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PLASTIC POLLUTION IN THE GREAT LAKES

AN OVERVIEW OF THE STATE OF POLLUTION, CURRENT RESEARCH AND RECOMMENDED NEXT STEPS

TEAM

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– Dr. Sherri A. “Sam” Mason

Sustainability Coordinator, Penn State Behrend

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Executive Summary

While discourse on environmental issues has fixated on climate change, the Great Lakes are also subject to plastic pollution, which has received less publicity. Plastic particles pose a danger to the environment due to adsorption of hazardous substances, bioaccumulation, and detrimental effects on biological organisms.

Water is an increasingly vital resource. The Great Lakes contain 18% of the world's surface freshwater and are of immense economic importance to industries and sectors directly or indirectly reliant on the state of the lakes. Protection of the Great Lakes from plastic pollution is a multidisciplinary effort that requires the collective expertise of engineers, scientists, lawmakers, businesspeople, and consumers. In the age of plastic, effective stewardship of the Great Lakes will require all stakeholders to work together in building the new cyclical plastic economy.

CHAPTER 1

Project Context and Background Information: The Great Lakes connect the interior of North America to the Atlantic Ocean and are of vital economic importance to both Canada and the US. While distinct, the Great Lakes constitute a single interconnected body of freshwater, and flow patterns within the system are affected by wind stress, surface heat flux, and lake depth.

Plastics are ubiquitous in modern life. While this everyday material has enabled humans to make large technological and economic advances, plastics possess harmful properties, such as adsorbing hazardous substances. Plastic particles in water are especially concerning, since they degrade in water, and the capacity for adsorption increases as particles decrease in size.

CHAPTER 2

Analysis of Current State: Research on plastic pollution has been hampered by variance in studies examining each of the Great Lakes. Inconsistencies in sampling frequency and methodologies have resulted in research gaps which need to be filled.

Generally, higher concentrations of plastic particles were found in the smaller, downstream bodies, Lake Erie and Lake Ontario. A 2012 study determined that the majority of particles were within the smallest size classification, which has been verified by subsequent studies in the lakes. However, studies vary greatly in particle types, and research gaps remain including the impact of microplastics in sediments and in the physiologies of living organisms.

Plastic pollution comes from a myriad of sources. Major sources are often located in or around large population centers, ranging from particles from industrial activity to effluent from wastewater treatment plants. Seemingly mundane consumer goods such as clothing and Styrofoam are notable sources of plastic particles.

CHAPTER 3

Plastic Pollution in Oceans: The impact of plastic pollution on wildlife in oceans have been well-documented, in way that is not true of freshwater bodies. Research and solutions on plastic pollution in the oceans provide useful insights into protecting the Great Lakes, particularly since wildlife in both settings are vulnerable to physical debilitations caused by entanglement, ingestion of plastic debris, and bioaccumulation of organic pollutants.

CHAPTER 4

Remediation Strategies: There are many remediation methods available to tackle plastic pollution in the Great Lakes. Microplastic filtration in wastewater treatment plants plays a central role, as this is generally the first step of remediation efforts. However, based on the 99% microplastic filtration rate of three Canadian WWTPs, it is calculated that two plants near the Greater Toronto Area release a combined 126,000 kg of microplastics per year, even after microplastic filtration. While WWTPs are the initial filtration means, further tools are needed.

Biodegradation by microorganisms presents an innovative solution, and future research efforts should focus on testing microorganisms for the optimal balance between remediation capacity and side effects. Entrepreneurial ventures have yielded new and exciting solutions that can be applied to the Great Lakes, including a floating debris interception device and initiatives that give plastics a second life. Although many devices and initiatives have been developed to tackle plastics pollution in the oceans, modifications can enable these innovations to pivot addressing freshwater bodies such as the Great Lakes.

CHAPTER 5

BUSINESS AND SOCIAL RESPONSE: Society has already made its first steps towards the new plastic economy. Around the world, businesses are adapting to society's changing attitude towards plastics pollution. However, there are still significant changes which must be made in consumer and industry habits to decrease plastic accumulation within the Great Lakes.

Changing consumer attitudes are spurring change and innovation. Companies producing hygiene and cosmetic products have innovated with more environmentally friendly offerings in menstrual underwear, menstrual cups, and refillable makeup. Some clothing manufacturers have made efforts to repurpose plastics and use more sustainable materials, often leading to better financial performance. Innovations in food and beverage packaging include beer six-packs, strawless lids, and plant-based alternatives. These changes have been well received by media and have been associated with reputational benefits.

CHAPTER 6

LEGAL IMPLICATIONS: Plastic pollution in the Great Lakes poses challenges associated with its transboundary nature. The matter is addressed at various levels of Canadian, Ontarian, and US legislation, as well as international treaties and agreements.

Legal mechanisms already address plastic pollution in the Great Lakes. The federal *Fisheries Act* prohibits the deposit of deleterious substances into fish habitats, and Ontario's *Water Resources Act* prohibits the discharge of polluting materials that may impair water quality. The recent federal ban on microbeads demonstrates the potential for targeted legislative action when policy is backed by hard evidence.

The International Joint Commission is tasked with providing recommendations to both the Canadian and US governments, but its effectiveness is hampered by internal and external factors. The Charlevoix Blueprint was drafted at the 2018 G7 summit held in Québec, and outlines specific steps moving countries towards a resource-efficient lifecycle management approach.

CHAPTER 7

RECOMMENDATIONS: Plastic pollution in the Great Lakes engages the interests of numerous stakeholders. A focus should be placed on educating consumers on the impacts of excessive plastic use, as a significant portion of plastic debris from urban waste. Research should be focused on understanding physiological impacts of plastics on organisms, as well as developing standardized methodologies and data collection. The law provides clear avenues for stronger protection of the Great Lakes, however, ambiguities and complex jurisdictional issues need to be changed to encourage societal change and maintain stewardship of this key resource.

MEET THE TEAM

Darby Brown

Darby Brown is a 4th year Chemical Engineering student at Queen's University. Her focus is biochemical engineering, and she is passionate about applications of chemical engineering in pharmaceutical development and drug delivery. Darby has enjoyed learning about the distribution of microplastics throughout the Great Lakes region, and is excited to see the development and impact of future technological remediation methods to remove plastics from water systems.

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Hilary Crossley is a 4th year Chemical Engineering student at Queen's University. Her focus is biochemical engineering, in which she enjoys learning about human physiology, engineering applications in medicine, and how engineering can help with environmental sustainability. Hilary has enjoyed learning about the sources of plastic, and is excited to see more societal action, such as the diversion from plastic straws and waste reduction.

Joshua Rim

Joshua Rim is a 2nd year law student at Queen's University, with a Bachelor of Commerce from the University of Calgary. Joshua is passionate about how legal mechanisms can spur private sector innovation in solving broad societal issues. He enjoys applying his legal and business background in multidisciplinary environments, and is excited to see domestic and international trends convert into further concrete steps on plastics pollution in the Great Lakes

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Callie Shannon is a 4th year Chemical Engineering student at Queen's University. Her focus is chemical process engineering, and she is passionate about designing and optimizing processes to make them as safe and sustainable as possible. Callie has enjoyed learning about the different studies that have been conducted in each of the Great Lakes, and is excited about new technologies being produced as a result of the changing societal attitudes towards plastic use.

Bonnie Zhang

Bonnie Zhang is a 4th year Commerce student at Queen's University, specializing in strategy and management. Bonnie has especially enjoyed learning about the state of current research and the initiatives that businesses are taking to address the plastics crisis, and she is excited to see further developments in consumers' attitudes towards plastics.

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Glossary

Anticyclonic: Gyres that move in the counter-clockwise direction [1].

Bioavailability: A measure of the amount of a compound is accessible to an organism for uptake or adsorption [2].

Biodegradation: Degradation caused by biological activity, leading to significant changes in the chemical structure of the material and resulting in the production of carbon dioxide, water, mineral salts and biomass [3].

Bioremediation: The treatment of pollutants or waste through the use of microorganisms (such as bacteria) that break down the unwanted substances [4].

Cyclonic: Gyres that move in the clockwise direction [1].

Fourier Transform Infrared Spectroscopy: The process of using IR radiation on a sample to form a spectrum representing its molecular 'fingerprint' [5].

Fragment: A part that has been broken or detached [6].

Gyre: A large system of circulation currents, particularly those involved with wind movements [1].

In Vitro: Outside the living body and in an artificial environment [7].

Monomer: A molecule of any class of compounds, mostly organic, that can react with other molecules to form polymers [8].

Nearshore: Regions of a lake relatively close to the shore [9].

Polymer: A chemical made up of many repeating units known as monomers [10].

Tributaries: Rivers or streams that flow into larger rivers or lakes [9].

Viable: Capable of growing or developing [11].

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CHAPTER 1

PROJECT CONTEXT AND BACKGROUND INFORMATION

Lake Superior | Photo Credit: Great Lakes Boating Federation

1.0 Project Overview

Plastic pollution in oceans is a widely-recognized issue that has been reported and studied for many years. However, the same cannot be said for plastic pollution in the Great Lakes, for which research has been limited [12]. The team, in collaboration with BlueGreen Innovations Group, has produced a detailed multidisciplinary research report on plastic pollution in the Great Lakes ("Report"), with an eye to providing useful recommendations moving forward. Research over the course of eight months has yielded a detailed literature review. Expert interviews were conducted with leading academic researchers, to unearth professional perspectives not captured in published literature. Current news events and ongoing political developments were assessed throughout the eight-month period, to inform current trends and future directions of action on plastic pollution.

Each chapter addresses a distinct aspect of the issue of plastic pollution in the Great Lakes. Recommendations are provided in each chapter and summarized in Chapter 6. While the Report is a comprehensive research document, it is not a complete solution to the issue. Plastic pollution in the Great Lakes is a far-reaching problem, which engages the interests of many stakeholders, including private businesses, government entities, and whole communities.

To Canada, the Great Lakes hold historical and cultural significance, with several industries reliant on them.

The Great Lakes are of great historical, cultural, and economic importance to Canada, with several key industries dependent on the state of the lakes. The economic capacity of the Great Lakes basin is comparable to some of the largest industrialized economies in the world, due to abundant natural resources, efficient transportation systems, and binational economic integration [13]. By researching the impacts of plastic pollution, potential solutions, legal considerations, and social implications, the team seeks to deliver a substantive report to help relevant stakeholders in achieving a more sustainable use of this resource.

1.1 The Laurentian Great Lakes

The Laurentian Great Lakes watershed system, found within both Canada and the United States, is an extensive, physically and biologically diverse environmental resource which consists of a series of large lakes connected by channels and rivers. The Great Lakes system is composed of Lake Superior, Lake Michigan, Lake Huron, Lake Erie (also including Lake St. Clair), and Lake Ontario. Water travels 1,200 km through the St. Lawrence River, which acts as the primary outlet, draining into the Atlantic Ocean [14]. The Great Lakes and St. Lawrence River collectively hold roughly 18% of the world supply of surface freshwater, with a volume of approximately 23,000 km^3, and a total surface area of 246,463 km^2 [15].

18% of the world's surface freshwater is held in the Great Lakes.

The drainage area of the Laurentian Great Lakes watershed is approximately 1,000,000 km^2—just under four percent of the North American surface area [15].

1.1.1 Physical Geography

Physical characteristics of the Great Lakes region, such as climate, soil types, and physical topography, vary significantly across the basin. The topography and climate within the basin are largely dependent on latitude. The Great Lakes and St. Lawrence River watershed is one of the world's most diverse ecosystems, containing over 3,500 known species of plants and wildlife, and over 250 known species of fish [16].

1.1.1.1 Geography

The map seen in Figure 1 shows the location of the region within the upper mid-east of North America. The region contains parts of Ontario, Quebec, Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin [17].

Figure 1: Map of the Laurentian Great Lakes [17].

The variability of this geographical region has significant impact on patterns seen within the lakes. Flow patterns are heavily impacted by changing climate, as well as seasonal variability throughout the region [1]. Additionally, each of the system's lakes and channels have their own unique combinations of interrelated and interdependent sets of wetlands, terrestrial regions, and aquatic ecosystems [14].

1.1.1.2 Topography

In the northern regions, the climate is cold, and the terrain is primarily composed of granitic bedrock under a thin layer of acidic soils, with mainly coniferous vegetation [15]. In the southern areas, however, the climate is much warmer, and the soils are typically deeper, composed of a mixture of clays, carbonates, silts, sands, gravels, and boulders deposited as a result of glacial drifts [15]. The southern area of the Great Lakes region contains relatively fertile soil, and much of the region has been drained for agricultural purposes [15].

1.1.1.3 Hydrology and Flow Patterns

Though the Great Lakes system is separated into five distinct lakes, they form one single interconnected body of fresh water [14]. These lakes form a chain which connects the interior of North America to the Atlantic Ocean [14].

The Great Lakes, while distinct, are a single body of water that connect inner North America to the Atlantic Ocean.

Water flows, in general, from the interior of the system to the outlet at the St. Lawrence River [18]. Water flows from Lake Superior into Lakes Huron and Michigan, and then southward to Lake Erie, followed by northward flow into Lake Ontario. Detailed specifications of each lake can be viewed in Table 1.

Table 1: Summary of Great Lakes Physical Data [19].

	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Average Depth (m)	147	85	59	19	86
Elevation Above Sea Level (m)	183	176	176	173	74
Maximum Depth (m)	406	282	229	64	244
Approximate Volume (km^3)	12,100	4,920	3,540	484	1,640
Shoreline Length (including islands) (km)	4,385	2,633	6,157	1,402	1,146
Retention Time (years)	191	99	22	2.6	6

Long-term circulation throughout the Great Lakes is primarily driven by wind stress, as well as surface heat flux which results in density-driven currents throughout the system. The interaction between these two factors results in complex circulation patterns, which continue to be studied to obtain a more thorough model of the overall system [1]. It is well known, however, that hydraulic residence times (often referred to as "retention time" [19]) serve as a method to estimate how quickly water quality within the lake changes in response to variance in contaminant loadings [20].

The impact of elevation above sea level on the overall flow pattern from Lake Superior towards the St. Lawrence River, exiting into the Atlantic Ocean [14], can be seen in Figure 2.

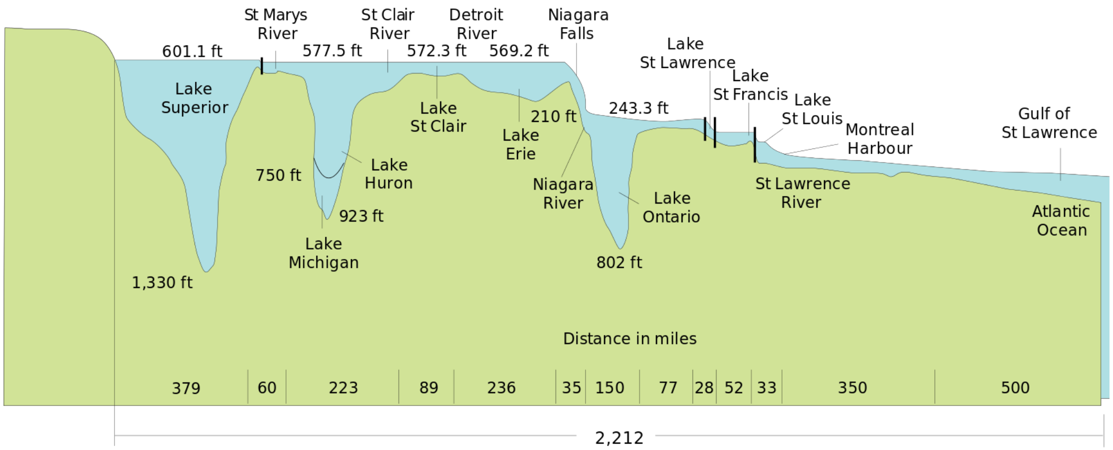

Figure 2: Great Lakes physical elevation diagram [21]. The variance in depth between lakes has a significant impact on the water current and flow patterns throughout the water systems. The change in water volume and depth of the lake may also have an impact on sediment sampling methodology and accuracy, and thus may impact the data obtained regarding microplastic pollution within benthic sediment **[21]**.

1.1.2 Human Geography

The Great Lakes system is surrounded by many urban centers with high populations. Approximately 8.5 million Canadians and 30.7 million Americans live in the Great Lakes basin, primarily in or around major cities which lie along the shorelines of the Great Lakes [22]. High population densities are predicted to be correlated with high accumulations of plastic pollution [23].

High population densities lead to higher accumulations of litter and plastic pollution.

1.1.2.1 Populated Regions around the Great Lakes

As seen in Figure 1, all the Great Lakes except Lake Michigan lie along the Canada-US border. Figure 3 outlines cities with populations greater than 10,000 in both Canada and the United States for Lake Michigan, Lake Erie and Lake Ontario, based on the 2016 Canadian Census and the 2017 approximated United States population data [24, 25].

Of the Great Lakes, Lake Ontario is surrounded by the most cities with populations greater than 100,000.

Lake Ontario is surrounded by the largest number of cities with populations greater than 100,000 compared to the other Great Lakes. Due to high population densities in the Greater Toronto Area, larger accumulations of plastic pollution are expected [9]. On Lake Superior, Thunder Bay, Ontario is the only city of more than 100,000 people. Sault Ste. Marie, also on the St. Clair River between Lakes Huron and Superior, has a population of approximately 80,000. Surrounding Lake Huron, there are no cities above 100,000, though Sarnia has a large industrial presence with a population of 71,594 as of 2016 [24].

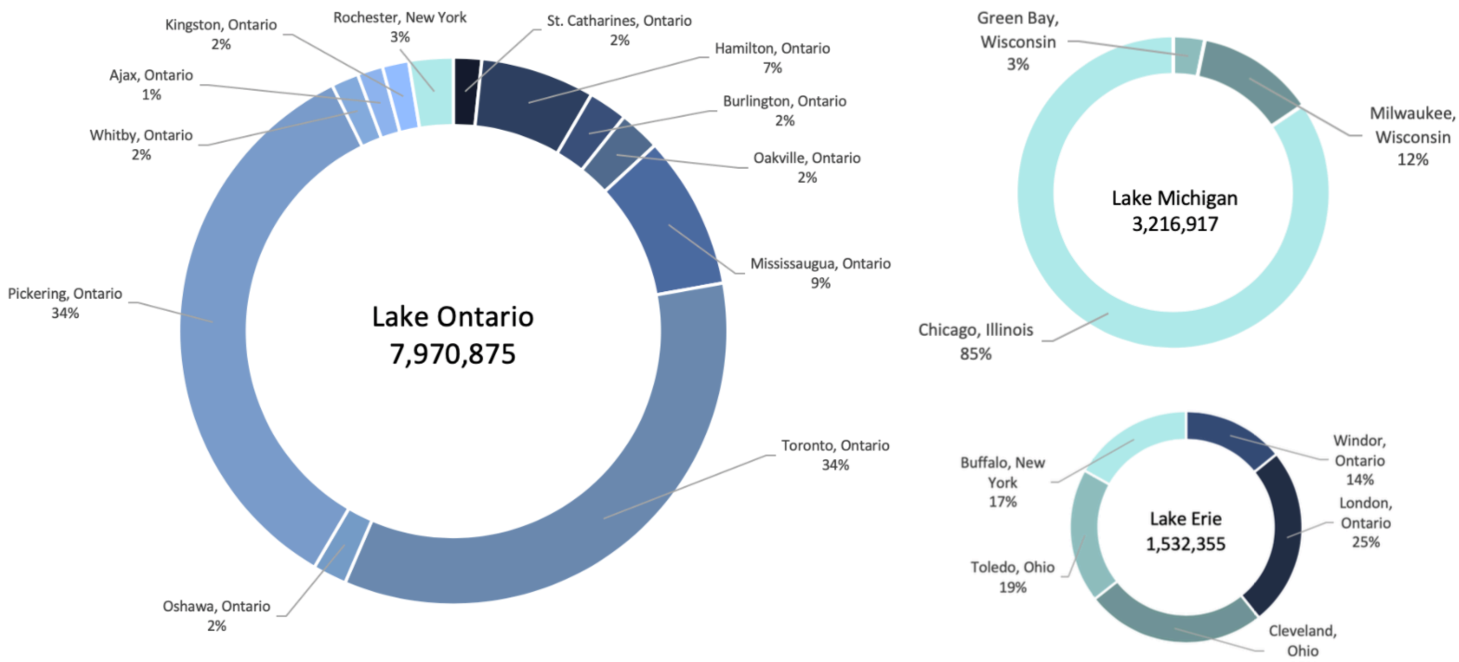

Figure 3: Distribution of population within cities with populations over 100,000 around the Great Lakes [24, 25].

1.2 Plastic – The Everyday Material

The history and usage of plastics by people dates back over 100 years. Their usage over the past century has allowed society to make large technological advances. From household items such as food containers, to piping for windows, plastics fulfill a wide variety of consumer needs and offer a large range of applications [26].

1.2.1 Key Definitions

Table 2 shows a list of important definitions of terms referenced throughout the report.

Table 2: List of key definitions used throughout the report.

Term	Definition
Polymer	Chemicals made of repeating units known as **monomers** [10].
Macroplastics	Polymer products greater than 5 mm in size [27].
Microplastics	Polymer products less than 5 mm in size [28].
Nanoplastics	Polymer products less than 0.1 µm in size [27, 29].
Primary Microplastics	Smaller pieces of plastic manufactured to be that size, usually used as resin pellets in manufacturing or in products such as facial scrubs [30].
Secondary Microplastics	Smaller pieces of plastic formed from the disintegration or degradation of larger plastics [30].

1.2.2 Chemical Composition

Plastics are made from a variety of materials including cellulose, coal, natural gas and crude oil. With the most common material, crude oil, plastic production begins with oil distillation in a refinery, where is it then separated into lighter components comprised of repeating chains. Once this phase is completed, the physical plastic is formed through polymerization, which takes the individual **monomers** and combines them to form the final **polymer** [31].

Plastics themselves can be divided into two different types- thermoplastics, and thermosets, as explained in Figure 4 [31].

