reduction in overseas transport and production**

Various sources of MP are linked to production sources outside Canada. As seen in the report, the majority of plastic input and waste mismanagement is originated from Asia. Therefore, putting in place regulations and legislation to control and limit the use and demand for overseas products will greatly impact Canadians' plastic footprint. Furthermore, displacing the source of plastic emission from Canada to other countries is also not an effective strategy. As seen in MP research in remote areas, some small plastic particles travel thousands of kilometres before settling.
- Theme B: Development of MP related water quality monitoring programs**

Canada has an abundance of freshwater with a diverse array of plants and animals, with rich ecosystems unique in the world. Furthermore, it provides Canadians with drinking water, food supplies, tourism, and recreational opportunities. Despite widespread monitoring and water quality surveillance in Canada, for instance, in Great Lakes, surveillance for MP particles is not included in such programs. This is while, all studies in the Canadian context have identified traces of MPs. Therefore, the development of surveillance programs helps identify the hotspots and accumulation of these emerging contaminants.
- Theme C: Support of interdisciplinary research**

It is clear from this report that regulations around the reduction of aquatic plastic emission are necessary. This report also highlights the state of the art knowledge of MP transport and fate. Researchers in numerous disciplines, including hydrodynamics, have started to investigate aspects of aquatic MPs. However, many MP research areas are complex, especially regarding their emission, long-term presence and transport, toxicology, and risk assessment and mitigation. In recent years the Canadian government has supported research on plastic pollution. Continued immediate support of interdisciplinary cooperation is necessary to tackle issues around MP pollution.
- Theme D: Education and outreach**

Education, awareness, and outreach are effective methods to limit plastic use, change consumer behaviour, and ultimately plastic waste. Investment in youth education on this issue is critical. Furthermore, the support of NGOs across Canada, focusing on environmental sustainability and health, can promote independent awareness and outreach programs.

9 Bringing it all together

Clean and predictable supplies of freshwater drive the ecological systems and many economic activities on which Canadians depend. Microplastics are found in high concentrations in sediments and water across the globe and in Canada, which impacts the provision of ecosystem services and lead to significant socio-economic-environmental losses for all stakeholders. This research has enhanced our understanding of the factors, transport pathways, and hydrodynamic mechanisms that significantly affect the distribution and accumulation of MP debris in aquatic ecosystems. This will greatly expand our capability to construct physical and numerical models to more accurately evaluate the

bioavailability of MP contaminants, their distribution, and environmental risks, and effectively deploy management strategies to alleviate the impact. The authors have also identified major knowledge gaps that require attention. They have also made policy and mitigation recommendations based on their findings. Plastics are considered relatively recalcitrant in aquatic systems as their decomposition and degradation can take up to several centuries, if not millennia. Plastics emitted today will breakdown into thousands of small pieces; therefore, plastic emission's footprint and its adverse impact can affect water quality globally and linger in the environment for centuries.

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