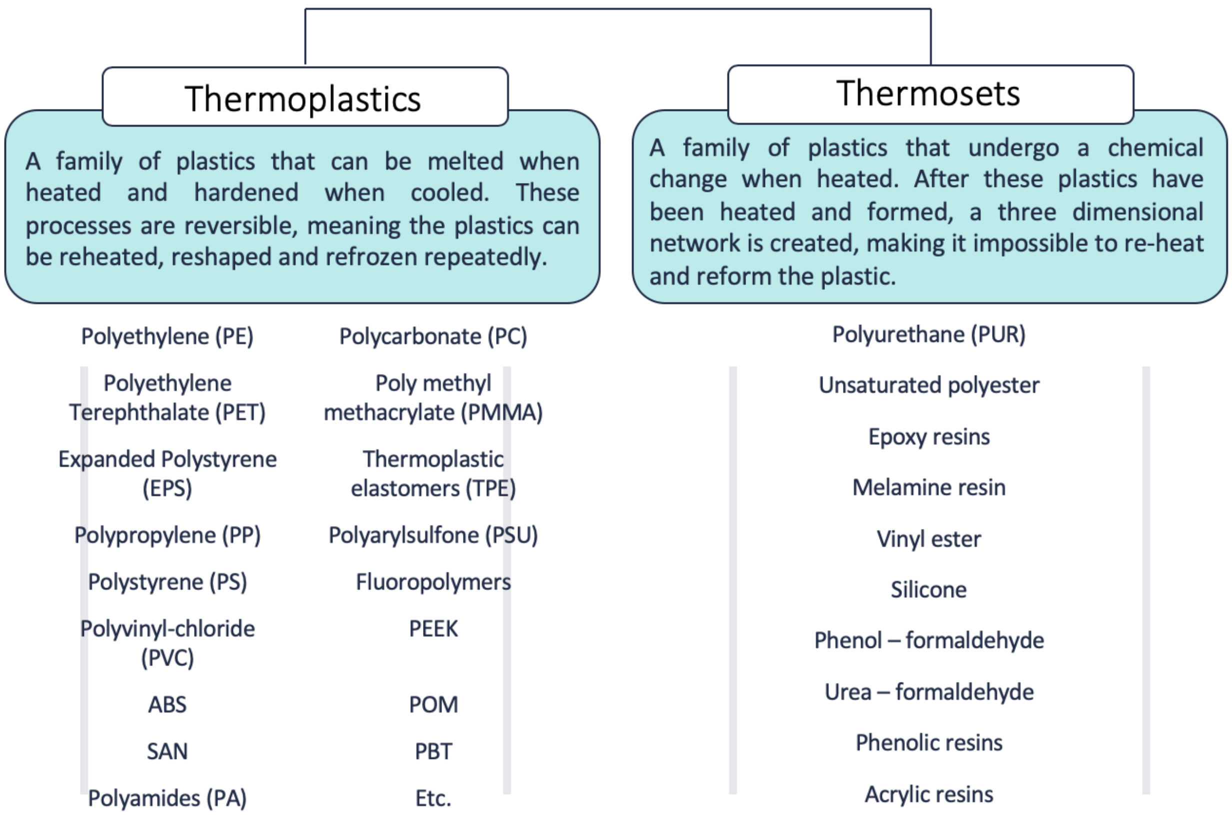

Figure 4: Summary table showing the differences between thermoplastics and thermosets as well as common examples [31]. Throughout the remainder of the report, abbreviations as shown above will be used to refer to plastic types.

1.2.3 Toxicity and Side Effects

Monomers can be configured in many ways, which results in versatile plastic properties. For example, Kevlar is used for bullet-proof vests, and PET is commonly used for drink bottles [10].

While plastics are very useful in society and have a wide range of applications, there are drawbacks to the material. Both macroplastics and microplastics adsorb hazardous substances and bacteria, with smaller particles having a higher adsorption capacity due to their large surface area-to-volume ratio [32].

Plastics have many benefits, but also many drawbacks, such as adsorbing hazardous substances.

Some chemicals within plastics have been found to have harmful side effects. For example, styrene and PVC plastic **monomers** are both carcinogenic and mutagenic, meaning they can cause mutations in an organism's DNA [32]. Many plastics also contain bisphenol A (BPA), which is a known endocrine disruptor. This chemical can cause developmental, reproductive, neurological and immune issues in both humans and wildlife [33]. Both Canada and the United States have banned the use of BPA in products such as baby bottles, and Canada has declared BPA to be a toxic substance. However, it was still reported as recently as 2010 by the United States Environmental Protection Agency that over one million pounds of BPA is released into the environment annually [34, 35].

Many plastics, including bulk plastics, microplastics, and nanoplastics, consist specifically of synthetic polymers such as PE, PP and PVC. The synthetic polymers can vary widely in their properties, and as such, provide different density, porosity and additive content values depending on which synthetic is chosen [36].

Plastic additives can constitute up to 50% of a plastic's mass and can be either organic or inorganic [36]. Plastics that contain additives such as biocidal additives, plasticizers, or flame retardants are likely to be environmentally detrimental, as they could leach into the surrounding environment and other organisms [37].

1.2.4 Particle Size and Density

Additionally, particle size affects the chemical composition of the plastic. Extra materials used within bulk plastics, such as gold or cerium dioxide, are relatively inert in larger forms. They tend to become more reactive as particle size decreases, which leads to an increase in surface area. The toxicity of relatively inert material increases as size decreases due to the increased reactivity [38].

Additionally, as particles decrease in size, they will generally have a larger capacity for adsorption of chemical substances, due to an increased surface area-to-volume ratio [39]. Consequently, microplastics accumulate high concentrations of persistent organic pollutants (POPs) [40].

Density is also an important property when discussing plastics. Plastics can have different densities as seen in Table 3, due to variations in the arrangement of molecules. This determines how the plastic will behave once they reach the water, which has a density of 1 g/cm^3 [41, 42].

Table 3: Average densities of common plastic types [42]

Plastic Type	Average Density (g/cm^3)
Polypropylene	0.92
Polyethylene	0.95
Polystyrene	1.01
Polyamide or Nylon	1.15
Cellulose Acetate	1.24
Polyvinyl Chloride	1.3
Polyester Resin	1.35

Floats in freshwater

Sinks in freshwater

1.2.5 Plastic Degradation

Many plastics slowly degrade in the environment, and can have long-term impacts, including the dispersion of POPs [30].

> ***Plastics degrade slowly in the environment.***

Plastic degradation occurs in stages: entering the environment, disintegrating into **fragments**, and releasing carbon dioxide through oxidation. Toxic chemicals from initial production or subsequent adsorption are released during plastic degradation [43, 44, 30, 45]. These chemicals can disrupt endocrine functions and cause harmful reproductive and developmental effects in aquatic organisms [46].

There are several factors that can affect the degradation rates of plastic. Photooxidation occurs when plastics are exposed to UV radiation and atmospheric oxygen and contributes to degradation [47]. Adhering particles are **fragments** that become lodged onto the surface of a plastic particle and create pits or large fractures which accelerate plastic particles to split apart [46]. Environmental factors such as wind and water currents can also cause degradation if the plastic comes into contact with them over long periods of time [48].

1.2.6 Industry and Usage

Plastics are used in every end-use segment of the economy, and have replaced paper, glass and metal from traditional applications [49]. The world plastic production was 348 million tonnes in 2017, which was an increase from 335 million tonnes in 2016.[1] Asia produces 50.1% of the world's plastics, with China producing 29.4%. Europe produces 18.5% and USMCA (formerly NAFTA) produces 17.7% [50]. Canada produces approximately two percent of total global volume of plastics [49]. In 2009, 47% of all establishments that process synthetic resins into plastic products were located in Canada. Since then, the distribution of the plastic industry location has not changed substantially, and approximately half of the

[1] Includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP-fibers. Not included PET-, PA- and polyacryl-fibers.

Canadian plastics industry is located in Ontario [49].[2]

1.3 Current State of Research

Pollution in the Great Lakes is not a well-explored subject, and it has only become a topic of interest in recent years.

Current research confirms the presence of macroplastics and microplastics in the Great Lakes. However, limited research has been done specifically on macroplastics.

Studies show there are microplastics in the Great Lakes.

Many journal articles identify gaps in knowledge, including the spatial and temporal distribution of plastic debris, environmental impacts, and their ecotoxicological consequences on the food web. Additionally, little is known surrounding the sources and composition of plastics, as discussed with Dr. Sherri Mason, sustainability coordinator at Penn State Behrend [51].

"Limited data exists on macroplastics. Nobody is actually going into the rivers and lakes and fishing out plastics, quantifying how much is there. We need to understand what kinds of plastics are entering the water bodies, and how the plastics are getting there."

– Dr. Sherri A. "Sam" Mason

Sustainability Coordinator,
Penn State Behrend

Figure 5 summarizes literature published on plastic pollution in the Great Lakes. It is important to note that there is minimal published literature about plastic pollution in the Great Lakes, but that there are a number of academics working on investigating the issue, which is discussed in the next chapters.

[2] Based on the Statistics Canada definition of the Plastics Industry.

Figure 5: Summary of published literature on plastic pollution in the Great Lakes.

Tributaries	Sediments	Shorelines	Surface Waters

Tributaries:

Plastic Debris in 29 Great Lakes Tributaries: Relations to Watershed Attributes and Hydrology
Baldwin et al., 2016

Sediments, Shorelines and Surface Waters:

Microplastics in the Great Lakes
Various authors, International Joint Commission, 2016

Plastic debris in the Laurentian Great lakes: a review
Driedger et al., 2015

Tributaries, Sediments and Shorelines:

Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary, and beach sediments
Ballent et al., 2016

Shorelines:

Hidden plastics of Lake Ontario, Canada, and their potential preservation in the sediment record
Corcoran et al., 2015

Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America
Zbyszewski et al., 2014

Assessing and Mitigating Plastic Pollution in Lake Huron
Hydra Horizons Consulting, 2013

Distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada
Zbyszewski et al., 2011

Surface Waters:

Microplastic pollution in the surface waters of the Laurentian Great Lakes
Eriksen et al., 2013

Microplastic Abundance and Composition in Western Lake Superior As Determined via Microscopy, Pyr-GC/MS, and FTIR
Hendrickson et al., 2018

Pelagic plastic pollution within the surface waters of Lake Michigan, USA
Mason et al., 2016

CHAPTER 2

CURRENT STATE OF PLASTIC POLLUTION

Lake Michigan | Photo Credit: SergiyN / Shutterstock

2.0 Introduction

The rise of plastic pollution as a prominent issue has corresponded with increasing academic interest in its effects on the Great Lakes. As a relatively new area of research, coverage varies by lake, with some lakes being subject of more scientific study than others. To make sense of the current state of research, this chapter seeks to synthesize the literature and scientific studies on each of the Great Lakes, and to distill the unique characteristics of each lake that may warrant further study.

2.1 Current State of Plastic Pollution

Plastic pollution has the potential to enter major waterways, such as the Laurentian Great Lakes, through drainage systems and sewage treatment overflow during high-volume rain storms, can blow off beaches littered with debris from human activity, or break off from developed structures such as docks and piers [52, 53]. The current issue of plastic pollution is of significant concern, as discussed with Sherri Mason.

> "[I] would put plastic pollution and the associated chemicals second to climate change, in terms of our species survival.
>
> – Dr. Sherri A. "Sam" Mason
>
> Sustainability Coordinator,
> Penn State Behrend

2.1.1 Lake Superior

Lake Superior is the world's largest freshwater lake by surface area (82,100 km^2) and contains more water than all the other Great Lakes combined (12,000 km^3) [54].

This lake is often considered to be relatively pristine due to its size, low population density along the shores, and location at the head of the Great Lakes drainage system.

Lake Superior has a residence time of 191 years, which is greater than any of the other Great Lakes [20]. Maximum current speeds in summer can be significant, reaching 7.1 cm/s near the tip of the Keweenaw Peninsula, the highest in the Great Lakes system [1].

At the current rate of declining ice cover, Lake Superior will be ice-free in winter in approximately three decades, due to rising lake temperatures, possibly leading to changes in flow patterns [55].

2.1.1.1 Experimental Methodology and Results

In a 2012 study, Eriksen et al. reported microplastic density higher than Lake Huron [56]. While this result was surprising due to the low population density along its shores, the surface water samples in Lake Superior were collected closer to shore than in Lake Huron, and thus closer to the land-based sources of plastic debris [30].

> ***The most frequent particles observed were fibers, followed by fragments and films.***

In a study of microplastics in western Lake Superior, the most frequent particles observed were fibers (228 particles), followed by **fragments** (200), and then films (121). Beads and spheres (9), foams (3), and others particle types (21) were observed in lesser quantities [57]. Given the distance of the open-lake sampling sites from the presumed sources of microplastic particles, atmospheric deposition is likely a significant source of microplastic pollution in Lake Superior, particularly given the low watershed-to-lake ratio which minimizes the impact of riverine inputs [57].

The distribution of microplastics in Lake Superior is possibly subject to physical processes more commonly observed in marine environments rather than smaller inland lakes. In Hendrickson et al.'s study, **nearshore** sites in Lake Superior had the lowest concentrations on average, while offshore open-water sites had higher concentrations, similar to microplastic distributions in the western Atlantic Ocean [57].

In the particle transport model developed by Hoffman & Hittinger (2017), Lake Superior had the fewest plastics. The model derived an estimated 4,553 plastic particles in Lake Superior, compared to the 1.4 million released in total [58].

On an item-by-item basis, plastics comprised the lowest proportion of anthropogenic debris in Lake Superior, compared to Lake Erie and Lake Huron, where it was the greatest [30]. In a 2014 surface water sampling, the highest abundance of microplastics were found offshore of Thunder Bay and near Sault Ste. Marie [59].

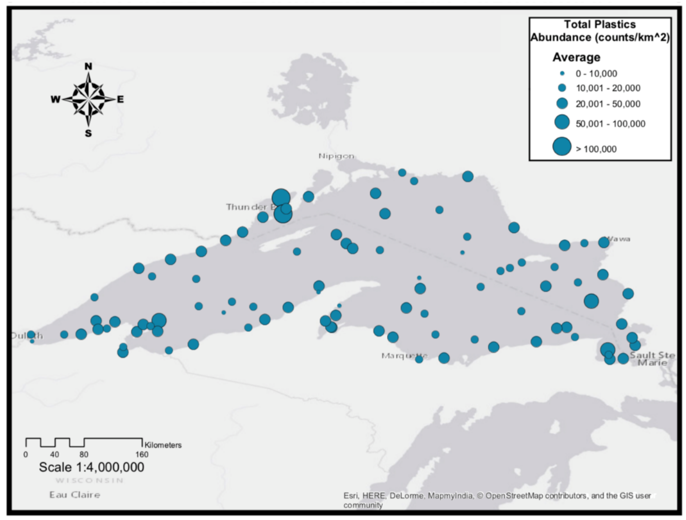

Figure 6: Microplastic abundance from 2014 surface water sampling [59].

2.1.1.2 Key Findings on Lake Superior

Studies on plastic pollution in Lake Superior yield the following results:

→ The most frequently observed particles were fibers, followed by **fragments** and films [57].

→ Microplastics distribution is similar to that of the western Atlantic Ocean, with **nearshore** sites having the lowest concentration and offshore open-water sites having the highest [57].

→ A particle transport model predicted that Lake Superior holds the lowest number of plastic particles of any of the Great Lakes [58].

Being at the head of the Great Lakes system, Lake Superior is expected to be least affected by pollution from major population centers. However, further research is needed to determine the effect of Lake Superior's uniquely marine environment characteristics.

2.1.2 Lake Michigan

Lake Michigan is the only Great Lake wholly within the borders of the United States, and includes portions of Indiana, Michigan, Wisconsin, and Illinois. The largest population center is the Chicago area, which has the potential to impact

Lake Michigan under wet weather conditions due to combined sewer overflow [53, 60]. Lake Michigan has a surface area of 58,030 km^2, and a water volume of 4,900 km^3.

2.1.2.1 Flow Patterns and Distribution

Lake Michigan is second only to Lake Superior in terms of residence time, at 99 years [51]. As a result of the lake's cul-de-sac formation and equal surface elevation to its sister Great Lake, Lake Huron, water entering Lake Michigan circulates slowly and tends to remain for nearly a century before discharging into Lake Huron. This can lead to a more even distribution of plastic pollution across the lake surface [1, 51]. Lake Michigan and Lake Huron are technically a single large lake, as flow through the five-mile-wide Straight of Mackinac reverses direction, resulting in a mean flow from Lake Michigan to Huron that is only a fraction of the magnitude of a typical flow [58].

An **anticyclonic gyre** within the southern basin of Lake Michigan develops over the course of the summer and is especially prominent in August [1]. Thus, one could expect greater particle abundance within the southern end of Lake Michigan. Results of a 2013 study, however, indicated a fairly even distribution of plastic particles across the lake surface, and no particular aggregation of plastic particles as a result of temporary **gyre** was shown [61]. Possible reasons for the relatively even distribution include: the long residence time of waters in Lake Michigan, the high variability of circulation currents, and the wind acting to move debris above-surface differently than surface currents carrying subsurface debris. Such windage effects were noted in the movement of debris following the Japanese tsunami [62]. There is strong inter-annual variability within Lake Michigan's circulation currents. Warmer years correlate with **anti-cyclonic** currents, resulting in aggregated particles, while colder years demonstrate **cyclonic** currents, which act to transport plastic particles downward [1].

Results indicated a fairly even distribution of plastic particles across the lake surface, and no particular aggregation as a result of temporary gyre.

2.1.2.2 Experimental Methodology and Results

In a 2013 study by Mason et al., 59 open-water samples were obtained by towing a mantra trawl along the lake surface. The distribution of plastic abundance for the samples is illustrated in Figure 7 [61].

Of the 59 samples collected by Mason et al., all but one contained plastic. Additionally, 52 of the samples contained particles within the smallest size classification (0.355-0.999mm), revealing that plastic particles less than 1mm were the dominant size classification. This was consistent with the 2012 Great Lakes survey conducted by Eriksen et al., where 59% of plastic particles were found to be within this size classification [56]. However, distribution differed substantially from the earlier study. While pellets were the dominant particle type in the 2012 study, **fragments** dominated the pelagic plastic obtained from Lake Michigan (79%), with pellets constituting a much smaller contribution (4%) [51]. Interestingly, fibers were the second most abundant type (14%), in contrast to the 2012 study where they were only a minor component [56].

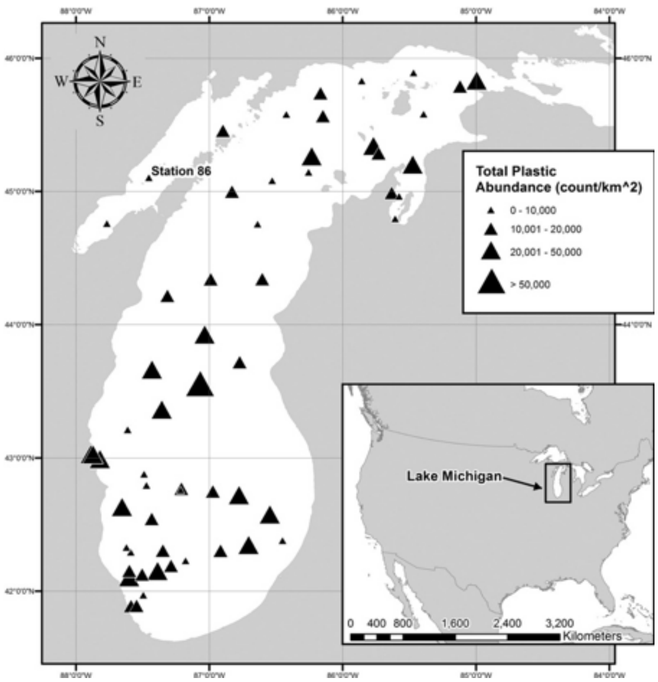

Figure 7: Distribution of plastic abundance (particles/km^2) for 59 open-water surface samples [61].

> ***Fragments are the dominant form of plastic found—this indicates that microplastics produced from the breakdown of macroplastics are significant and outweigh the more popular sources, such as microbeads.***

The prominence of **fragments** compared to pellets seems to indicate that secondary sources, produced by degradation of plastic bags, bottles, and other litter types into smaller **fragments**, outweigh primary sources, such as preproduction pellets, polyethylene, and microbeads [51]. According to Mason et al., the prominence of pellets in the 2012 study could also be due to a greater concentration of pellet producers and consumer in the Sarnia area of Lake Huron and around Lake Erie, in comparison to Lake Michigan.

In response to insufficient studies covering the entirety of the Great Lakes system, Hoffman & Hittinger created a hydrodynamic particle transport model, derived from previous census data and methodologies. Over a six-year period from 2009 to 2014, approximately 1.4 million particles were released into the model. Lake Michigan was the recipient of more than half of this plastic input, with a staggering 707,531 particles released into the lake [58].

Across the Lake Michigan surface, plastic particle abundances averaged 17,276 particles/km^2 [51]. According to Mason et al., this data suggested that there are on the order of one billion particles across the surface of Lake Michigan, with 95% confidence values ranging from 750 million to 1.26 billion particles [61].

The main primary sources are large population centers such as Chicago and Milwaukee, from which most particles end up accumulating on the eastern shores of Lake Michigan [58]. Cigarette filters were found to be a major source of shoreline accumulation of microplastic debris [63].

2.1.2.3 Key Findings for Lake Michigan

Studies on plastic pollution in Lake Michigan yield the following findings:

→ Plastic particles are fairly evenly distributed across the lake surface, with no particular aggregation as a result of temporary seasonal **gyre** [61].

→ **Fragments** are the dominant form of plastic found, indicating that the breakdown of macroplastics are significant and outweigh the more popular sources such as microbeads [61].

→ Primary sources are Chicago and Milwaukee, with most particles accumulating on the eastern shores of Lake Michigan [58].

→ Given the dominance of fragments as the most commonly found particle type compared to other lakes, further **research should be conducted to determine other unique characteristics of Lake Michigan.**

2.1.3 Lake Huron

Numerous studies have been conducted to determine the distribution, types, and abundance of plastic **fragments** on the beaches, surface water, and within the sediments of Lake Huron.

2.1.3.1 Flow Patterns and Distribution

Flows throughout the Great Lakes have been studied for many years. A study was conducted and published in 1980 which focused on winter currents throughout Lake Huron [64]. This study used automatic current meters to track current movement. From this study, it was suggested that Lake Huron was occupied by counterclockwise circulation in the western part of the lake, and clockwise circulation in the northern part of the main basin and within Georgian Bay [64]. More modern studies concur with this observation, and state that Lake Huron has a predominantly **cyclonic** surface circulation pattern with currents which move southward along the west coast and northward along the east coast [12].

The overall flow pattern of Lake Huron can be seen in Figure 8.

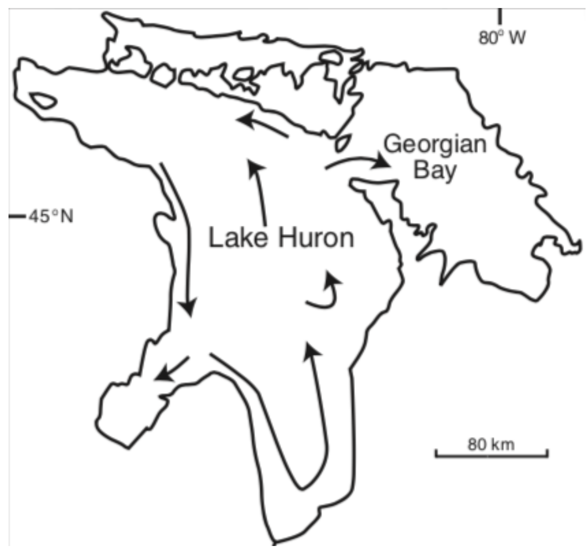

Figure 8: Mean circulation in Lake Huron [64].

2.1.3.2 Experimental Methodology and Results

A study was conducted by Zbyszewski and Corcoran at the University of Western Ontario in 2011, in which seven beaches were sampled along Lake Huron with a transect line set parallel to the shoreline at each location, and perpendicular sampling lines attached to the transect line at 10m intervals. Figure 9 shows the locations of all the sampling points used in this study.

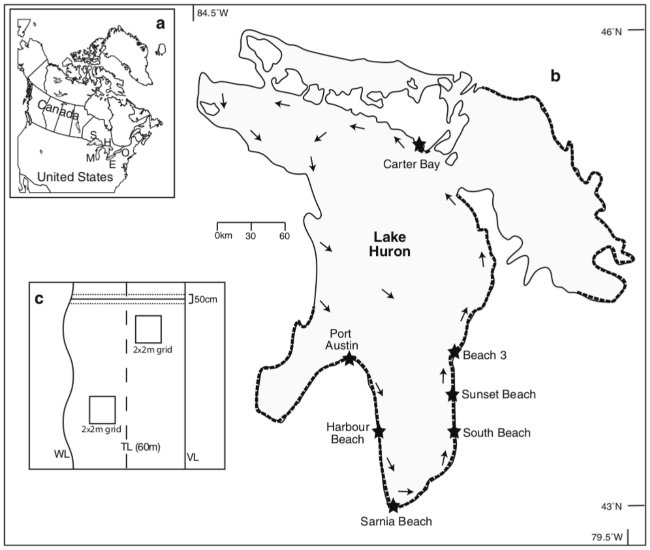

Figure 9: Map of the Lake Huron study region [12].

All visible plastic debris was sampled within 1m of each sampling line, and in addition, plastics were sampled from two 2x2m grids placed randomly on each beach. The plastics collected were then air-dried and separated into microplastic pellets (<5mm), broken plastic **fragments** (>5mm), and polystyrene. The samples were treated to remove excess sand and calcium carbonate residue in a Branson 8510 ultrasonic bath, and then dried in a laboratory oven. Plastic composition and level of surface oxidation was determined using scanning electron microscopy. This study indicated that four of the seven beaches yielded 3,209 plastic pieces, which included 2,984 pellets, 108 **fragments**, and 117 pieces of Styrofoam, over an area of only 85 m^2.

Over 94% of total plastic pellets were found on the Sarnia, ON beach.

The beach located in Sarnia, ON, yielded over 94% of the total plastic pellets, with 408 pieces/m^2, while the beach labelled “Beach 3” in Figure 9 contained only 13 pellets and 74 pieces of Styrofoam along the sampling lines. Further compositional analysis was conducted in this study on 45 samples using **Fourier Transform Infrared Spectroscopy** to determine the type of plastics which were prevalent [12]. Based on this analysis, it was determined that 32 plastic particles were composed of polyethylene, while 12 were composed of polypropylene and one was composed of polyethylene terephthalate [12].

Plastic abundance on the shores of Lake Huron rivals that of oceanic beaches.

The volume of plastics found on the shores of Lake Huron rivals the abundance of plastic pellets per square area on oceanic beaches, including those studied on the shores of New Zealand [65]. It has been suggested in many that human density and activities significantly impact the types and volume of microplastics present in nearby regions, with the greatest concentration of pellets located near industrial areas studies [65, 56, 66]. This hypothesis is supported by the study conducted by Zbyszewski & Corcoran. A gradual decrease in pellets from Sarnia to Kingcardine, along with a lack of plastic found along the west and north shores, can be attributed to the northern flow of water and suggests the debris may have originated from the industrial sector in and near Sarnia [12].

Following the beach study conducted by Zbyszewski & Corcoran in 2011, a study was conducted at the Gyres Institute in Los Angeles in

2013 which studied plastic pollution in open water throughout the Laurentian Great Lakes system [56]. In this study, samples were collected from Lake Erie, Lake Superior, and Lake Huron, with 8 samples being collected in Lake Huron. In this study, samples were collected using a rectangular manta trawl dragged along the surface of the water aside the ship over a defined surface area, allowing particle abundance per square kilometer to be determined [56]. The samples were rinsed, and plastic was manually removed from natural material, and then sorted by size and type of plastic.

The samples obtained throughout Lake Huron showed significant variability, with one count region having a count of <480 particles/km^2, while two others had counts of 10,001-25,000 particles/km^2 [56]. Additionally, this study found many coal and fly ash particles to be within the collected samples. There are 8 states which border the Laurentian Great Lakes, within which there are 144 coal-burning electric generation facilities [67]. It is suggested that a large percentage of the coal and fly ash particles may be sourced from these facilities, which release aluminum silicates in the form of coal ash into waterways through wastewater discharge [56].

2.1.3.3 Key Findings on Lake Huron

Though there is significant variability throughout the lakes, as shown by the range of values obtained by numerous studies, it has been deduced that Lake Huron has the smallest abundance of plastics per square kilometer out of the three lakes sampled by Eriksen et al., including Lake Huron, Lake Erie, and Lake Superior [56].

From the studies conducted, the following conclusions about Lake Huron may be drawn:

→ Four of seven beaches sampled on Lake Huron yielded 3,209 plastic pieces over an area of 85 m^2, composed of primarily small pellets, plastic fiber **fragments**, and Styrofoam [12].

→ The majority of plastic particles found were composed or PE, PP, or PET [12].

→ Human density and human activity has a significant impact on the types and volume of microplastics present, and a gradual decrease in plastic volume can be seen from Sarnia toward Kingcardine, suggesting the majority of debris within Lake Ontario may have originated from the industrial sector in and near Sarnia, ON [48].

Further research is required, however, to conclusively determine the significance of the volume of plastics within Lake Huron.

2.1.4 Lake Erie

Lake Erie is the second smallest Great Lake, with a length of 388 km and a breadth of 92 km. Its northern shorelines are made up mostly of villages and towns where tourism and agriculture are the main industries; and its eastern and southern shorelines border major cities, including Buffalo, NY, Erie, PA, and Cleveland, OH, where major industries include steel and plastics manufacturing

[48]. The Lake Erie basin also includes Lake St. Clair.

Numerous studies have been conducted to determine the volume, distribution, and sources of plastic pollution in the beaches and surface waters of Lake Erie.

2.1.4.1 Experimental Methodology and Results

One of the most prominent studies which explore the abundance and count of microplastic pollution in Lake Erie was conducted by Eriksen et al in 2013, where a 3-week expedition was jointly organized between the Gyres Institute and SUNY Fredonia, and eight samples were collected in Lake Erie [56].

Natural fibers, aluminum silicate particles and paint fragments were removed from all visually sorted samples. The adjusted microplastic abundance for all samples is given in Table 4 [56].

Table 4: Count, location, and abundance of plastic pollution from Lake Erie [56].

Count, location and abundance of plastic pollution in the Great Lakes

Sample id.	Latitude	Longitude	Count total	Tow length (km)	Abundance (count/km^2)
Lake Erie					
14	41.8979	−83.0498	26	3.78	11,282
15	41.7523	−82.9450	9	3.15	4686
16	41.7830	−82.7569	20	3.85	8511
17	41.8953	−82.3409	131	3.76	57,122
18	42.1425	−81.5131	13	3.52	6056
19	42.2441	−80.7501	21	3.78	9112
20	42.3938	−79.9536	1101	3.87	466305
21	42.3000	−80.0259	657	3.83	280947

The study took samples from Lakes Erie, Huron, and Superior, and the samples from Lake Erie were consistently the most concentrated, at an average of 0.1055 plastic items/m^2. Not only did Lake Erie samples account for 90% of all the pelagic plastic debris, but samples 20 and 21 alone also made up 85% of all microplastic particles collected in all 21 samples in total [56]. Polychlorinated biphenyl (PCB) concentrations in Lake Erie are cited as the world's third highest [68].

> ***A study found that Lake Erie consistently contained the highest concentration of microplastics.***

Another major paper that studied the inventory and transport of plastic debris in the Laurentian Great Lakes was conducted by Hoffman et al in 2017.

By using census data and methodologies used to study ocean debris, the researchers calibrated a hydrodynamic model to derive surface microplastic mass estimates of 4.41 metric tonnes in Lake Erie [58].

2.1.4.2 Flow Patterns and Distribution

In the 2014 study by Zbyszewski et al., researchers studied distribution patterns, compositions and textures of plastic debris along the Lake Erie and Lake St. Clair shorelines to determine the roles of source locations, surface currents, and shoreline types in the accumulation of plastic litter [48].

The flow patterns of Lake Erie are shown in Figure 10.

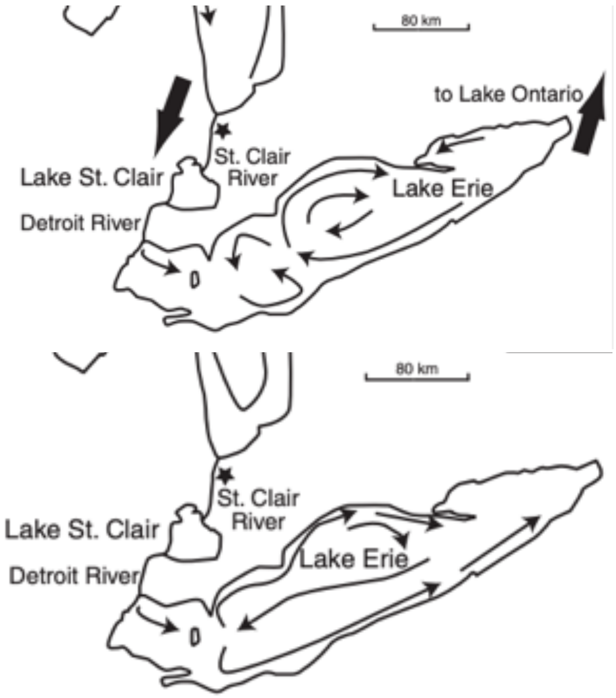

Figure 10: Flow patterns of Lake Erie in summer (top) and winter (bottom) [48].

Most notably, the Lake Erie basin has converging currents in the east, and annual mean current modeling suggests that currents are pushed southward along the shoreline [1]. Lake St. Clair receives discharge from Lake Huron through the St. Clair river and flows into the Detroit River before reaching Lake Erie, which then flows into Lake Ontario.

These converging surface currents in the east yielded the highest particle counts in the eastern basin of Erie, as shown in the aforementioned Eriksen et al study. The convergence of currents in Lake Erie may also account for why the last two samples collected during that study were anomalies in terms of their abundance of micro debris and accounted for 85% of all microplastics collected [56].

During the summer months, Lake Erie is dominated by an **anticyclonic gyre** with a smaller **cyclonic gyre** located in the western region of the lake. During the winter months, however, a two-**gyre** current pattern is present, as shown by **anticyclonic** movement in the north and **cyclonic** flow in the south of the lake [1].

These flow patterns impact the distribution of plastic debris along Lake Erie and Lake St. Clair. The results of the Zbyszewski et al study, which outline distribution by sampling location and type of plastic, are summarized in Table 5 and Table 6 [48].

Table 5: Distribution and types of plastic debris along Lake Erie by sampling location [48].

Location	Beach type	Pellets	Fragments	Styrofoam	Total	Distribution (pieces/m^2)
Colchester Beach	Sandy	25	83	2	110	1.57
Cedar Beach	Sandy	3	81	4	88	0.63
Holiday Harbour	Sandy	17	101	12	130	1.85
Port Stanley	Sandy	0	88	0	88	0.36
James N Allen	Sandy	2	32	0	34	0.56
Crescent Beach	Sandy	54	54	8	116	0.83
Evangola	Sandy	57	51	8	116	1.84
Presque Isle	Sandy	284	234	0	518	3.70
Fairport Harbour	Sandy	140	171	3	314	2.25
Port Clinton	Sandy	21	39	2	62	1.78
Total		**603**	**934**	**39**	**1576**	

Table 6: Distribution and types of plastic debris along Lake St. Clair by sampling location [48].

Location	Beach type	Pellets	Fragments	Styrofoam	Intact or near-intact fragments	Total	Distribution (pieces/m^2)
Burke Park	Sandy	1	11	9	25	46	0.23
Harsen's1	Gravelly	0	5	2	11	18	0.32
Harsen's2	Sandy	0	6	3	6	15	0.18
Mitchell's Bay1a	Organics on concrete boat launch	0	8	16	13	37	0.62
Mitchell's Bay1b	Sandy park behind boat launch	1	14	0	9	24	0.34
Tremblay Beach	Sandy, organics	53	83	21	135	292	2.55
Puce Road	Sandy	0	7	40	6	53	0.79
Grosse Pointe	Muddy, organics	11	23	127	66	227	8.38
Metro Beach	Sandy	44	35	16	10	105	2.12
Total		**110**	**192**	**234**	**281**	**817**	

The ten beaches sampled along Lake Erie are classified as sandy and are all frequented by visitors. Of the total 1,576 pieces of plastic collected, 603 (39%) were pellets, 934 (59%) were **fragments**, and 39 (2%) were Styrofoam [48]. Most of the plastic collected around Lake Erie came from Presque Isle State Park near Erie, PA (33% of the total plastics) and Fairport Harbour near Cleveland, OH (20% of total plastics) [48]. This distribution pattern shows a decrease in abundance from potential input sources such as industrial clusters and heavily populated areas.

The nine sampling locations along Lake St. Clair yielded a total of 817 plastics, of which 234 (29%) were Styrofoam, 192 (24%) were **fragments**, 110 (13%) were pellets, and 281 (34%) were intact or near-intact **fragments** [48].

Lake St. Clair shorelines contains the least amount of plastic debris.

Lake St. Clair shorelines nonetheless contained the least amount of plastic debris, which is a function of the breakwaters and retaining walls built along Lake St. Clair to replace natural sandy or muddy sinks for floating polymers [48]. Figure 11 and Figure 12 show the relative abundance and distribution along Lake Erie and Lake St. Clair shorelines [48].

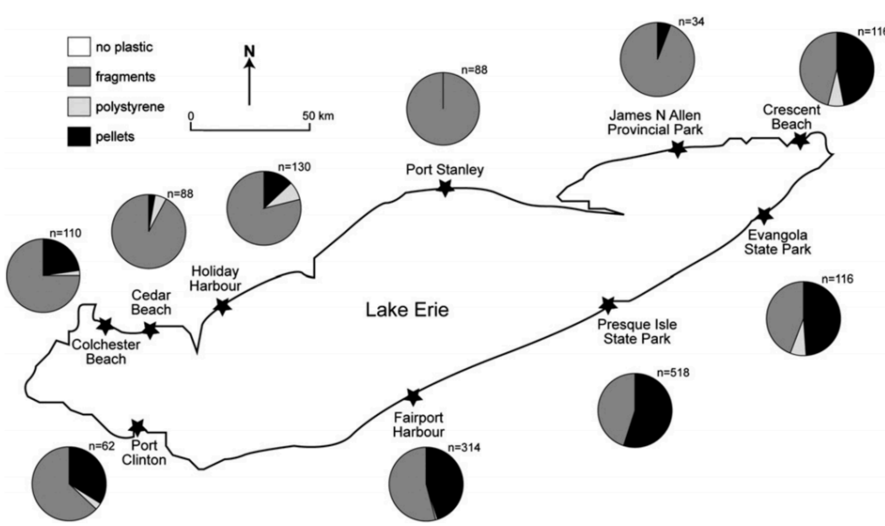

Figure 11: Abundance and distribution of plastic debris along Lake Erie shoreline [48].

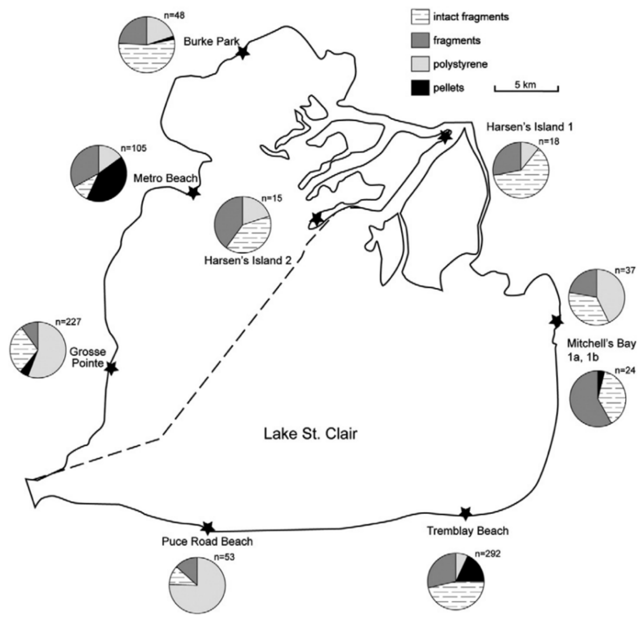

Figure 12: Abundance and distribution of plastic debris along Lake St. Clair shoreline [48].

2.1.4.3 Key Findings on Lake Erie

Although Lake Erie is the second smallest Great Lake, it has the highest concentration of plastics in its surface waters.

→ Concentration of plastics in its surface waters: 0.1055 plastic items/m^2 [56].

→ Proximity to large urban centers such as Detroit, Michigan and Erie and industrial activity such as coal burning, and petrochemical production are main sources for pollution [48].

→ Converging water currents in its east basin contribute to gathering plastics in high concentrations [1].

→ The most ubiquitous type of plastic found on the shorelines of Lake Erie and Lake St. Clair are **fragments** [48].

→ Only 3 research papers explicitly explore the shorelines and surface waters of Lake Erie.

2.1.5 Lake Ontario

Of all the Great Lakes, Lake Ontario is the smallest in surface area at 19,000 km^2 (10,000 km^2 in Canada) [69]. Lake Ontario receives most of its water supply from other Great Lakes through the Niagara River. It drains from the St. Lawrence River into the North Atlantic Ocean through a large drainage area of 64,000 km^2 [70].

The average flow influx is approximately 273 km^3/year, with peak levels occurring during the spring months due to snow melt and low evaporation rates. Several large urban and industrial centers, including both the cities of Toronto and Hamilton, are located along the western and northwestern shores of Lake Ontario respectively. These regions contain a large fraction of industry related to the production of materials like synthetic resins, fibers and rubbers. Due to the high populations and large amounts of industrial activity, it is expected that Lake Ontario has greater accumulations of microplastics, especially near and around the Greater Toronto Area [9].

> ***Due to industrial activities and high populations around the Greater Toronto Area, there are increased numbers of microplastics.***

2.1.5.1 Flow Patterns in Lake Ontario

Water currents travel in a counter-clockwise direction around Lake Ontario, due to the Coriolis Effect. As a result of this effect, wind from the north would move southward and right, resulting in flow along the west shore of Lake Ontario [71].

In Lake Ontario, the circulation is a combination of a large **cyclonic gyre** and a smaller **anticyclonic gyre** within the Western part of the lake [1, 71]. Though both **gyres** are present in the summer and winter months, it has been found that the two-**gyre** circulation seems to be more stable in the summer months. A visual of the annual current patterns in Lake Ontario can be seen in Figure 13 [1].

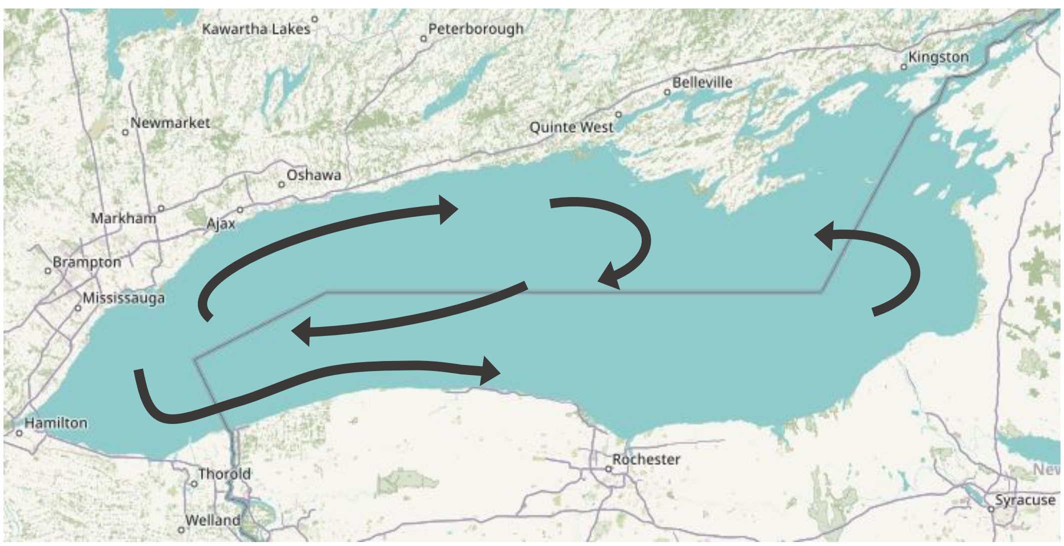

Figure 13: Water circulation patterns of Lake Ontario, adapted from Google Maps [72].

2.1.5.2 Experimental Methodology and Results

A study was conducted by Ballent & Corcoran at the University of Western Ontario in 2016, in which 50 sediment samples were collected from the **nearshore**, **tributaries**, and beaches along the Canadian shoreline of Lake Ontario. These samples were then processed using density isolation techniques to isolate the organic plastic matter form the inorganic sediment [9].

A total of 25 **nearshore** lake-bottom sediments were collected from 21 different areas. These samples were obtained using a sediment grab with a 400 cm^2 square opening, and a half cylindrical cup radius of 10 cm [73]. These traps were placed approximately 2 m above the lake bottom sediment [9]. Tributary sediments were collected from seven different sample locations with a handheld stainless-steel Petite Ponar sediment grab with dimensions of 16 cm x 14.5 cm [73, 9]. Beach sediments were collected from five beaches along the northwestern shore of Lake Ontario, between Burlington and Eastern Toronto. Collection of sediments was achieved through the use of a stainless-steel split spoon corer with a maximum depth of 30 cm, and an internal diameter of 5 cm. In this study, the sampling depth was limited to 20 cm due to the high-water content below that depth [9].

In total, 6,331 particles were identified as microplastics from the 50 sediment samples. This total amount was then converted to particles per kilogram of dry sediment for each sample site. A visual of this across the 50 selected sites can be seen in Figure 14 [9].

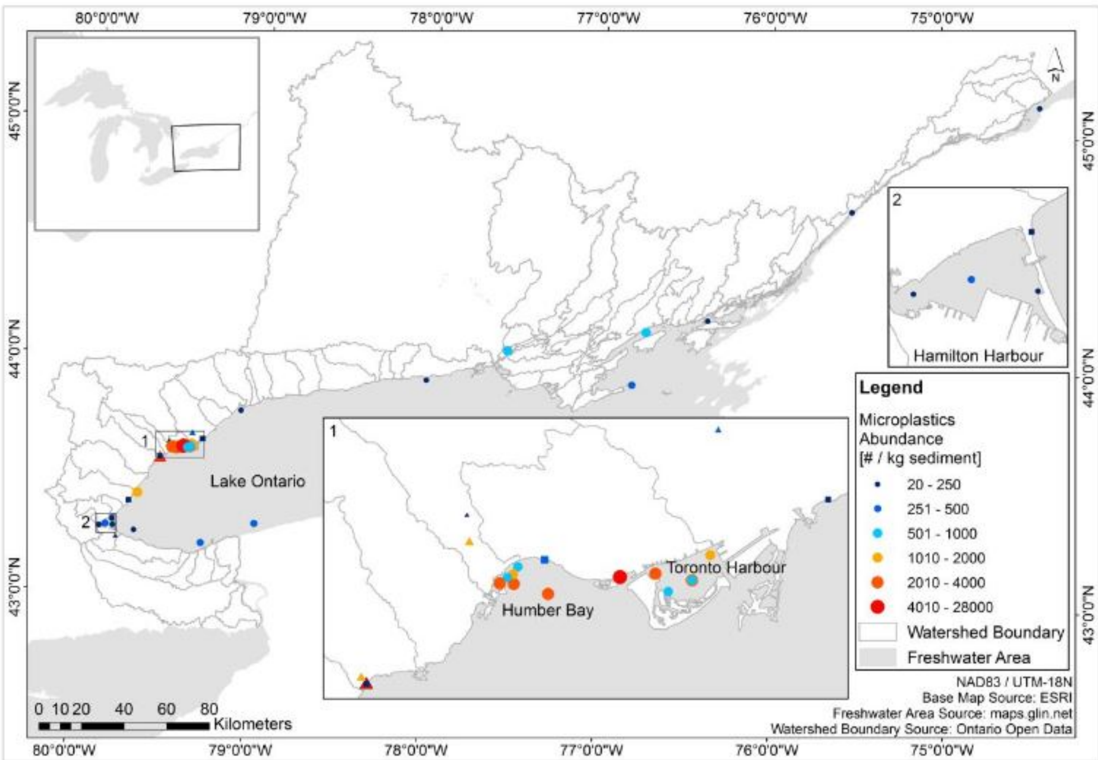

Figure 14: Microplastic abundance in particles/kg of sediment across the 50 sites surveyed [9].

From this study, the overall microplastic abundance was found to be approximately 700 particles/kg of sediment. The largest accumulation was found at the mouth of the Etobicoke Creek, with 800 microplastics found over an area of 232 cm^2. The **nearshore** sediments were found to have the highest levels of microplastics, with 980 particles/kg of sediment, followed by tributary sediments with 610 particles/kg of sediment, and then beach sediments with 140 particles/kg of sediment [9].

In the **nearshore** samples, most were concentrated in Humber Bay and Toronto Harbour, with concentrations of 1000 microplastics/kg of sediment being seen at sites within the Greater Toronto Area.

Looking at tributary sediments, microplastic abundance was found to vary greatly between individual sites depending on how far upstream or downstream the sample was taken. For example, in the sediments taken at the Humber River, downstream sites contained accumulations one to two orders of magnitude greater than upstream sites. As replicate samples were not taken for all sites, statistically significant differences could not be concluded across the different **tributaries** [9].

With regards to the beach sediment, microplastics were found to be most abundant in the top 10 cm of sand at Sunnyside beach. It was also noted that as the beach sites moved further away from Toronto, the total amount of microplastics decreased [9].

In the **nearshore** areas, the plastics were almost all less than 2 mm in size, with microplastics above 2 mm only being found in one **nearshore** site in Toronto Harbour. In comparison, larger microplastics ranging from 2 to 5.6 mm were more common in tributary and beach sediments, with approximately four percent and eight percent being in that size range respectively [9].

Microplastics were found to vary in colour, texture, size, shape and level of degradation. However, some microplastics were found to be more common across all sites than others. For example, fibers and **fragments** were the dominant plastic seen in sizes less than 2 mm at all collection sites. Microplastics were found to be most abundant in **nearshore** sediments, followed by beach collection sites, and then **tributaries** [9].

Fibers and fragments were the dominant type of plastic found.

Another study conducted by Corcoran et al was conducted in 2015, in which the Humber Bay region located along the northwest shoreline of Lake Ontario was studied. This location was chosen due to its proximity to the Greater Toronto Area, being geographically close to the drainage point of several **tributaries**, and due to a nearby wastewater treatment plant [74].

In this study, a 25 m x 4 m quadrant on the Humber Bay Park West Beach was surveyed for any visible plastic debris. Sampling was conducted over this area over the course of three weeks to determine accumulation rates. Within the beach location, any visible sediments were collected to a depth of 5 cm, which were then placed into one of four categories: industrial pellets, plastic **fragments**, intact/near intact debris, and expanded polystyrene [74].

Over 6,172 pieces of plastic debris were found at the Humber Bay Park West Beach over the course of the surveying period. A breakdown of the debris found per m^2 over the course of the three weeks can be found in Table 7 [74].

Table 7: Summary of plastic debris found at the Humber Bay Park West Beach per m^2 of surveying area [74].

	Week 1-2	Week 2-3
Pellets	21.2	8.8
Fragments	4.5	3.6
Intact Debris	0.8	1
Polystyrene (g)	1.7	1.3

2.1.5.3 Key Findings on Lake Ontario

Although Lake Ontario is the smallest of all of the Great Lakes, there were still large amounts of microplastic accumulation in its sediment [69].

→ The average concentration of plastics found was 700 particles per kg of sediment [9].

→ Proximity to large urban centers such as Toronto, were seen to correlate with an increase in the amount of microplastics found per kg of sediment [9].

→ Sediments found on beach samples were found to be most abundant within the top 10 cm [9].

→ Fibers and **fragments** were the dominant plastic particles found across **tributaries**, beaches and **nearshore** sites [9].

2.1.6 Conclusions

Overall, it was seen that **fragments** and fibers were the most common type of microplastic found for all studies conducted on all of the lakes

It was also found in many studies near large urban centers that pollution/the abundance of plastics found increased as the proximity to these areas increased

Each study was conducted with very different sampling methods and data was displayed in different units. For example, one study showed their findings on a plastic/m^2 basis, while another showed their data in terms of particles/kg of sediment. Additionally, samples were taken using a variety of tools across studies, from sediment grabs to using a trawl across a lake surface. This makes direct comparisons, as well as final conclusions about current pollution, challenging.

Focus also tended to concern microplastics and small plastic **fragments**. With larger macroplastics not being considered in a majority of these studies. As well, there has not yet been conclusive studies within the Great Lakes regarding the effects of plastic pollution on the aquatic flora and fauna, a conclusion supported by Dr. Sherri A. Mason, a Professor of Geology and Environmental Sciences at the State University of New York at Fredonia.

> "There is currently no true understanding of the impacts of smaller plastics throughout the gastrointestinal tract, or on reproductive ability, as microplastics may have a negative effect on sperm count. The biggest question surrounding plastic pollution currently is what the true effects are."
>
> – Dr. Sherri A. "Sam" Mason
>
> Sustainability Coordinator,
> Penn State Behrend

It is evident that though some research has been done surrounding plastic pollution within the Great Lakes, the quantity of research of some lakes significantly exceeds that of others. Existing research has been hindered by the lack of uniform sampling methodology. Further research is required before conclusive statements can be drawn regarding the volume of plastic pollution in each of the Laurentian Great Lakes.

The particle transport model developed by Hoffman & Hittinger has yeilded results that are inconsistent with other studies. For instance, the model predicted the lowest concentration of plastic particles in Lake Superior, the study by Eriksen et al. found Lake Huron to have the lowest abundance [58, 56].

These inconsistencies reveal a research gap identified by Hoffman & Hittinger. While most of the current knowledge comes from cleanup programs and several sampling studies, there is much work to be done. The Hoffman & Hittinger modelling study represents a first attempt at estimating total plastic input and transport throughout the Great Lakes system over a mulit-year period, the results of which can advise future sampling efforts [58]. The input and output of each lake in the model is illustrated in Figure 15.

Lake	Superior	Michigan	Huron	Erie	Ontario
Total input	4353	707,531	87,477	350,854	224,419
From Shore	4353	707,531	86,970	338,353	193,065
From Superior		0	264	0	0
From Michigan			243	1	0
From Huron				12,417	83
From Erie					31,271
Total leaving	264	243	12,537	31,362	2860
Pcnt. leaving	6%	0.03%	14%	9%	1.3%

Figure 15: Predicted input and output from each of the Great Lakes (in particles) [58].

Recommendation

→ Conduct further research and initiate long-term studies to determine the **impact of microplastics in sediments**.

→ Conduct further research on the **implications of plastics on the physiological systems** of biological organisms.

→ **Develop uniform sampling methodology** for use across all studies. Many researchers have called for this, and part of a UN working group is currently charged with harmonized data collection, as highlighted by Dr. Sherri Mason in her interview [51].

→ **Develop method of information sharing,** as suggested by Dr. Sherri Mason in her interview. For example, a worldwide database could be used for all researchers to upload data, and researchers can filter, and view data based on location, methodology, and other factors. This reduces duplication and ensures maximized utility of limited research resources.

→ Encourage additional research on state of **macroplastic pollution**, in addition to the current focus on microplastics. In recent years, minimal research has been conducted focused solely on the effects of macroplastics.

2.2 Sources of Plastic

There are many sources that may contribute to the abundance of plastics in the Great Lakes, including population, consumer goods, and industrial activity.

2.2.1 Population

The most polluted parts of the lake are those closest in proximity to cities that are heavily populated. For example, the cities around Lake Erie are heavily populated and its beaches are directly downstream from the cities of Detroit, MI, Cleveland, OH and Erie, PA, which might account for the consistently high counts obtained in each of the eight samples collected in the Eriksen et al. 2014 study. There are also high concentrations of plastic debris on the Lake Erie beaches that receive high numbers of visitors each year [48]. Similarly, on Lake Ontario, the largest amount of plastic in **nearshore** sediments was found to be at Toronto Harbour [9].

Litter can be unintentional, such as when winds blow plastic debris from industrial or heavily populated regions into nearby lakes [51].

> "The greatest contributor [to plastic pollution] is common society—people like you and me. Our waste does not always end up in landfills. Sometimes it ends up in water systems."
>
> – Dr. Patricia Semcesen
>
> PhD Student, University of Toronto Scarborough

Figure 16 shows the volume of industrial, commercial, and institutional non-hazardous waste disposed of between 2008 and 2016 [75]. It can be seen that as time has gone on, the amount of plastic being properly disposed of has decreased. This implies that there may be more waste entering the environment and waterways as litter.

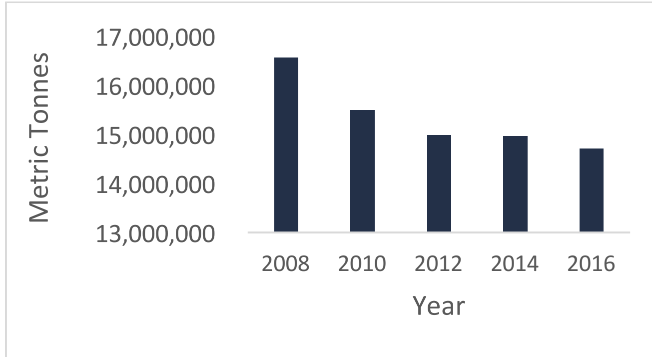

Figure 16: Industrial, Commercial, and Institutional (IC&I) waste from 2008 to 2016 [75].

2.2.2 Consumer Goods

Almost all consumer goods in the market will have plastic, be it in the actual product, the packaging, or the bag used to carry the purchase out of the store [51]. Most intact plastic waste found on the beaches of the Great Lakes comes from urban waste [48].

The study conducted by Driedger et al. in 2015 that reviewed plastic debris in the Laurentian Great Lakes noted that a major fraction of pellets found in the lakes in the Eriksen et al. study are most likely microbeads used as abrasive agents in a range of cosmetic products, including exfoliating creams, soaps, toothpastes, shampoos, lip gloss, eye liner, sunscreens, and deodorants [56]. Microbeads that are flushed down sink and shower drains enter the wastewater collection system [30].

Plastics are also ubiquitous in synthetic materials and clothing. From the manufacturing of fibers and clothing to washing these materials, microplastics are being released into the environment throughout the entire process [51]. With a single wash, one piece of synthetic clothing can release up to 700,000 fibers [76]. To further complicate the problem, these synthetic materials often are made of layers of different materials, making these materials difficult to recycle [51].

One piece of clothing made from synthetic material can release 700,000 plastic fibers in one washing cycle.

Currently, it is the standard for consumer products such as bags, straws, and pens to be made of plastic [51]. People's habits and mindsets are the driving forces behind the large-scale plastic production that eventually becomes litter [51].

Styrofoam is an additional material which is frequently found on beaches and in lakes. As discussed by Dr. Corcoran, his material has the potential to be eliminated from society through changes in legislation, which would lead to a significant decrease in plastic pollution within lakes and rivers caused by human activity [77].

"The amount of Styrofoam in the Great Lakes system has decreased. This is a product which could easily be eliminated and would result in a significant decrease in macroplastic pollution."

– Dr. Patricia Corcoran

Associate Professor & Chair of the Department of Earth Sciences, University of Western Ontario

Recommendation

→ **Develop awareness programs** to educate the consumer on recycling, proper disposal, alternative materials to plastic, and opportunities for product reuse and reduction. Everyday items such as clothing, cosmetics, and utensils are made of plastic, but many of these have viable alternatives. Industrial activity is driven by consumer demand, so large-scale change must start with the consumer. As Dr. Sherri Mason discussed in her interview, tackling consumers is a great way to push industry. As people change their mindsets, they will demand changes from industry. Similarly, as Anika Ballent, master's student in geology, says, it should not be "I'm an environmentalist"; it should be "I'm a politician, engineer, businessperson, and I care about the environment".

→ Create legislation to gradually **phase out the use of Styrofoam** by consumers and industry.

→ **Reduce the number of types of plastics manufactured** in synthetic materials. As Dr. Sherri Mason discussed in her interview, a major factor of an item's recyclability is the amount of different types of plastics in that product.

→ **Alter the shape of conventional recycling bins** used by municipalities to eliminate unintentional littering caused by winds and weather.

→ **Develop filtration device for washing machines** to eliminate effluent fibers from entering the wastewater system, because with a single wash, over 700,000 fibers can be released.

Recycling – Not the Solution

Though recycling is thought by many to be an easy way to prevent pollution from reaching the environment, recycling cannot mitigate the complete issue of plastic pollution. It has been estimated that of the 8.3 billion metric tonnes of plastic that have been produced globally, 6.3 billion have become plastic waste, with only nine percent of this waste being recycled [78]. The remaining 91% of this waste either accumulates in landfills, or enters the environment as litter, often ending up in the oceans [78]. Within Canada, it is currently estimated that approximately 11% of the plastic used is recycled, leaving the rest to end up as possible environmental pollutants [79]. In 2010, Canada released about 8,000 tonnes of plastic into waterways [79]. In the United States, the recycling figure for plastic is similar, with approximately nine percent, or 3.1 million tonnes of plastic being recycled in 2015 [80], while 26 million tonnes of plastic was sent to landfills [80].

Though recycling is helpful in preventing further pollution, there is currently too much plastic sent into the environment for recycling alone to be considered a viable option [81]. Though recycled plastics can be used to create new products and reuse existing ones, there is a finite number of opportunities for plastic to be reused. This is because as plastics are recycled, their **polymer** chains grow shorter and shorter, decreasing the quality of the product [82]. Therefore, the average plastic product can be recycled between 7-9 times, after which they are discarded as waste [83]. Many times, plastic is also discarded as waste if it has been contaminated with food, or if it has multiple types of different plastics [82]. For example, many coffee cups contain both paper and a thin layer of plastic. As these layers are usually very thin and tightly placed together, it is usually not cost-effective to separate them, and they are thrown out as waste [82].

> "A lot of times there will be layers of different types of plastics in a product – not just one material, making it hard to recycle."
>
> - Dr. Sherri A. "Sam" Mason
>
> Sustainability Coordinator, Penn State Behrend

The Economics of Recycling

Promoted as the answer to humanity's environmental crisis when it was first introduced in the 1980s, recycling is now a $200B global industry that is susceptible to fluctuations in the economy, like any other business [84].

Plastic is a petroleum product, and thus is impacted by the price of oil. If oil prices are low, it is more economical to make new plastic than to recycle. This is especially true for products, such as plastic bags, that have to be cleaned many times before being processed [85, 86]. For example, Waste Management, the largest recycler in the United States, has stopped recycling plastic bags as it is no longer economically viable to do so [85]. Higher quality plastics, such as those that come from products like detergent bottles, can still be sold for higher prices and thus recycled, but these are still depressed when oil prices decrease [85].

Foreign currency exchange rates also greatly affect the profitability of recyclers, since historically 60% of G7 countries' plastic waste was exported to China and Hong Kong [84].

China introduced the "Green Fence" policy in 2013, followed by the "National Sword" policy in 2017, both of which drastically tightened regulations on recycling [84]. These policies saw China refusing to take the world's scrap, as it had become a net deficit to the country. As a result, many recyclers worldwide have gone bankrupt [84].

As China refused to become the world's "dumping grounds", most plastic waste was redirected to Southeast Asia. However, within a few years, countries like Vietnam also declared that they would not "become the landfill of the world" [84]. This has forced developed countries to invest in their own recycling capacity, but for now, as many recyclers are still reeling from Asia's refusal to accept plastic scrap, recycling has become constrained and limited.

The economics of recycling play a crucial role in whether or not plastic items are actually recycled. Thus, even though recycling is a beneficial process, it is only a temporary fix for the long-term problem of overproduction of plastic.

Recommendation

→ **Place tax on plastic production** to ensure recycling remains economically viable, similar to a carbon tax in which significant producers have larger associated tax expenses.

2.2.3 Industrial Activity

The relationship between industry and consumers is tightly intertwined, since consumers are the ones who drive the demand for products, and industrial activity is one of the largest sources of plastic pollution in the Great Lakes. It is said that for every one bin of garbage that a consumer produces, industry will have produced seven bins [51].

The areas of lakes that are in close proximity to industrial activity show higher concentrations of plastic pollution. Lake Huron lies in the center of a major shipping route, as it divides the Great Lakes system into upper and lower Great Lakes [12]. The proximity to this major shipping route, in combination with heavy industrial activity along the southeastern shore of Lake Huron, increases the potential for buildup of plastic material throughout the lake [12]. Furthermore, Lake Erie is in close proximity to several coal-burning power plants as well as petrochemical plants that produce plastic resin pellets [48]. The highly industrialized area along the eastern shore of the St. Clair River is known as "Chemical Valley" [48].

In industry, the largest polluter is spillage within factories or during transport and offloading of pre-production plastic pellets, also known as nurdles

[48, 51]. Plastic pellets are small pieces of plastic that are transported from oil refineries to factories. Every step of the transportation process, be it at rail car, truck, holding tank, or final processing equipment, results in nurdles are release [51]. Figure 17 shows the accumulation of nurdles on the shores of Lake Superior, captured in Nipigon by CBC Thunder Bay [87].

Figure 17: Nurdle spill on the shores of Lake Superior [87].

In the 1990s, a train carrying nurdles was derailed and millions of pellets were released. Almost three decades later, these pellets are still in the surface waters and shorelines of Lake Superior.

Recommendation

→ **Review method of transportation for nurdles** and plastic to decrease volume of spilled particles which enter the environment and create method of direct transfer for pellets between transportation points to eliminate potential spillage points.

2.2.4 Municipal Wastewater Treatment Plants

Wastewater treatment plant (WWTP) influent can have 10^4 to 10^5 microplastics/m^3, meaning insufficient removal can lead to microplastic pollution in effluent water streams [88]. Studies finding elevated levels of microplastics in rivers containing effluent of WWTPs confirm that treated sewage is a source of microplastics in the water system [89]. At different WWTPs, there is a range of variation in type and volume of microplastics, largely due to inconsistent sampling techniques [88]. While some WWTPs may remove the majority of microplastic particles, such as the 99% retention rate found in the WWTP servicing 1.3 million Vancouver residents, 30 billion ± one billion particles were still released in the effluent annually [90].

While only 1% of microplastics remain in the WWTP effluent, 30 billion particles are still released annually.

In the Vancouver region, two wastewater treatment plants were observed, at Lion's Gate, and Annacis Island. Based on 2017 quality control reports, the total suspended solids released daily from these plants were 14,500 kg/day and 20,000 kg/day respectively [91]. The assumption has been made that 1% of these solids released were microplastics, due to the 99% efficiency in which treatment plants can remove plastic waste [90]. Under this assumption, it was determined that these plants released approximately 53,000 and 73,000 kg of plastics each year, respectively, within their effluent.

A similar calculation was done with Toronto wastewater treatment plants- specifically the Highland Creek wastewater facility. With suspended solids being released in their effluent at a rate of approximately 2,406 kg/day, it was determined that this plant would release around 8,800 kg of particles per year [92]. It should be noted that the true percentage of microplastic in wastewater effluent is not currently reported on, and many of these plants do not operate at a 99% retention rate.

Suspected microplastics, including fibers, were categorized using **Fourier Transform Infrared Spectroscopy**. It was determined that 32.4% of suspected microplastics were plastic polymers [90]. The breakdown of textiles and larger plastics are both key contributing factors of microplastic a pollution, as indicated by the presence of fibers, **fragments**, and flakes at multiple WWTPs [89].

In a 2016 study conducted upstream and downstream of four major municipal WWTPs in New Jersey by Estahbanati and Fahrenfeld, microplastics as small as 125 µm were collected and classified as primary and secondary. Microplastics of this size were found in high abundance yet are often not quantified in studies [88]. Concentrations of microplastics classified within 125–250 µm and 250–500 µm size categories significantly increased downstream of the WWTP in New Jersey. Secondary microplastics were also more abundant. 500 µm microbeads, which have been the focus of microplastic attention, were found to have low concentrations compared to other microplastic types [88]. Microplastics were also present upstream of the WWTPs, confirming there are other sources of microplastics, and not solely WWTP influent [88].

Microplastics were found to settle predominantly in primary sludge, with some settling in secondary sludge [90]. Sewage sludge is used in agriculture, meaning microplastic contamination may compromise agricultural land [89].

Recommendation

→ **Increase tertiary filtration methods in wastewater treatment plants** to further remove microplastics from the water and improve clarity of effluent stream entering the environment.

2.2.5 Conclusion

It is evident that plastic can enter the Great Lakes environment through a variety of sources, including through increased population, consumer activities, industrial activity, and wastewater treatment systems. Many changes are required, both to daily consumer activity and plastic use, and to industrial transportation methods and disposal practices, in order to decrease the current volume of plastics entering the Great Lakes watershed. These proposed recommendations include, but are not limited to, increasing consumer education on daily plastic use, recycling methods, alternative materials and reuse methods; decreasing the number of plastic types manufactured to ease the recycling and disposal process; creating additional filtration on washing machines and within wastewater treatment plants; and adjusting plastic transportation methods to eliminate waste created from spillage. Significant adjustments will be required in order to alter and remediate the current state of plastic pollution within the Great Lakes.

CHAPTER 3

IMPACTS OF OCEANIC PLASTIC POLLUTION

Lake Huron | Photo Credit: Destination Northern Ontario Magazine

3.0 Introduction

The impacts of plastic pollution in the Great Lakes are yet to be defined, but by looking at the impact that plastic has had on the oceans, parallels can be drawn. Plastics within the marine environment are a major concern due to their persistence at sea, and their adverse consequences to marine life and potentially human health [93]. It is known that plastic in the marine environment is primarily derived from two sources: garbage dumped by ships at sea, and land-based sources such as runoff from rivers, recreational litter left on beaches, and wind-blown litter [94]. Though research has only recently begun on pollution in the Laurentian Great Lakes, pollution within the oceans has been an area of concern for decades, with reports discussing the presence of small plastic particles as early as the 1970s [95, 96].

> ***Though oceanic environments differ significantly from freshwater environments, many parallels may be drawn between the two regarding the impact of plastic on marine life and ecosystems, as well as potential methods of remediation.***

Evidence suggests that freshwater systems, such as the Great Lakes, may share similarities to oceanic systems in types of forces which transport microplastics, as well as the prevalence of microplastics, the approaches used for detention and identification, and the potential impacts of this pollution [66].

3.1 Plastic Accumulation in Oceanic Environments

Plastics are lightweight and incredibly durable, which make them an extremely useful material for humans. However, these characteristics are what make the material so detrimental to the environment. Around 60% of plastics produced is less dense than seawater [97]. As a result, these plastics can be readily transported for long distances from their source region, and frequently accumulate in sinks, such as oceans [94]. The proportion of plastic among litter increases with distance from source because they transport more easily than dense materials such as glass or metal [52]. Floating plastic has become a global issue because it is carried across entire ocean basins and can contaminate even the most remote regions [52].

A large portion of buoyant plastics enters oceanic **gyres**, which refers to regions of large sustained, rotating currents which often contain a large buildup of plastics [98]. There are five major **gyres** throughout the globe, as seen in Figure 18. These

Figure 18: Garbage accumulation throughout the world's oceans [98].

gyres are labelled in the diagram as denoted in Table 8.

Table 8: Location of plastic accumulation.

Number in Figure 18	Gyre Name
1	North Pacific
2	Indian
3	South Pacific
4	South Atlantic
5	North Atlantic

Significant research has been conducted on all **gyres**, including the Great Pacific Garbage Patch, which is the largest of the five offshore zones of plastic accumulations, and is located in the North Pacific Ocean between Hawaii and California [99, 100]. This oceanic region has been predicted to contain between 45 and 129 thousand tonnes of ocean plastic within an area of 1.6 million km^2 [99]. Many studies have been conducted on this region in an attempt to determine the size, quantity, and potential impacts of plastics in the water. Most data has been obtained using small sea surface trawls initially developed to collect neustonic plankton, and, as a result of their small aperture of 0.5 to 1 meter width and 0.15 to 1 meter depth, could underestimate loads of larger plastic objects obtained over the tested surface area [99]. In many studies, to overcome this numerical misrepresentation, the data obtained through surface sampling has been contained with visual sighting surveys and geo-referenced imagery, such as in the major study conducted by the Ocean Cleanup Foundation [99].

3.2 Impact of Plastics on Marine Life

Plastic debris in marine environments is known to be extremely harmful to marine organisms living in these ecosystems [101]. Marine debris is listed among the major potential threats for oceanic biodiversity and is of major concern due to its abundance and durability within the marine environment [102, 103]. Despite attempts to remove debris, as well as increasing restrictions on dumping into the marine environment, plastic quantities continue to increase in some regions [102]. A literature review conducted by Gall and Thompson searched 340 original publications and determined that at least 690 species have been impacted by marine debris in some manner. 76.5% of all reports listed plastic among the debris, making it the most commonly reported type of debris [102].

3.2.1 Entanglement

Plastic can be detrimental to marine life as a result of entanglement [102]. The literature review conducted by Gall and Thompson determined that all known species of sea turtles, 54% of all marine mammal species, and 56% of all seabirds were impacted by entanglement or ingestion of marine debris [102]. Species most heavily affected by entanglement include turtles, penguins, albatrosses, petrels and shearwaters, gulls and auks, baleen whales, toothed whales and dolphins, earless or true seals, sea lions, fur seals, manatees and dugong, sea otters, fish, and crustaceans [104]. Over the past 50 years, natural materials for fishing and other marine activities have been replaced by stronger and more durable synthetic plastic materials [104]. Many marine animals can easily become entangled in this netting, rope, and monofilament lines sourced from discards and losses from commercial fishing activities. Many animals, once entangled, find it difficult to escape the plastic netting, which results in drowning or serious injury, starvation, or general debilitation [104]. Other physical debilitations resulting from entanglement include, but are not limited to, suppurating skin lesions, ulcerating body wounds, interruption of feeding activity, and failed predatory avoidance [105].

Figure 19: Red-eared slider turtle permanently deformed by plastic ring [106].

3.2.2 Ingestion

Ingestion is an additional means by which plastic pollution may cause harm to marine organisms. Ingestion can have a wide variety of impacts on organisms, including, but not limited to, choking, internal and external wounds, ulcerating sores, internal blockages, reduction in quality of life and reproductive capacity, drowning, and the possibility that plastic resin pellets may adsorb and concentrate potentially damaging compounds from sea water [65].

> ***Ingestion of plastic has a wide variety of harmful health impacts on marine organisms.***

When anthropogenic litter enters aquatic habitats, it becomes rapidly colonized by microbial biofilms composed of bacteria, fungi, and algae within an extracellular matrix [63]. Numerous studies have been conducted on a variety of organisms to study the impact of ingested plastic particles on internal organ systems. For example, a study done in 1990 on 1,033 birds off the coast of North Carolina determined that 55% of the tested species had plastic particles in their guts, as seen in Figure 20 [107], while a study conducted on the impact of polythene bags on sea turtles found that the organisms ingested them due to their similar appearance to their prey, and listed 79 cases of turtles whose guts were full of various forms of plastic debris [108].

Figure 20: An albatross with significant plastic accumulation [109].

At least 26 species of cetaceans, including a pygmy sperm whale found in Texas, USA, and an endangered West Indian manatee, have been documented to contain plastic debris which has resulted in the demise of the organism [110]. Though the impacts of toxins adsorbed by small plastic pellets that leach into organisms remains relatively unknown, it is known that ingestion is a harmful effect of plastic pollution, and poses a severe threat to existing marine organisms, both in oceanic and freshwater environments.

3.2.3 Bioaccumulation

Numerous reports have speculated that microplastics in marine environments may have negative impacts on marine life and may result in an increased bioaccumulation of persistent organic pollutants within the organisms [111, 112].

Microplastics present within aquatic environments can be ingested by a variety of organisms, including species commonly used in the human diet [111, 113]. In a study conducted by Besseling et al., the effect of polystyrene microplastic were assessed in bioassays with *Arenicola marina (L.)*. It was determined that a low dose of polystyrene increased bioaccumulation of polychlorinated biphenyls [111]. In another study conducted by Barboza et al., toxicological interactions between microplastics and mercury were found, and it was determined that microplastics and mercury caused neurotoxicity, oxidative damage, and changed energetic enzymes of *Dicentrarchus labrax* [112].

It is believed that microplastics may adsorb harmful chemicals introduced into organisms when microplastics are taken up, which may lead to increased accumulation of these substances within food webs [44]. Further studies are required to conclusively state the impact of microplastics on bioaccumulation within organisms, however.

3.3 Conclusion

Significant research has been conducted throughout the world's oceans focusing on plastic pollution and the impacts of plastic on marine environments. Through significant research, it has been found that plastic pollution can result in serious negative impacts to wildlife due to hazards posed by plastic, including entanglement, ingestion, and bioaccumulation within the organism. It is evident that this material, and its accumulation in marine environments, must become a primary focus within society to remediate the pollution caused by humans and decrease its negative impacts on marine species. As discussed by geologist Anika Ballent, it is crucial that all people become educated and aware of the current state of pollution in all water systems, including both oceans and fresh water, in order to create change and reduce the volume of plastic entering these systems [114].

> "It should not be, 'I am an environmentalist.' It should be, 'I am a [career title] and I care about the environment'. We are all environmentalists."
>
> – Anika M. Ballent
>
> MSc Geology, Western University

Though the impacts of plastic pollution on species within the Great Lakes have yet to be identified, it is thought that correlations exist between the impacts of plastics on oceanic species and freshwater species [66]. Further research is required, however, to conclusively determine that this relationship between freshwater and marine environments exists.

Recommendation

→ **Increase education and awareness** of the environmental implications of plastics.

→ Increase funding to **conduct studies on the impact of microplastics on bioaccumulation** within aquatic organisms.

CHAPTER 4

REMEDIATION STRATEGIES

Lake Erie | Photo Credit: Richard Cummins / Getty Images

4.0 Introduction

Remediation initiatives have begun in the oceans as people have realized the impact that plastic has on the immediate ecosystems and food chains. While there has been a major focus on marine pollution, some action has been taken to help clean the Great Lakes, such as by the U.S. Alliance for the Great Lakes, who led the banning of cosmetic microbeads and runs an adopt-a-beach program that has 15,000 volunteers pick up over 18 tons of trash from Great Lake beaches, of which over 85% are plastics [115].

Technology that has been developed and research that has been done for marine plastic pollution should be explored for use in the Great Lakes system.

Recommendation

→ Implement **mandated cleanup periods** and hire government positions which focus on beach and freshwater cleanup.

4.1 Microplastic Filtration in Wastewater

Generally speaking, all wastewater treatment plants (WWTP) have similar processes and methods of removing pollutants and organisms from sewage.

The first stage of wastewater treatment is known as preliminary treatment. Before water enters the treatment plant, the incoming wastewater, or influent passes through screens consisting of metal bars spaced 1-3 inches apart [116]. This screening is meant to remove large floating objects such as sticks or rocks, that may damage equipment or pipes during later treatment steps [117]

Once this initial phase has been completed, the influent moves into primary treatment. This phase, also known as physical treatment is meant to remove fine particulates from the water that were not able to be removed from screening alone [116, 117]. Influent is pumped into settling or sedimentation tanks and left to sit for one to two hours. This allows heavier solids to sink to the bottom, while the lighter materials will float to the top. The lighter materials can then be skimmed from the surface, while the settled solids, called primary sludge, are pumped into de-gritters, which use centrifugal force to separate sand and gravel from the water. The partially-treated water left inside the settling tanks can then move into the next phase of treatment [117].

Following primary treatment comes secondary or biological treatment. This phase is very important and can remove approximately 85% of organic matter from sewage. After the wastewater leaves the sedimentation tank, it is pumped through an aeration tank and into an activated sludge process. In this process, the effluent is mixed with air, bacteria filled sludge and left to sit. During this time, the bacteria in the sludge break down any organic matter in the effluent into harmless by-products. Following this, the treated sewage is sent to another sedimentation tank to remove any excess bacteria [117].

The last phase is known as tertiary or chemical treatment. Even after primary and secondary processes, there may still be dangerous organisms remaining in the treated water. Therefore, nutrients such as phosphorus and nitrogen are removed, and the effluent is disinfected with various chemicals [118]. The wastewater is treated primarily with chlorine and UV, after which the effluent can be released back into local waterways [116, 119].

Though most microplastics found in wastewater are removed before it becomes effluent, with some plants being able to remove 99% of microplastics, it is important to note that WWTP can be large sources of pollution [120]. In a study conducted by Kay et al., river catchments located downstream of six WWTP were analyzed to determine if microplastics were present [89]. It was found that all catchments had some form of microplastic, with fibres, **fragments** and flakes being the most common plastic seen [89].

> ***WWTPs can be a large source of pollution.***

This illustrates that even WWTP with high plastic removal percentages, can still contribute to plastic pollution, and are not fully equipped to handling the problem.

4.2 Biodegradation

Bioremediation occurs when microorganisms are able to degrade and transform pollutants such as hydrocarbons, oil, heavy metals, or plastics [121].[3] **Biodegradation** of plastics occurs when microorganisms use a synthetic **polymer** as the primary source of carbon and energy, resulting in the **polymer** being metabolized and transformed to a different chemical structure [122, 121]. **Bioremediation** can be successful in degrading, removing, and detoxifying chemical and physical waste using bacteria, fungi and plants. Efficiency of **bioremediation** depends on nutrients available, environmental conditions such as temperature and pH, and **bioavailability** of the contaminant [121].

Biodegradation is beneficial as it can lead to complete destruction of pollutants. Further, dangerous chemicals are not used, and it is typically nonintrusive and sustainable. However, **biodegradation** can lead to byproducts that are more toxic than the original pollutant. It is very specific, it often requires a longer time frame than other remediation methods, and it is difficult to scale from bench-scale to full-scale field operations [121].

Microbial degradation of plastic is an eco-friendly and promising plastic waste management strategy. There is significant potential due to recent discovery of plastic-degrading organisms for natural cleaning of plastic waste in oceans [122]. Further research should be done to determine if **biodegradation** is feasible in the freshwater eco-systems of the Great Lakes.

4.2.1 Potential Bioremediation in Marine Environments

Marine bacteria are used to adverse environments and can adapt well, making them good candidates for **bioremediation**. Similar principles may be applied in freshwater environments such as the Great Lakes. In **in vitro** testing for potential **viable** marine organisms, *Rhodococcus ruber* degrades eight percent of dry weight of plastic in 30 days in concentrated liquid culture. In one-month,

[3] The terms bioremediation and biodegradation are considered interchangeable. Bioremediation applies to multiple strategies, including but not limited to, bioaugmentation (addition of additional microbes), biostimulation (addition of required nutrients to promote remediation from naturally occurring organisms), and bioattenuation (natural eradication of pollutants). Each method has advantages and disadvantages depending on the environment and the contaminant present [121].

bacterial species *Micrococcus*, *Moraxella*, *Pseudomonas*, *Streptococcus*, and *Staphylococcus* were also found to degrade 20% of plastic [123].

4.2.2 Additional Potential for Biodegradation

Additionally, bacterial strains of *Bacillus* and *Enterobacter asburiae* with the capacity to degrade PE were isolated in *Plodia interpunctella* guts (waxworms or Indian moth). *Exiguobacterium* with the capacity to degrade PS were isolated in insect larvae of *Tenebrio molitor* guts (mealworms). PS foam is completely mineralized in mealworm guts within 12–24 hours [124].

Multiple studies have reviewed the microbial degradation of different plastics. The results presented by Caruso (2015), stating various microbes that have shown **biodegradation** capabilities, are summarized in Figure 21. Generally, polyhydroxyalkanoates (polyhydroxybutyrate PHB), and PLA are very biodegradable, however, synthetic polymers such as PE, PCL, and PS have low biodegradability capacity [122].

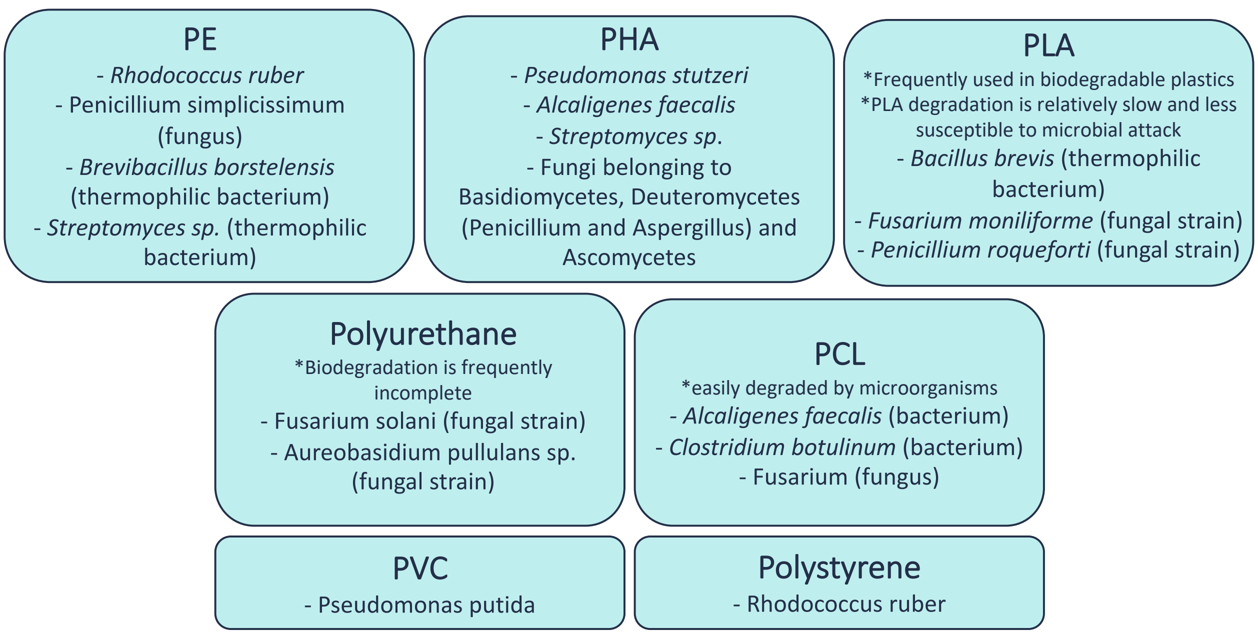

Figure 21: Summary of microbial degradation of different plastics [122].

Recommendation

→ **Continue to study potential organisms** for **bioremediation** in the Great Lakes system.

→ **Determine feasible methods of implementing bioremediation** within the Great Lakes system.

4.3 Innovative Plastic Detection and Ocean Cleanup Initiatives

Multiple entrepreneurial initiatives have been started to help combat plastic pollution in the oceans and have the potential for use in the Great Lakes. The following information in Section 4.3 is from press releases and news articles and has not been published in peer reviewed journals.

4.3.1 The Seabin Project

The Seabin is a floating debris interception device that is used in ports and marinas. The Seabin was conceptualized in 2014 and was available for presale in 2017, making it a very new technology. The Seabin moves with the tide and draws in surface water, catching debris in a filter bag. The unit can displace 25,000 litres of water a day. The Seabin can trap both macroplastics and microplastics. Capabilities of the Seabin technology are outlined in Figure 22.

Figure 22: Plastic catching capabilities of the Seabin.

The Seabin is 50 cm by 50 cm and can hold 20 kg. The daily running cost is approximately one USD and is estimated to catch 1.5 kg of litter per day. The bin must be plugged in, hence the requirement of being in a port or harbour. The vessel requires power of 500 W [125].

4.3.2 Microplastic Removing Rover

As part of the 2018 Discovery Education 3M Young Scientists Challenge, a 12-year-old from Massachusetts, USA has developed a plastic detection rover. The rover has a navigation system with motors and propellers, as well as an identification system that uses infrared LEDs. The rover analyzes different wavelengths from the infrared LEDs and an infrared camera to identify and analyze the plastic present [126].

4.3.3 The Ocean Cleanup

The Ocean Cleanup is an initiative that aims to cleanup 90% of the Great Pacific Garbage Patch by 2040 [127].

> ***By 2040, The Ocean Cleanup has a goal of removing 90% of the Great Pacific Garbage Patch.***

The Ocean Cleanup project designed a 600 m floating device with a three-metre deep skirt. The floating device moves with the ocean current along with the plastic debris. As the floatation device sits slightly above the water surface, the device moves faster than the plastic, ultimately allowing it to be captured. The system is autonomous, energy neutral and scalable as improvements are available [127].

4.3.4 4Ocean

4Ocean is an organization that sells bracelets made of recycled materials to fund ocean cleanup. Each bracelet provides funding for one pound of garbage removal from the ocean and coastlines.

> ***Through bracelet sales, 4Ocean has funded the removal of 4,031,045 pounds of garbage.***

To date, the initiative has removed 4,031,045 pounds of garbage from the oceans and shorelines in under two years. 4Ocean employs over 150 people worldwide [128].

4.4 Conclusion

There are promising remediation tools available for the cleanup of plastic pollution. While WWTPs play a critical role in removing plastic particles from wastewater, they are not equipped to resolve the issue of plastic pollution in the Great Lakes. The remediation of plastic pollution in the Great Lakes demands a comprehensive approach that makes best use of all available measures.

Remediation efforts should combine natural and manmade processes. **Biodegradation** provides an attractive avenue for degrading, removing, and detoxifying waste particles with microorganisms in the oceans. Further research efforts should focus on identifying microorganisms that maximize remediation potential while minimizing harmful byproducts in freshwater environments. Additionally, the entrepreneurial solutions provided in this chapter demonstrate the potential for private sector initiatives to produce creative solutions, and innovation will undoubtedly play an increasingly important role in remediation efforts moving forward.

Recommendation

→ Increase **incentives which encourage alternative materials** to plastics, and that decrease consumer demand for plastics.

CHAPTER 5

BUSINESS AND SOCIAL RESPONSE

Lake Ontario | Photo Credit: Darby Brown

5.0 Introduction

As seen from the creation of the Charlevoix Blueprint, many G7 nations are beginning to realize the importance of reducing plastic pollution in the environment [129]. However, it is not enough to just reduce plastic pollution in today's society. As stated by Dr. Michael Twiss, Professor at Clarkson University, education and awareness of current regulations and consumer actions are crucial to address the issue [130].

> "There are significant existing regulations on pollution, both at state and provincial levels, as well as international agreements on pollution. The construct already exists to protect the waters; the next step is to increase education on consumer actions."
>
> – Dr. Michael Twiss
>
> Professor, Clarkson University Department of Biology

Many nations in turn, have created education programs to help inform the public of the growing plastic problem. Within Canada, environmental agencies have joined with advocacy groups such as the Ocean School, Ocean Wise, Sea Smart, Student on Ice and WE to create a new learning module for Canadian schools [131]. Known as the Ocean Plastics Education Kit, it provides a curriculum on plastic pollution from elementary to high school, and includes student workbooks, teacher unit plans, as well as additional study resources if people wish to find more information [132].

With these new resources, consumers have begun to demand that their products are made sustainably. Many businesses have begun to implement initiatives that aim to reduce the use of plastics in consumer products, and these have resulted in strong financial and corporate social responsibility outcomes.

5.1 Hygiene and Cosmetic Products

Sanitary napkins, tampons, makeup and other cosmetics contain microplastics that end up in marine environments [133]. The average consumer will use 10,000 to 12,000 disposable menstrual products in their lifetime [134]. The production of sanitary pads involves oil extraction, processing and production of low-density polyethylene (LDPE), and every pad takes from 500 to 800 years to biodegrade [135, 136]. Although tampons do not contain plastic in the actual product, 88% of the estimated $1.1 B worth of tampons sold in 2015 came with plastic applicators [135]. During a 2014 cleanup of 70 beaches, Cindy Zipf, executive director of New Jersey-based marine protection coalition Clean Ocean Action, reported over 3,000 plastic tampon applicators [137]. Cosmetic products like face wash, make up, cotton buds, and even makeup remover wipes all contain plastic [133]. In recent years, consumers have been demanding more sustainable alternatives to these plastic-dependent products [135].

5.1.1 Menstrual Underwear

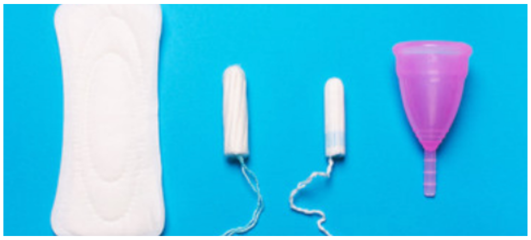

Figure 23: Various menstrual products.

Menstrual underwear has greatly reduced the environmental impact of the menstruation industry [135]. Companies like Knix and Thinx make fast-drying cotton underwear with built-in leak-resistant liners that can absorb up to 15 mL of liquid, the equivalent of 2 tampons' worth of blood. This eliminates the need for panty liners, and even pads and tampons entirely [135, 138].

5.1.2 Menstrual Cups

Figure 24: Menstrual cups are a sustainable replacement for tampons and sanitary napkins.

Menstrual cups have been around since 1932, but their use has only recently become more mainstream [135, 139]. These are typically bell-shaped silicone cups that sit in the vaginal canal and collect blood. They can be used for up to 10 years, and once they are discarded, the silicone can be easily recycled [140].

5.1.3 Refillable Makeup

Figure 25: Refillable makeup containers can be filled with new product without the packaging waste.

Many makeup products now come in metal packaging that is meant to be reused. Refills can be purchased to cut down on overall waste. Instead of merely recycling, makeup brands are now also encouraging consumers to reduce by providing discounts when customers bring back a certain number of reusable containers [141].

5.1.4 Outcomes

Innovative companies have shown that profit and sustainability do not have to be mutually exclusive. Joanna Griffiths, graduate of Queen's University and founder of Knix, has raised $1.6M CAD in one round of funding, when others have taken much longer to achieve the same [142]. The global market for menstrual cups is expected to reach $1.4B USD by 2023, further validating that investors and consumers alike are interested in and demand sustainable hygiene products [143]. Makeup brands such as Kjaer Weis are pioneering the movement for zero-waste products, and they are extremely well received by customers and garner large amounts of public recognition and approval [144]. The year-on-year growth in organic beauty is increasing at 8-10% annually and the natural beauty industry is projected to reach $22B USD by 2024, soon to make up more than 5% of the total $445B USD beauty industry [145]

Conservation of Nature calculates that 35% of marine microplastic pollution comes from synthetic textiles [146]. Europe and Central Asia dump the equivalent of 54 plastic bags' worth of microplastics per person into the oceans each week [76]. Consumers now prioritize sustainability as a critical criterion in choosing apparel brands

5.2 Clothing and Textiles

Although synthetic fibers require no pesticides and use less water than cotton during production, they are still a main reason that the fashion industry is polluting the marine environment [51]. Polyester has led to the explosion of "fast fashion"[4], and the material is now used in 60% of all clothes [76]. With a single wash, one piece of synthetic clothing can release up to 700,000 fibers [76]. The International Union for Conservation of Nature calculates that 35% of marine microplastic pollution comes from synthetic textiles [146]. Europe and Central Asia dump the equivalent of 54 plastic bags' worth of microplastics per person into the oceans each week [76]. Consumers now prioritize sustainability as a critical criterion in choosing apparel brands [147]

5.2.1 Repurposing Plastic

Figure 26: Repurposed plastic used to make shoes.

There is now a myriad of brands in the market that make clothing from plastic waste, including but not limited to Adidas with recycled ocean plastic shoes, Girlfriend with leggings made of recycled plastic, and Nike with recycled polyester Flyknit technology. Although it is helpful in increasing awareness of plastic pollution, using recycled plastic to make apparel is not a long-term solution, as plastics cannot be recycled indefinitely [51].

5.2.2 Use of Sustainable Materials

Figure 27: Sustainable textiles can significantly reduce waste.

Another trend in sustainable fashion is the rise in brands that use non-synthetic materials. For example, Allbirds is a shoe company that uses merino wool instead of typical polyester fabrics, and they have also implemented a new packaging shoebox and shipper that uses 40% less materials than traditional e-commerce shoe packaging.

5.2.3 Outcomes

Sustainable apparel companies are increasingly seeing the value in answering consumers' demand for environmentally-conscious products. Gap Inc's CFO Chris Samway says, "from a purely financial perspective, the return on investment associated with aligning interests of business with those of society is compelling. We know the next

[4] Fast fashion refers to inexpensive clothing that has a short lifecycle and is produced rapidly by mass market retailers to respond to the latest trends

generation of consumers increasingly cares about brands that stand for something" [148]. By incorporating environmental sustainability into its core mission and value, Patagonia has repeatedly won B Corp's annual Best for Environment honour and has over $700M in annual revenue, which is three times greater than its next competitor, North Face at $156.9M [149]. Allbirds is valued at $1.4B USD only two years after starting [150]. By comparison, Warby Parker, the digital eyeglasses company, took eight years to secure its current valuation of $1.75B, which demonstrates the impact and weight of a truly sustainable brand [150].

5.3 Food and Beverage Packaging

A large amount of plastic waste comes from disposable plastic packaging used in the food and beverage industry. The movement to eliminate single-use plastic is gaining momentum globally, with consumers showing increased concern and heightened awareness for plastic packaging. A number of companies have responded to the growing push for businesses to be more sustainable with innovative solutions, with consumers showing increased concern and heightened awareness for plastic packaging. A number of companies have responded to the growing push for businesses to be more sustainable with innovative solutions.

5.3.1 Beer "Snap Packs"

Figure 28: Picture of Carlsberg's new "Snap Pack" from press release [151].

Beer companies such as Carlsberg is innovating an alternative to plastic rings: sticking cans together with glue. To make carrying easier, a soft handle goes around the two middle cans. The glue is strong enough to keep cans together during travel and can be split with a simple twist [152].

5.3.2 Strawless Lids

Figure 29: Starbucks' strawless lid [153].

Food and beverage chains such as Starbucks have committed to eliminating plastic straws from its stores globally by 2020. The coffeehouse company has designed a recyclable strawless lid that is currently available for cold beverages in stores in Canada and the US, with a global rollout planned next year [154].

5.3.3 Plant-Based Options

The global "plant-based" trend is driving the search for plant-based options. Plant-based packaging is now on the minds of most consumers, and is fuelling innovation within the industry, prompting companies to experiment with ingredients and packaging [155].

5.3.4 Outcomes

Once Carlsberg converts all of its plastic ring packs to the snap packs, the Danish brewery estimates it will save 1,200 tons of plastic annually, using 76% less plastic in its packaging [152]. The innovation has won accolades for Carlsberg, including the Best Sustainability Initiative award at the 2018 World Beverage Innovation Awards [156]. In the future, similar solutions could be applied to other products, with different glue variants to find the right balance between durability and ease of use.

The strawless lid forms part of Starbucks' global strategy to adapt to rapidly changing consumer trends [154]. With its commitment to ethically-sourced coffee, discount for customers who bring reusable cups, and foodbank donations program, Starbucks' initiatives have been well received, garnering support from public media [157, 158].

There is a strong business case for plant-based packaging. According to a 2018 study, 46% of shoppers try to buy packaging made of plant-based materials, and 47% consider plant-based packaging extremely or very important for healthy beverages [155]. In Canada, there have been a number of consumer-led petitions for food packaging made from plant-based materials such as plant cellulose or bamboo [159].

5.4 Plastic Bags

Consumers use approximately 500 billion single-use plastic bags annually [160]. Consumers are becoming increasingly aware of the environmental impacts of plastic bags. As a result, they are more willing to replace packaging materials with alternatives with a lower carbon footprint, or alternatives composed of renewable materials, thus driving the development and use of more sustainable options.

5.4.1 Biodegradable Bags

An Indonesian company has created an alternative to plastic bags, made of a vegetable root called cassava [161]. The bags feel and look like plastic but are completely biodegradable and compostable. The bags dissolve in water and can even be eaten by humans and animals [161].

5.4.2 Reusable Tote Bags

Figure 30: Reusable bags used to replace conventional plastic grocery bags.

Many grocery stores have begun to sell tote bags. Reusable bags are made from many different materials. The two most common types are cotton and nonwoven polypropylene (PP), although hemp fibre is also commonly used.

5.4.3 Outcomes

In 2018, the biodegradable packaging market was valued at $85.11B USD and by 2024, is expected to reach a value of $119.3B USD [162]. Biodegradable packaging solutions are increasing in popularity due to their low environmental impact. Biodegradable packaging made from renewable resources decreases dependence on petroleum and reduces the amount of waste material, while still yielding a product that provides benefits similar to traditional plastics [163].

The growing popularity of reusable tote bags has prompted companies to respond with more personalized and customizable options [164]. The global tote bags market is predicted to grow at a significant pace over the next five years [165].

While reusable tote bags have been touted as a solution to plastics pollution, cotton bag production causes a higher impact on the environment, due to its high-water requirements, pesticides, and chemical fertilizers [166]. An average cotton bag would have to be used 131 times before becoming more environmentally friendly than a plastic bag [167, 168]. In fact, Denmark's Environmental Protection Agency published a 2018 study finding that an organic cotton bag would have to be reused 149 times for climate change, and 2,000 times considering all indicators [169].

5.5 Conclusion

Sustainability and economic viability do not have to be mutually exclusive. Players in the cosmetic, hygiene, apparel, food and beverage industries have recognized that consumers are increasingly demanding sustainable products. Those who have answered the call have been met with strong business outcomes, and they are paving the way to bringing sustainability into the consumer mainstream.

Recommendation

→ **Consumers should reduce use of plastics.** As multiple researchers such as Dr. Patricia Corcoran have highlighted in their interviews with us, recycling is a start, but it is not the solution. Ultimately, only a reduction in the production of plastic will result in significant changes. Products such as reusable hygiene and cosmetic products, apparel with limited synthetic components, plant-based food and beverage containers, and reusable and/or biodegradable bags are only some of the many ways that consumers can reduce their use of plastic.

CHAPTER 6

LEGAL IMPLICATIONS

Lake Superior | Photo Credit: iStock

6.0 Introduction

Pollution in the Great Lakes is a long-standing issue that has been addressed through various levels and avenues by the legislatures in Canada and the US. Recent governmental interest in plastic pollution has been prompted by activism and a growing awareness in media, public opinion, and academic circles, as opined by Professor Jutta Brunnée.

This chapter examines the legal dimension of plastic pollution in the Great Lakes. This legal analysis discusses the multijurisdictional nature of plastic pollution in the Great Lakes, current legislative frameworks, the history of binational cooperation, as well as recent developments both domestically and abroad. The recommendations in this chapter primarily focus on legislative and policy changes.

> "Growing awareness of plastics pollution seems to me to be a function of a range of factors (activism, scientific research, press reports on dramatic phenomena like the "garbage patches" in the oceans, or the presence of micro fibres in various organisms, even in remote areas), all of which have prompted governments, like Canada's, to focus on the issue."
>
> – Jutta Brunnée
>
> Professor & Environmental Law Chair,
> University of Toronto Faculty of Law

6.1 Overview of Legislation

From a governance perspective, there is no single "Great Lakes system." Rather, there are many overlapping natural resources and jurisdictions within the Great Lakes, and similarly overlapping regulations concerned with specific resources and activities [170].

Throughout the years, pollution in the Great Lakes has been addressed directly and indirectly by various legislation, regulations, and international agreements. This historical evolution is illustrated in Figure 31.

Figure 31: Timeline of Relevant Legal Developments. While lawmakers were initially concerned with the resource, trade, and territorial dimensions of the Great Lakes, focus in the 21st century has gradually shifted to addressing pollution.

In Canada, jurisdiction over water is shared between federal and provincial governments. The concept of federalism in Canada splits lawmaking powers between federal and provincial legislatures, with sections 91 and 92 of the Canadian Constitution specifying which level of government may legislate on certain matters. Importantly, the federal government exercises jurisdiction over **navigation and shipping** under section 91(10) and **sea coast and inland fisheries** under section 91(12). The provinces on the other hand have jurisdiction over **local works and undertakings** under section 92(10) as well as **property and civil rights** under section 92(13) [171].

Thus, while the provinces clearly have the primary role for managing *internal* water resources, the management of transboundary water is far less clear. This is partly because the federal government has not taken an active role in interjurisdictional water management, unlike its counterpart in the US. It is also partly because interjurisdictional water disputes have not been the subject of federal-provincial or interprovincial litigation [172].

The fragmented treatment of water management in the Canadian Constitution is problematic for preventing plastic pollution. The capacity for federal government action has been blunted by Parliament's primary focus on fisheries, navigation, and international relations [172].

There are clear avenues for both levels of government to enforce stronger protection of the Great Lakes regarding plastic pollution. Federal regulations prohibit the deposit of deleterious substances into fish habitats, which presumably includes plastic pollution in the Great Lakes. Provincial regulations also prohibit the discharge of pollution that would impair water quality. Whether the current level of plastic particles in the Great Lakes rises to the level of impairment is yet unclear, as it has not been the subject of litigation.

> ***Provinces clearly have the primary role for managing internal water resources, but the management of transboundary water is far less clear.***

6.1.1 Federal Legislation

In Canada, the ***Fisheries Act*** gives the federal government broad powers to protect fish habitats. The Act contains two key provisions. First, section 35 (key habitat protection provision) prohibits any work or undertaking that would cause harmful alteration, disruption, or destruction of fish habitats. Second, section 36 (key pollution prevention provision), which is administered by Environment and Climate Change Canada, and prohibits the deposit of "deleterious substances" into waters frequented by fish, unless authorized by regulations under the *Fisheries Act* or other federal legislation [173]. The key provisions are administered by the Department of Fisheries and Oceans (DFO) and Environment and Climate Change Canada (ECCC), respectively.[5]

[5] Other prohibitions include section 25(2) (removal of gear) and section 36(a) (throwing overboard of certain substances), although these are seldom enforced.

The regulations administered by ECCC include the federal ***Wastewater Systems Effluent Regulations***, which set national effluent quality standards. Wastewater systems that fail to meet the standards must upgrade to secondary treatment within a timeline, which is determined by the level of risk and sensitivity of the receiving environment [174]. The Regulations apply to wastewater systems in all provinces apart from Quebec, which has equivalent controls [175].

Approximately 25% of the wastewater systems across Canada require upgrades under the Regulations. The Regulations also require all wastewater system owners or operators to monitor, record information, and submit reports on effluent quality and quantity. Most wastewater systems in Canada are owned and operated by municipalities, although some are owned and operated by other governmental bodies and First Nations communities [174].

The Supreme Court of Canada has made clear that any federal legislation based on the fisheries power must be confined to those matters truly affecting fish, effectively precluding the use of the Act as a more general vehicle for managing water quality or quantity [172].

Section 36 of the *Fisheries Act* provides an avenue for tacking plastic pollution in the Great Lakes. The prohibition of depositing deleterious substances into fish habitats could be clarified, by naming certain types or concentrations of plastics as “deleterious substances”, with fines attached for those who leave these near waters frequented by fish. This could be achieved by issuing regulations under the *Fisheries Act* [176].

Figure 32: Cosmetic product containing microbeads [204].

Another avenue for change would become available upon the passage of **Bill C-68** [177]. The Bill, which the Liberal government is attempting to pass by the end of June 2019, intends to make “the conservation and protection of fish and fish habitat, including by preventing pollution” one of the two purposes of the *Fisheries Act*, thus empowering the Minister of the Environment to make regulations for the conservation and protection of marine biodiversity [178, 176].

Plastic pollution can harm fish through entanglement or consumption, since plastic can be mistaken for food [179]. Thus, amendments to the *Fisheries Act* present an attractive and logical avenue for Canada to address plastic pollution in the Great Lakes, particularly since the Act already contains industry-specific regulations.[6]

[6] Current industry-specific regulations include the *Wastewater Systems Effluent Regulations*, and the *Pulp and Paper Effluent Regulation*s.

Recommendation

→ **Clarify the meaning of "deleterious substances" in the *Fisheries Act*,** by listing criteria such as types or concentration.

→ Add pollution prevention as one of the purposes of the *Fisheries Act*.

6.1.2 Provincial Legislation

In Ontario, the ***Water Resources Act*** focuses on both groundwater and surface throughout the province. To this end, the Act regulates sewage disposal and sewage works, and prohibits the discharge of polluting materials that may impair water quality. The Act further regulates well construction, operation, and abandonment in addition to the approval, construction, and operation of "water works" [180].

On October 7, 2015, Ontario officially passed the ***Great Lakes Protection Act***, making Ontario the first province in Canada with a legal mandate to promote "swimmable, drinkable, fishable" waters [181]. The law means that Ontario has to report regularly on its efforts to protect the Great Lakes. It complements other provincial laws which prohibit pollution or habitat destruction, such as the *Water Resources Act*, by making it easier for government bodies to work together to protect the lakes.

> ***In 2015, Ontario became the first province with a legal mandate to promote "swimmable, drinkable, fishable waters."***

Recommendation

→ **Strengthen labelling standards** of plastic type and disposal methods to enable consumers to make more sustainable decisions.

6.1.3 Federal Action on Microbeads

One recent subject of regulation is the prohibition of microbeads [182]. Microbeads are commonly found in health products, chewing gum, and cleaning products, as seen in Figure 32. In 2014, Illinois became the first jurisdiction in North America to ban cosmetics that contain microplastics, after the Illinois General Assembly found that microbeads "have been documented to collect harmful pollutants already present in the environment and harm fish and other aquatic organisms that form the base of the aquatic food chain" [183]. Several other states followed, before they were banned nationwide by the United States Congress with bipartisan support in 2015. The *Microbead-Free Waters Act 2015* phased out microbeads in "rinse-off cosmetics" by July 2017 [184].

The out-of-favor polyethylene beads were also banned by Canada in 2018, reflecting a global shift away from microbeads. The ***Microbeads in Toiletries Regulations*** came into force in January 2018, pursuant to the *Canadian Environmental Protections Act, 1999*. These regulations affect all businesses that manufacture, import, or sell toiletries that contain plastic microbeads including cosmetics, non-prescription drugs and natural health products. The onus is on the businesses to ensure that these toiletries do not contain plastic microbeads, and if necessary, to have testing performed by an accredited laboratory [185].

While the Canadian response is aligned with the global shift away from microbeads, the ban has thus far been limited to those contained in toiletries [186, 187].[7] While personal cleaning and hygiene products were identified as a leading cause of microbeads, the regulations do not address other sources of microbeads. As stated by Dr. Paul Helm, a wide variety of actions must be taken, in addition to the regulatory changes on microbeads, in order to address the issue of pollution in water systems [188].

The global movement away from microbeads has prompted a market response. German chemical producer BASF launched a new wax-based substitute version of the microbeads, which is biodegradable while retaining its functionality [189, 190]. This is one case of a positive market reaction in response to legislative action.

> "The action on microbeads is a necessary first step, but we will need a range of initiatives to address the issue."
>
> – Dr. Paul Helm
>
> Professor & Senior Research Scientist, University of Toronto Scarborough Department of Physical & Environmental Sciences

6.1.4 Potential Provincial Ban on Single-Use Plastics

In March 2019, the Ontario government released a discussion paper on reducing waste in communities [179]. The paper poses questions to the public, to guide future decision-making.[8]

Notably, the paper asks whether a ban on single-use plastics would be effective. Similar bans have already been implemented in several countries and cities, detailed in Table 9 Supply chain limitations pose a challenge to a blanket ban on single-use plastics in Ontario. Consumers and businesses face limited options for plastic alternatives, which are often associated with higher price points [191]. Thus, a single-use plastics ban may be detrimental to small businesses and communities.

The discussion paper potentially signals the Ontario government making plastic pollution prevention a key policy directive moving forward. While similar bans have been implemented elsewhere, policy actions should first focus on enabling industry to lead in creating a more affordable and accessible market for plastic alternatives.

[7] According to Section 1 of the *Microbeads in Toiletries Regulations*: "toiletries" means any personal hair, skin, teeth or mouth care products for cleansing or hygiene, including exfoliants and any of those products that is also a *natural health product* as defined in the *Natural Health Products Regulations* or a non-prescription drug.

[8] Feedback on the discussion paper is being collected until April 20, 2019: <https://ero.ontario.ca/notice/013-4689?utm_source=tbnewswatch.com&utm_campaign=tbnewswatch.com&utm_medium=referral> .

Table 9: Countries and Cities with Bans on Single-Use Plastics. This is not a conclusive list, with other notable examples including New Delhi, Kenya, and Morocco **[192, 193, 194]**.

Location	Description of Ban
France	• Became the first country to completely ban production of single-use plastics, beginning in 2020
Taiwan	• Restriction on single-use plastic bags, straws, and utensils—constituting one of the farthest-reaching bans on plastic in the world
Montréal, Canada	• Ban on single-use plastic bags. • First-time offenders face a fine of $1,000 for individuals and $2,000 for corporations
Malibu, California	• Ban on the sale, distribution, and use of single-use plastic straws, stirrers, and cutlery
Seattle, Washington	• Ban on plastic straws and single-use plastic utensils—the first US city to do so
Australia	• Four state-wide bans on single-use plastic bags
Hamburg, Germany	• Ban on non-recyclable plastic coffee pods

Recommendation

→ **Increase legislation surrounding plastic usage**, including banning single-use plastics.

→ **Increase enforcement of existing legislation**, including but not limited to industrial disposal methods and consumer littering.

6.2 International Cooperation

International cooperation over the Great Lakes is governed by several treaties and agreements between Canada and the US. As seen in Figure 33 , the Great Lakes basin is at the cross-section of not only two countries, but also of one province and eight states. An ideal governance model of the Great Lakes is necessarily international in nature, since plastic pollution flowing from Canada to the US, or vice versa, has important policy implications regarding the international boundaries [58].

Figure 33: Cross-section of jurisdictions covering the Great Lakes basin [195]. While the Canadian side lies wholly within Ontario, the US side is covered by eight different states.

6.2.1 Canada-US Boundary Waters Treaty

Signed in 1909, the ***Boundary Waters Treaty*** was an agreement that neither country would pollute boundary waters, or waters that flow across the boundary, to an extent that would cause injury to health or property in the other country. This treaty established mutual obligations to protect the Great Lakes, protocols for information exchange, and an investigative and adjudicative body called the International Joint Commission (IJC) [196].

At the time of signing, the principle concern was navigation and access to boundary waters, rather than environmental management [170]. The subsequent ***Great Lakes Water Quality Agreement***, on the other hand, was purposed with restoring and maintaining the chemical, physical, and biological integrity of the waters of the Great

Lakes, as well as prohibiting the discharge of toxic substances [170]. Implementation, however, has been undermined by the lack of enforcement provisions in the Agreement.

Amendments in 2012 addressed new areas of concern, such as increased phosphorous loadings, harmful vessel discharges, and habitat degradation. However, plastic pollution is not among the stated objectives of the Agreement, and mention of plastic is limited to a prohibition on the discharge of garbage from vessels, which includes “all plastics” [197].

6.2.2 The International Joint Commission

The IJC is mandated with reporting to national governments on legislative recommendations in both countries “relating to pollution of the Great Lakes System with a view […] to harmonize and strengthen such legislation" [198]. While the IJC is charged with acting independently from the US and Canadian governments, its authority is restricted in two important respects.

First, Commissioners are appointed by the national governments. The politicization of the appointment process has led to significant challenges to the IJC, including a gradual erosion of government reliance on the IJC. During the Raegan administration, the US and Canadian governments formed the “Binational Executive Committee” for the purposes of coordinating activities and exchanging information directly between Environment Canada and the US Environmental Protection Agency. While the ostensible intent of this change was to foster greater inter-jurisdictional cooperation, the practical effect was to create a new, non-accountable mechanism outside the Great Lakes agreements [199].

Second, the IJC is severely limited in its ultimate adjudicative power. Article X of the *Boundary Waters Treaty* requires a reference from both Canada and the US for a binding decision, as well as consent of the US Senate. Thus, if Canada were to allege that US industries were polluting boundary waters to the injury of Canadian citizens, both Canada and two-thirds of the US Senate must agree to submit the matter to the IJC. This has never occurred in the history of the Boundary Waters Treaty [170].

The treaty has proven highly flexible in meeting new challenges since its inception. The IJC has taken a significant role in environmental issues, identifying water pollution as a matter of public concern as early as 1912 [172].

The IJC emphasized the need for a truly binational approach, engaging a diverse set of stakeholders from both countries.

In April 2016, the IJC hosted a workshop with 33 experts from Canada and the US to address microplastics in the Great Lakes and their potential impacts on the ecosystem and human health. Participants represented a broad range of sectors, including federal, state, provincial, and municipal governments, non-profit organizations, and academics. Most significantly, the IJC emphasized the need for a truly binational approach, engaging a diverse set of stakeholders from both countries [200].

Recommendation

→ Increase use of the International Joint Commission by **eliminating the two-thirds consent of the United States Senate** or decreasing the fraction of Congress who must consent to 50%.

→ **Support platforms for information sharing**. Implement legislation requiring sharing of data to increase awareness and consistency of research data between research organizations.

→ Develop **financial incentives** for use of secondary markets for plastics to encourage repurposing and reuse.

6.2.3 The Charlevoix Blueprint

At a G7 summit in Québec in 2018, member states committed to a global framework for sustainable development, recognizing the need for action in line with previous G7 commitments.[9] While much of the focus was on the US' forthcoming withdrawal from the Paris Agreement, the meeting produced something of a breakthrough for climate adaptation by coastal communities [201]. The **Charlevoix Blueprint for Healthy Oceans, Seas, and Resilient Coastal Communities** ("Charlevoix Blueprint") promotes collaborative partnerships with local, Indigenous, and remote coastal and small island communities, as well as with the private sector, international organizations and civil society to identify and assess policy gaps, needs and best practices [202]. The Blueprint outlines specific steps moving countries towards a "resource-efficient lifecycle management approach" [203].

Although the Charlevoix Blueprint focuses on plastic pollution in oceans, the principles laid out are highly applicable to the Great Lakes. The legal issues associated with a primarily land-based source of pollution with water-based consequences is a common element of plastic pollution in both oceans and freshwater bodies, as stated by Hugh Adsett, who instructs in International Environmental & Resource Law and has worked for Global Affairs Canada since 1995.

"When looking at plastics in the ocean, the issues are similar. The interesting legal question is the connection between managing a source of pollution that comes from land-based activities, and the consequences which are largely felt in water. Legal regimes often separate land and water, but with plastics you have this really strong connection between the two."

– Hugh Adsett

Adjunct Assistant Professor & Public Servant-in-Residence, Queen's University Faculty of Law

[9] Parties who did not sign onto the framework include Japan and the United States.

Recommendation

→ The annex of the Charlevoix Blueprint—the "Oceans Plastics Charter"—outlines specific steps towards a "resource-efficient lifecycle management approach." While the recommendations revolve around plastic pollution in the ocean, most of the recommendations also pertain to plastic pollution in the Great Lakes. The commitment by signing states to 100% reusable, recyclable, or recoverable plastics by 2030, and to strengthen labelling standards for instance, dovetail neatly with the other recommendations provided in this report. Given that the Charlevoix Blueprint was created at a G7 summit in Canada, largely at the initiative of the current government, **Canada should remain undeterred by the US' intention to withdraw from the Paris Agreement, and demonstrate global leadership on plastic pollution**, along with the other signatory states which include France, Germany, Italy, and the United Kingdom.

6.3 Conclusion

The wide array of available long-standing legal mechanisms has not translated into effective protection of the Great Lakes from modern plastic pollution. While legislation at both federal and provincial levels clearly demonstrates a shared interest in protecting the Great Lakes, there is much work to be done in specifically addressing plastics moving forward.

Future legislative efforts should focus on reorienting pre-existing acts to effectively address the rising concern of plastics pollution. Achieving this through federal legislation is desirable as the Fisheries Act already contains a relevant provision that needs only clarification. As illustrated above, Bill C-68 aims to empower the Ministry of Environment to prevent plastic pollution, and would be a welcome, powerful step towards stronger enforcement.

CHAPTER 7

RECOMMENDATIONS

Lake Ontario | Photo Credit: Shutterstock

7.0 Recommendations

Plastic pollution in the Great Lakes is a multifaceted subject engaging overlapping stakeholders, jurisdictions, and disciplines. Understanding the past, present, and future of the issue therefore requires a multidisciplinary and multi-stakeholder approach that gives full treatment to the various facets of the problem. The TEAM has developed a segmented framework of recommendations tailored for each stakeholder group moving forward. As articulated in the preceding chapters, tackling plastic pollution in the Great Lakes is a team effort, and each player has a critical role to play.

7.1 Consumer Recommendations

Reduce use of plastics. As multiple researchers such as Dr. Patricia Corcoran have highlighted in their interviews with us, recycling is a start, but it is not the solution. Ultimately, only a reduction in the production of plastic will result in significant changes. Products such as reusable hygiene and cosmetic products, apparel with limited synthetic components, plant-based food and beverage containers, and reusable and/or biodegradable bags are only some of the many ways that consumers can reduce their use of plastic. (Chapter 5)

7.2 Industry Recommendations

Alter the shape of conventional recycling bins used by municipalities to eliminate unintentional littering caused by winds and weather. (Chapter 2)

Develop filtration device for washing machines to eliminate effluent fibers from entering the wastewater system, because with a single wash, over 700,000 fibers can be released. (Chapter 2)

Reduce the number of types of plastics manufactured in synthetic materials. As Dr. Sherri Mason discussed in her interview, a major factor of an item's recyclability is the amount of different types of plastics in that product. (Chapter 2)

Review method of transportation for nurdles and plastic to decrease volume of spilled particles which enter the environment and create method of direct transfer for pellets between transportation points to eliminate potential spillage points. (Chapter 2)

Increase tertiary filtration methods in wastewater treatment plants to further remove microplastics from the water and improve clarity of effluent stream entering the environment. (Chapter 2)

Determine feasible methods of implementing bioremediation within the Great Lakes system. (Chapter 4)

7.3 Educator Recommendations

Develop awareness programs to educate the consumer on recycling, proper disposal, alternative materials to plastic, and opportunities for product reuse and reduction. Everyday items such as clothing, cosmetics, and utensils are made of plastic, but many of these have viable alternatives. Industrial activity is driven by consumer demand, so large-scale change must start with the consumer. As Dr. Sherri Mason discussed in her interview, tackling consumers is a great way to push industry. As people change their mindsets, they will demand changes from industry. Similarly, as Anika Ballent, master's student in geology, says, it should not be "I'm an environmentalist"; it should be "I'm a politician, engineer, businessperson, and I care about the environment". (Chapter 2)

7.4 Researcher Recommendations

Conduct further research and initiate long-term studies to determine the **impact of microplastics in sediments** as well as **on physiological systems of biological organisms.** Minimal research on these topics currently exist, and this was a research gap identified in this literature review. (Chapter 2)

Develop uniform sampling methodology for use across all studies. Many researchers have called for this, and part of a UN working group is currently charged with harmonized data collection, as highlighted by Dr. Sherri Mason in her interview. (Chapter 2)

Develop method of information sharing, as suggested by Dr. Sherri Mason in her interview. For example, a worldwide database could be used for all researchers to upload data, and researchers can filter, and view data based on location, methodology, and other factors. This reduces duplication and ensures maximized utility of limited research resources. (Chapter 2)

Conduct research on macroplastic pollution in the Great Lakes. In recent years, minimal research has been conducted focused solely on the effects of macroplastics. (Chapter 2)

Continue to study potential organisms for **bioremediation** in the Great Lakes system. (Chapter 4)

7.5 Government Recommendations

7.5.1 Government of Ontario

Gradually phase out Styrofoam use by consumers and industry, as suggested in interviews with Mason and Corcoran. The ban should be phased in over a medium to long-term period to alleviate stresses on the supply chain and pricing pressures on small businesses (Chapter 2 and 3).

Strengthen labelling standards on products containing or packaged in plastics, to enable consumers to make more sustainable decisions in purchasing products (Chapter 3).

Gradually phase out single-use plastics by implementing a ban on single-use plastics to take effect in later years, in line with similar bans imposed in other developed countries and cities, including in Australia, France, and Montreal, Canada (Chapter 3).

Foster the development of a secondary plastics market through financial incentives and tax credits for companies that repurpose or reuse plastics for secondary consumption (Chapter 3).

Allocate government funding to conduct studies on microplastics' impact on bioaccumulation within aquatic organisms (Chapter 1).

7.5.2 Federal Government

Place tax on plastic production to ensure recycling remains economically viable, similar to a carbon tax in which significant producers have larger associated tax expenses (Chapter 2).

Clarify the meaning of "deleterious substances" in the *Fisheries Act*, by enumerating categories or listing concentrations of plastics that rise to the level of "deleterious substances." This could be accomplished through amendments to the *Fisheries Act*, or by passing regulations under the Act to clarify the ambiguous term (Chapter 6).

Increase the independence and adjudicative powers of the International Joint Commission, by negotiating a softening of the two-thirds consent requirement of the United States Senate (Chapter 6).

Support the development of a universal data sharing network. Federal research grants can reduce inconsistencies in data between different studies, by incentivizing researchers to share data and adopt uniform sampling methodologies, either as prerequisite conditions for receiving the grants or as separate incentives (Chapter 2).

Prioritize beach and freshwater cleanup, by mandating periodic cleanup requirements and hiring government positions to monitor and enforce cleanup (Chapter 4).

Encourage the development of market solutions, by providing financial incentives to innovative companies and entrepreneurs that develop alternative materials to plastics consumption and/or reduce plastic use in manufacturing and supply chain processes (Chapter 4).

Demonstrate global leadership on plastic pollution. The annex of the Charlevoix Blueprint—the "Oceans Plastics Charter"—outlines specific steps towards a "resource-efficient lifecycle management approach." While the recommendations revolve around plastic pollution in the ocean, most of the recommendations also pertain to plastic pollution in the Great Lakes. The commitment by signing states to 100% reusable, recyclable, or recoverable plastics by 2030, and to strengthen labelling standards for instance, dovetail neatly with the other recommendations provided in this report. Given that the Charlevoix Blueprint was created at a G7 summit in Canada, largely at the initiative of the current government, Canada should remain undeterred by the US' intention to withdraw from the Paris Agreement, and demonstrate global leadership on plastic pollution, along with the other signatory states which include France, Germany, Italy, and the United Kingdom (Chapter 6).

Works Cited

[1] D. Beletsky, J. Saylor and D. Schwab, "Mean Circulation in the Great Lakes," *Journal of Great Lakes Research,* vol. 25, no. 1, pp. 78-93, 1999.

[2] E. Flynn, xPharm: The Comprehensive Pharmacology Reference, 2007.

[3] S. Bandyopadhyay-Gosh and M. Sain, "19 - The use of biobased nanofibres in composites," in *Biofiber Reinforcement in Composite Materials*, 2015, pp. 571-647.

[4] Merriam-Webster, "Bioremediation," [Online]. Available: https://www.merriam-webster.com/dictionary/bioremediation. [Accessed 25 March 2019].

[5] C. Dwivedi, I. Pandey, H. Pandey, P. W. Ramteke, A. C. Pandey, S. B. Mishra and S. Patil, "Chapter 9 - Electrospun Nanofibrous Scaffold as a Potential Carrier of Antimicrobial Therapeutics for Diabetic Wound Healing and Tissue Regeneration," in *Nano- and Microscale Drug Delivery Systems* , 2017, pp. 147-164.

[6] Merriam-Webster, "Fragment," [Online]. Available: https://www.merriam-webster.com/dictionary/fragment. [Accessed 25 March 2019].

[7] Merriam-Webster, "In Vitro," [Online]. Available: https://www.merriam-webster.com/dictionary/in%20vitro. [Accessed 25 March 2019].

[8] Encyclopaedia Britannica , "Monomer," [Online]. Available: https://www.britannica.com/science/monomer. [Accessed 23 March 2019].

[9] A. Ballent and P. Corcoran, "Anthropogenic particles in natural sediment sinks: Microplastics accumulation in tributary, beach and lake bottom sediments of Lake Ontario, North America," Western Electronic Thesis and Dissertation Repository, London, ON, 2016.

[10] American Chemistry Council, "The Basics: Polymer Definition and Properties," 2018. [Online]. Available: https://plastics.americanchemistry.com/plastics/The-Basics/. [Accessed 03 10 2018].

[11] Merriam-Webster , "Viable," [Online]. Available: https://www.merriam-webster.com/dictionary/viable. [Accessed 25 March 2019].

[12] Zbyszewski, Maciej; Corcoran, Patricia, "Distribution and Degradation of Fresh Water Plastic Particles Along the Beaches of Lake Huron, Canada," *Water, Air & Soil Pollution,* vol. 220, no. 1, pp. 365-372, 2011.

[13] M. Campbell, M. J. Cooper, K. Friedman and W. P. Anderson, "The economy as a driver of change in the Great Lakes–St. Lawrence River basin," *Journal of Great Lakes Research,* vol. 41, no. 1, pp. 69-83, 2015.

[14] Long Point Region Conservation Authority, "Natural Hazards Great Lakes Tech Guide Part 1: The Great Lakes - St Lawrence River System: Physical Features and Processes," Government of Ontario, Tillsonburg, ON, 2017.

[15] J. T. Waples, M. Squires, B. Eadie, J. Cotner, J. V. Klump and G. McKinley, "Chapter 7: The Laurentian Great Lakes. North American Continental Margins: A Synthesis and Planning Workshop.," in *North American Continental Margins: A Synthesis and Planning Workshop. Report of the North American Continental Margins Group for the U.S. Carbon Cycle Scientific Steering Group and Interagency Working Group*, Washington, DC, 2008.

[16] International Joint Commission, "Great Lakes- St. Lawrence River," 2018. [Online]. Available: https://www.ijc.org/en/watersheds/great-lakes. [Accessed 12 10 2018].

[17] State of Michigan, "Great Lakes," State of Michigan, 2018. [Online]. Available: https://www.michigan.gov/deq/0,4561,7-135-3313_3677-15926--,00.html. [Accessed 05 10 2018].

[18] B. Neff, S. Day, A. Piggott and L. Fuller, "Base Flow in the Great Lakes Basin," U.S. Geological Survey, Information Services, Denver, CO, 2005.

[19] United States Environmental Protection Agency, "Physical Features of the Great Lakes," U.S. Federal Government, 19 January 2017. [Online]. Available: https://www.epa.gov/greatlakes/physical-features-great-lakes. [Accessed 01 11 2018].

[20] F. H. Quinn, "Hydraulic Residence Times for the Laurentian Great Lakes," *Journal of Great Lakes Research,* vol. 18, no. 1, pp. 22-28, January 1992.

[21] W. L. Robert, "Wells of wisdom," *Nature of Climate Change,* vol. 1, pp. 302-303, 26 August 2011.

[22] Canadian Geographic, "The Great Lakes," 2018. [Online]. Available: http://www.canadiangeographic.com/atlas/themes.aspx?id=watersheds&sub=watersheds_flow_thegreatlakes&lang=En. [Accessed 05 10 2018].

[23] J. Zalasiewicz, C. N. Waters, J. A. Ivar do Sul, L. P. Corcoran, A. D. Barnosky, A. Cearreta, M. Edgeworth, A. Gałuszka, C. Jeandel, R. Leinfelder, J. McNeill, W. Steffen and C. Summerhayes, "The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene," *Anthropocene,* vol. 13, no. 1, 2016.

[24] Government of Canada, "Census Profile, 2016 Census," 21 July 2017. [Online]. Available: https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/search-recherche/lst/results-resultats.cfm?Lang=E&TABID=1&G=1&Geo1=&Code1=&Geo2=&Code2=&GEOCODE=35. [Accessed 01 11 2018].

[25] United States Census Bureau, "City and Town Population Totals: 2010-2017," 4 September 2018. [Online]. Available: https://www.census.gov/data/datasets/2017/demo/popest/total-cities-and-towns.html.

[26] American Chemistry Council, "Lifecycle of a Plastic Product," 2018. [Online]. Available: https://plastics.americanchemistry.com/Lifecycle-of-a-Plastic-Product/. [Accessed 25 09 2018].

[27] S. Lambert and M. Wagner, "Microplastics Are Contaminants of Emerging Concern in Freshwater Environments: An Overview," *Freshwater Microplastics,* vol. 58, pp. 1-23, 2017.

[28] Wageningen University & Research, "Microplastics and Nanoplastics," 09 2017. [Online]. Available: https://www.wur.nl/en/Dossiers/file/Microplastics-and-Nanoplastics.htm. [Accessed 07 10 2018].

[29] J. Gigault, A. ter Halleb and M. Baudrimont, "Current opinion: What is a nanoplastic?," *Environmental Pollution,* vol. 235, pp. 1030-1034, April 2018.

[30] A. G. Driedger, H. H. Dürr, K. Mitchell and P. Van Cappellen, "Plastic debris in the Laurentian Great Lakes: A review," *Journal of Great Lakes Research,* vol. 41, no. 1, pp. 9-18, March 2015.

[31] Plastics Europe, "How Plastics are Made," 2018. [Online]. Available: https://www.plasticseurope.org/en/about-plastics/what-are-plastics/how-plastics-are-made. [Accessed 17 10 2018].

[32] European Union, "Toxicity of Plastics," Interreg Central Baltic, 2016. [Online]. Available: https://www.blastic.eu/knowledge-bank/impacts/toxicity-plastics/. [Accessed 28 January 2019].

[33] National Institute of Environmental Health Sciences, "Endocrine Disruptors," U.S. Federal Government, 22 January 2019. [Online]. Available: https://www.niehs.nih.gov/health/topics/agents/endocrine/index.cfm. [Accessed 10 02 2019].

[34] C. Erler and J. Novak, "Bisphenol A Exposure: Human Risk and Health Policy," *Journal of Pediatric Nursing,* vol. 25, no. 5, pp. 400-407, October 2010.

[35] Government of Canada, "Bisphenol A (BPA)," 31 December 2018. [Online]. Available: https://www.canada.ca/en/health-canada/services/home-garden-safety/bisphenol-bpa.html.

[36] S. Rist and N. B. Hartmann, "Aquatic Ecotoxicity of Microplastics and Nanoplastics: Lessons Learned from Engineered Nanomaterials," *Freshwaster Microplastics. ,* vol. 58, pp. 25-49, 2017.

[37] J. Oehlmann, U. Schulte-Oehlmann and W. Kloas, "A critical analysis of the biological impacts of plasticizers on wildlife," *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences,* vol. 364, no. 1526, pp. 2047-2062, 27 July 2009.

[38] A. Nel, T. Xia and L. Madler, "Toxic potential of materials at the nanolevel," *Science,* vol. 311, no. 5761, pp. 622-627, 03 2006.

[39] Z. LM, E. A, H. K, K. KJ and K. Driscoll, "Microplastics as vectors for bioaccumulation of hydrophobic organic chemicals in the marine environment: A state-of-the-science review," *Environ. Toxicol. Chem.,* vol. 35, no. 7, pp. 1667-1676, July 2016.

[40] R. Lohmann, "Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans-but should microplastics be considered POPs themselves?," *Integrated Environmental Assessment and Management,* vol. 13, no. 3, pp. 460-465, May 2017.

[41] United States Geological Survey, "Water Density," U.S. Federal Government, 9 Apr 2018. [Online]. Available: https://water.usgs.gov/edu/density.html. [Accessed 10 Nov 2018].

[42] Statista , "Density of selected plastic materials that float or sink in relation to seawater density (in grams per cubic centimeter)," [Online]. Available: https://www.statista.com/statistics/595434/plastic-materials-density/.

[43] G. Bittner, C. Yang and M. Stoner, "Estrogenic chemicals often leach from BPA-free plastic products that are replacements for BPA-containing polycarbonate products," *Environmental Health,* vol. 13, no. 1, pp. 460-465, 28 May 2014.

[44] E. Teuten, S. Rowland and T. Galloway, "Potential for Plastics to Transport Hydrophobic Contaminants," *Environmental Science & Technology,* vol. 41, no. 22, pp. 7759-7764, 20 Oct 2007.

[45] B Corp, "Allbirds," B Corp, nd. [Online]. Available: https://bcorporation.net/directory/allbirds-inc. [Accessed 18 March 2019].

[46] Y. Shi, L. Escobar and W. Meeker, "Accelerated Destructive Degradation Test Planning," *Technometrics,* vol. 51, no. 1, pp. 1-13, 2009.

[47] Plastics Europe , "Plastics - The Facts 2018," 2018. [Online]. Available: https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf .

[48] M. Zbyszewski, P. L. Corcoran and A. Hockin, "Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America," *Journal of Great Lakes Research,* vol. 40, no. 2, pp. 288-299, June 2014.

[49] Government of Canada, "Archived — Industry Profile for the Canadian plastic products industry," 4 Jan 2017. [Online]. Available: https://www.ic.gc.ca/eic/site/plastics-plastiques.nsf/eng/pl01383.html. [Accessed 5 Nov 2018].

[50] PlasticsEurope, "Plastics - the Facts 2018," European Association of Plastics Recycling & Recovery Organisations, Brussels, 2018.

[51] D. S. Mason, Interviewee, *TEAM Group 4 Interview: Impact of Plastic Pollution on the Great Lakes System.* [Interview]. 4 March 2019.

[52] P. G. Ryan, C. J. Moore, J. A. van Frankeker and C. L. Moloney, "Monitoring the abundance of plastic debris in the marine environment," *Philosophical Transactions of the Royal Society B: Biological Sciences,* vol. 364, no. 1526, pp. 1999-2012, 27 July 2009.

[53] United States Environmental Protection Agency, "Report to Congress: Combined Sewer Overflows to the Lake Michigan Basin," U.S. Federal Government, Washington, DC, 2007.

[54] Minnesota Sea Grant, "Lake Superior," University of Minnesota, 13 June 2017. [Online]. Available: http://www.seagrant.umn.edu/superior/. [Accessed 27 11 2018].

[55] J. A. Austin and S. M. Colman, "Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback," *Geophysical Research Letters,* vol. 34, no. 6, 23 March 2007.

[56] M. Eriksen, S. Mason, S. Wilson, C. Box, A. Zellers, W. Edwards, H. Farley and S. Amato, "Microplastic pollution in the surface waters of the Laurentian Great Lakes," *Marine Pollution Bulletin,* vol. 77, no. 1, pp. 177-182, 2013.

[57] E. Hendrickson, E. C. Minor and K. Schreiner, "Microplastic Abundance and Composition in Western Lake Superior As Determined via Microscopy, Pyr-GC/MS, and FTIR," *Environmental Science & Technology,* vol. 52, no. 4, pp. 1787-1796, 18 January 2018.

[58] M. J. H. E. Hoffman, "Inventory and transport of plastic debris in the Laurentian Great Lakes," *Marine Pollution Bulletin,* vol. 115, no. 1-2, pp. 273-281, 2017.

[59] K. Cox, "Distribution, Abundance, and Spatial Variability of Microplastic Pollution in Surface Waters of Lake Superior (Thesis)," University of Waterloo, 2018.

[60] J. G. Derraik, "The pollution of the marine environment by plastic debris: a review," *Marine Pollution Bulletin,* vol. 44, no. 9, pp. 842-852, September 2002.

[61] S. Mason, L. Kammin, M. Eriksen, G. Aleid, S. Wilson, C. Box, N. Williamson and A. Riley, "Pelagic plastic pollution within the surface waters of Lake Michigan, USA," *Journal of Great lakes Research,* vol. 42, no. 4, Jun 2016.

[62] J.-P. W. Desforgesa, M. Galbraith, N. Dangerfield and P. S.Ross, "Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean," *Marine Pollution Bulletin,* vol. 79, no. 1-2, pp. 94-99, 15 February 2014.

[63] T. Hoellein, M. Rojas, A. Pink, J. Gasior and J. Kelly, "Anthropogenic litter in urban freshwater ecosystems: distribution and microbial interactions," *PLoS ONE,* vol. 9, no. 6, 23 June 2014.

[64] R. L. Pickett, "Observed and Predicted Great Lakes Winter Circulations," *Journal of Physical Oceanography,* vol. 10, pp. 1140-1146, 8 April 1980.

[65] M. R. Gregory, "Plastic Pellets on New Zealand Beaches," *Marine Pollution Bulletin,* vol. 8, no. 4, pp. 82-84, April 1977.

[66] D. Eerkes-Medrano, R. Thompson and D. Aldridge, "Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs," *Water Research,* vol. 75, pp. 63-82, 15 May 2015.

[67] National Resources Defense Council, "Poisoning the Great Lakes: Mercury Emissions from Coal-Fired Power Plants in the Great Lakes Region," NRDC, New York, NY, 2012.

[68] S. T. R. O. K. Endo, "Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: Variability among individual particles and regional differences," *Marine Pollution Bulletin,* vol. 50, no. 10, pp. 1103-1114, 2005.

[69] N. Rukavina and F. M. Boyce, "Lake Ontario," The Canadian Encyclopedia, 4 March 2015. [Online]. Available: https://www.thecanadianencyclopedia.ca/en/article/lake-ontario. [Accessed 2019 February 28].

[70] A. L. W. Kemp, N. S. Harper and G. A. MacInnis, "Sedimentation Rates and Revised Sediment Budget fot Lake Erie," *Journal of Great Lakes Research,* vol. 3, no. 3-4, pp. 221-233, 1976.

[71] Toronto and Region Conservation Authority, "Currents," Toronto and Region Conservation Authority, 2019. [Online]. Available: https://trca.ca/conservation/watershed-management/lake-ontario-waterfront/projects/western-durham-nearshore-monitoring-program/currents/. [Accessed 28 February 2019].

[72] Google Maps, [Online]. Available: https://www.google.com/maps. [Accessed 24 March 2019].

[73] Wildco, "Wildco," 2018. [Online]. Available: https://shop.sciencefirst.com/wildco/search?controller=search&orderby=position&orderway=desc&search_query=hpage-bs. [Accessed 9 March 2019].

[74] P. L. Corcoran, N. T. Ceccanese, M. J. Walzak and P. A. Helm, "Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment record," *Environmental Pollution,* vol. 204, pp. 15-25, 2015.

[75] Recycling Council of Ontario, "Waste Statistics: How Much Canada Throws Out," Government of Ontario, 28 June 2018. [Online]. Available: https://rco.on.ca/canada-waste-statistics/. [Accessed 1 March 2019].

[76] K. Brodde, "What are microfibers and why are our clothes polluting the oceans?," Greenpeace, 2 March 2017. [Online]. Available: https://www.greenpeace.org/international/story/6956/what-are-microfibers-and-why-are-our-clothes-polluting-the-oceans/. [Accessed 18 March 2019].

[77] P. Corcoran, Interviewee, *TEAM Group 4 Interview: Impact of Plastic Pollution on the Great Lakes System.* [Interview]. 13 February 2019.

[78] National Geographic, "A Whopping 91% of Plastic Isn't Recycled," 19 July 2017. [Online]. Available: https://news.nationalgeographic.com/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/. [Accessed 6 November 2018].

[79] Government of Canada, "Moving Canada toward zero plastic waste: Closed Consultation," 12 October 2018. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/consultations/moving-toward-zero-plastic-waste.html. [Accessed 17 March 2019].

[80] United States Environmental Protection Agency , "Facts and Figures about Materials, Waste and Recycling," 19 July 2018. [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data. [Accessed 18 March 2019].

[81] National Geographic, "Planet or Plastic?," [Online]. Available: https://www.nationalgeographic.com/magazine/2018/06/plastic-planet-waste-pollution-trash-crisis/. [Accessed 06 November 2018].

[82] National Geographic, "7 Things You Didn’t Know About Plastic (and Recycling)," 4 April 2018. [Online]. Available: https://blog.nationalgeographic.org/2018/04/04/7-things-you-didnt-know-about-plastic-and-recycling/. [Accessed 21 March 2019].

[83] Auckland Council , "How Many Times Can it Be Recycled," [Online]. Available: http://www.makethemostofwaste.co.nz/recycling/how-many-times-can-it-be-recycled/. [Accessed 6 November 2018].

[84] L. Hook and J. Reed, "Why the world’s recycling system stopped working," Financial Times, 25 October 2018. [Online]. Available: https://www.ft.com/content/360e2524-d71a-11e8-a854-33d6f82e62f8. [Accessed 19 March 2019].

[85] P. Money, Composer, *Trash!.* [Sound Recording]. NPR. 2018.

[86] J. Mouat, R. Lopez Lozano and H. Bateson, "Economic Impacts of Marine Litter," *Kommunenes Internasjonale Miljøorganisasjon (KIMO): Grantfield,* p. 105, 2010.

[87] Canadian Broadcasting Corporation, "Plastic beads washing up on Lake Superior shore," 25 April 2016. [Online]. Available: https://www.cbc.ca/news/canada/thunder-bay/nipigon-bay-nurdles-microplastics-lake-superior-1.3552360. [Accessed 18 March 2019].

[88] S. Estahbanati and N. Fahrenfeld, "Influence of wastewater treatment plant discharges on microplastic concentrations in surface water," *Chemosphere,* vol. 162, pp. 277-284, Nov 2016.

[89] P. Kay, R. Hiscoe, I. Moberley, L. Bajic and N. McKenna, "Wastewater treatment plants as a source of microplastics in river catchments," *Environmental Science and Pollution Research,* vol. 25, no. 20, p. 20264–20267, July 2018.

[90] E. A. Giesab, J. L. LeNoble, M. Noël, A. Etemadifar, F. Bishay, E. R. Hall and P. S. Ross, "Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada," *Marine Pollution Bulletin,* vol. 133, pp. 553-561, August 2018.

[91] Metro Vancouver, "The 2017 Greater Vancouver Sewerage and Drainage Distric tEnvironmental Management and Quality Control Annual Report," Vacancouver, 2017 .

[92] Toronto Water , "Highland Creek Wastewater Treatment Plant," Toronto, 2017.

[93] L. Lebreton, J. van der Zwet, J.-W. Damsteeg, B. Slat, A. Andrady and J. Reisser, "River plastic emissions to the world's oceans.," *Nature communications.,* vol. 8, 7 June 2017.

[94] J. M. Coe and D. B. Rogers, Marine debris: sources, impacts, and solutions., New York, NY: Springer, 1997.

[95] A. Abu-Hilal and T. Al-Najjar, "Marine litter in coral reef areas along the Jordan Gulf of Aqaba, Red Sea.," *J Environ Manage,* vol. 90, pp. 1043-1049, 2009.

[96] R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. G. John, D. McGonigle and A. E. Russell, "Lost at sea: where is all the plastic?," *Science,* vol. 304, no. 5672, p. 838, 7 May 2004.

[97] A. L. Andrady, "Microplastics in the marine environment.," *Mar. Pollut. Bull.,* vol. 62, pp. 1596-1605, 2011.

[98] M. Eriksen, M. Thiel and L. Lebreton, "Nature of Plastic Marine Pollution in the Subtropical Gyres," *The Handbook for Environmental Chemistry.,* 2017.

[99] L. Lebreton, B. Slat, F. Ferrari, B. Sainte-Rose, J. Aitken, R. Marthouse, S. Hajbane, S. Cunsolo, A. Schwarz, A. Levivier, K. Noble, P. Debeljak, H. Maral, R. Schoeneich-Argent, R. Brambini and J. Reisser, "Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic," Nature, Delft, The Netherlands, 2018.

[100] National Ocean Service, "What is a gyre?," U.S. Department of Commerce, 25 June 2018. [Online]. Available: https://oceanservice.noaa.gov/facts/gyre.html. [Accessed 1 March 2019].

[101] M. R. Gregory, "Environmental implications of plastic debris in marine settings," *The Royal Society Publishing,* pp. 1-15, 2009.

[102] S. Gall and R. Thompson, "The impact of debris on marine life.," *Marine Pollution Bulletin.,* vol. 92, no. 1, pp. 170-179, 2015.

[103] J. S. Gray, "Marine biodiversity: patterns, threats, and conservation needs," *Biodiversity and Conservation,* vol. 6, no. 1, pp. 153-175, 1997.

[104] M. R. Gregory, "Environmental implications of plastic debris in marine settings- entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions," *Philosophical Transactions of the Royal Society B,* vol. 364, pp. 2013-2025, 2009.

[105] M. R. Gregory, "The hazards of persistent marine pollution: drift plastics and conservation islands.," *J. R. Social. N.Z.,* vol. 21, pp. 83-100, 1991.

[106] Minnesota & Iowa Conservation Corps, "The Story of Peanut the Turtle," 2018. [Online]. Available: https://www.conservationcorps.org/peanut-the-turtle. [Accessed 10 March 2019].

[107] M. L. Moser and D. Lee, "A fourteen-year survey of plastic ingestion by western North Atlantic seabirds.," *Colonial Waterbirds,* vol. 15, pp. 83-94, 1992.

[108] G. Balazs, "Impact of ocean debris on marine turtles: entanglement and ingestion.," *Shomura, R.S., Yoshida, H.O, Proceedings of the Workshop on the Fate and Impact of Marine Debris,* pp. 387-429, November 1984.

[109] M. Dyson, "Why do birds eat plastic?," 26 June 2018. [Online]. Available: https://www.open.edu/openlearn/nature-environment/environmental-studies/why-do-birds-eat-plastic. [Accessed 17 February 2019].

[110] R. W. Baird and S. Hooker, "Ingestion of plastic and unusual prey by a juvenile Harbour Porpoise.," *Marine Pollution Bulletin,* vol. 40, pp. 719-720, 2000.

[111] E. Besseling, A. Wegner, E. Foekema, M. van den Heuvel-Greve and A. Koelmans, "Effects of Microplastic on Fitness and PCB Bioaccumulation by the Lugworm Arenicola marina (L.)," *Environ. Sci. Technol.,* vol. 47, no. 1, pp. 593-600, 2013.

[112] L. G. A. Barboza, L. R. Vieira, V. Branco, N. Figueriredo, F. Carvalho, C. Carvalho and L. Gguilhermino, "Microplastics cause neurotoxicity, oxidative damage and energy-related changes and interact with the bioaccumulation of mercury in the European seabass, Dicentrarchus labrax (Linnaeus, 1758)," *Aquatic Toxicology,* vol. 195, no. 1, pp. 49-57, February 2018.

[113] P. Battaglia, C. Pedà, S. Musolino, V. Esposito, F. Andaloro and T. Romeo, "Diet and first documented data on plastic ingestion of Trachinotus ovatus L. 1758 (Pisces: carangidae) from the Strait of Messina (central Mediterranean Sea).," *Italy J. Zool.,* vol. 83, no. 1, pp. 121-129, 2016.

[114] A. Ballent, Interviewee, *TEAM Group 4 Interview: Impact of Plastic Pollution on the Great Lakes System.* [Interview]. 22 January 2019.

[115] Alliance for the Great Lakes, "Great Lakes Plastic Pollution," 2019. [Online]. Available: https://greatlakes.org/great-lakes-plastic-pollution-fighting-for-plastic-free-water/. [Accessed 22 January 2019].

[116] NYC Environmental Protection, "New York City's Wastewater Treatment System," [Online]. Available: https://www1.nyc.gov/html/dep/html/wastewater/wwsystem-process.shtml. [Accessed 10 March 2019].

[117] Office of Water, "How Wastewater Treatment Works... The Basics," United States Environmental Protection Agency, Washington, DC, 1998.

[118] Municipal Wastewater Effluent Development Committee , "Municipal Wastewater Effluent in Canada," Canadian Council of Ministers of the Environment , 2006.

[119] M. Gomez, F. Plaza, G. Garralon, J. Perez and M. A. Gomez, "A comparative study of tertiary wastewater treatment by physico-chemical-UV process and macrofiltration–ultrafiltration technologies," *Desalination,* vol. 202, no. 1-3, pp. 369-376, 2007.

[120] J. Sun, X. Dai, Q. Wang, M. C. M. Loosdrecht and B.-J. Ni, "Microplastics in wastewater treatment plants: Detection, occurrence and removal," *Water Research,* vol. 152, pp. 21-37, 2019.

[121] E. Abatenh, B. Gizaw, Z. Tsegaye and M. Wassie, "The Role of Microorganisms in Bioremediation- A Review," *Open Journal of Environmental Biotechnology,* pp. 38-46, 2017.

[122] G. Caruso, "Plastic Degrading Microorganisms as a Tool for Bioremediation of Plastic Contamination in Aquatic Environments," *Journal of Pollution Effects and Control,* vol. 3, no. 3, p. 1000, 2015.

[123] H. R. Dash, N. Mangwani, J. Chakraborty, S. Kumari and S. Das, "Marine bacteria: potential candidates for enhanced bioremediation," *Applied Microbiology and Biotechnology,* pp. 561-571, 2012.

[124] W. Wei-Min, J. Yang and C. S. Criddle, "Microplastics pollution and reduction strategies," *Frontiers of Environmental Science & Engineering,* 2016.

[125] Seabin Project, "Seabin V5," The Seabin Project for Cleaner Oceans, 2017.

[126] S. Sloat, "A 7th-Grader Built an Underwater Rover to Save Oceans From Microplastics," 28 July 2018. [Online]. Available: https://www.inverse.com/article/47488-young-innovator-anna-du-rov-microplastic.

[127] The Ocean Cleanup, "Technology | How it Works," 2019. [Online]. Available: https://www.theoceancleanup.com/technology/. [Accessed 22 February 2019].

[128] 4Ocean, "Our Story," 2019. [Online]. Available: https://4ocean.com/pages/our-story. [Accessed 22 February 2019].

[129] G7 Charlevoix , "Ocean Plastic Charter," 2018. [Online]. Available: https://g7.gc.ca/wp-content/uploads/2018/06/OceanPlasticsCharter.pdf. [Accessed 25 March 2019].

[130] M. Twiss, Interviewee, *TEAM Group 4 Interview: Impact of Plastic Pollution on the Great Lakes System.* [Interview]. 6 March 2019.

[131] Ocean Wise, "Ocean Plastic Education," [Online]. Available: http://plasticsedkit.ocean.org/]. . [Accessed 25 March 2019].

[132] Ocean Wise, "Ocean Plastic Education Resources," [Online]. Available: http://plasticsedkit.ocean.org/resources.html. [Accessed 25 March 2019].

[133] BBC News, "How the plastic in your beauty regime could be harming the environment," BBC News, 12 May 2018. [Online]. Available: https://www.bbc.com/news/newsbeat-44040996. [Accessed 18 March 2019].

[134] United Nations Environment Programme, "What all women should know to beat plastic pollution," UNEP, nd. [Online]. Available: http://web.unep.org/youngchampions/story/what-all-women-should-know-beat-plastic-pollution. [Accessed 18 March 2019].

[135] F. Edraki, "Tampons, pads, menstrual cups, period underwear: What's best for the environment?," ABC News, 3 November 2017. [Online]. Available: https://www.abc.net.au/news/2017-10-27/which-period-product-is-best-for-the-environment/9090658. [Accessed 18 March 2019].

[136] CHOICE, "Menstrual Cups and Period Underwear," CHOICE, 11 February 2019. [Online]. Available: https://www.choice.com.au/health-and-body/reproductive-health/womens-health/articles/menstrual-cups-and-period-underwear. [Accessed 18 March 2019].

[137] K. Butler, "Stop Using Plastic Tampon Applicators," Mother Jones, March/April 2016. [Online]. Available: https://www.motherjones.com/environment/2016/03/plastic-tampon-applicator-beach-pollution/. [Accessed 18 March 2019].

[138] Knix, "We're Knix," Knix, nd. [Online]. Available: https://knix.ca/pages/about-us. [Accessed 18 March 2019].

[139] K. Clarke, "Could these trends in period products mark the demise of tampons and pads?," CBC, 29 June 2017. [Online]. Available: https://www.cbc.ca/life/style/could-these-trends-in-period-products-mark-the-demise-of-tampons-and-pads-1.4184767. [Accessed 18 March 2019].

[140] K. Lalancette, "Alternative menstrual products reinventing periods," The Star, 5 August 2018. [Online]. Available: https://www.thestar.com/life/2018/08/05/alternative-menstrual-products-reinventing-periods.html. [Accessed 18 March 2019].

[141] Kjaer Weis, "About the Brand," Kjaer Weis, nd. [Online]. Available: https://kjaerweis.com/about/brand. [Accessed 18 March 2019].

[142] Crunchbase, "Knix Wear," Crunchbase, nd. [Online]. Available: https://www.crunchbase.com/organization/knix-wear#section-overview. [Accessed 18 March 2019].

[143] Reuters, "Menstrual Cups Market Demand, Size, Share, Types, Growth, Use, Cost, Product, Trends and Global Industry Analysis Forecast 2018-2023," Reuters, 2 July 2018. [Online]. Available: https://www.reuters.com/brandfeatures/venture-capital/article?id=40951. [Accessed 18 March 2019].

[144] E. Bennett, "Refillable Beauty Products Will Help Save The Planet — & Your Money," Refinery 29, 15 August 2018. [Online]. Available: https://www.refinery29.com/en-us/refillable-beauty-products-eco-friendly-packaging. [Accessed 18 March 2019].

[145] Formula Botanica, "Natural and Organic Beauty Market to reach $22bn by 2024," Formula Botanica, nd. [Online]. Available: https://formulabotanica.com/global-organic-beauty-market-22bn-2024/. [Accessed 18 March 2019].

[146] J. F. D. Boucher, "Primary microplastics in the oceans," *IUCN Publication ,* 2017.

[147] M. L. Rolland, "Ethical Fashion: How to Meet Industry Needs and Demands," Euromonitor International, 5 April 2018. [Online]. Available: https://blog.euromonitor.com/ethical-fashion-meet-industry-needs-demands-2/. [Accessed 18 March 2019].

[148] B Corp, "Meet the 2018 Best For The World Honorees," B Corp, 21 May 2018. [Online]. Available: https://bthechange.com/best-for-the-world-2018-all-honorees-f30a880f8ac0. [Accessed 18 March 2019].

[149] Crunchbase, "Patagonia," Crunchbase, nd. [Online]. Available: https://www.crunchbase.com/organization/patagonia#section-competitors-revenue-by-owler. [Accessed 18 March 2019].

[150] R. Syme, "The Algorithmic Emptiness of Allbirds Shoes," The New Yorker, 12 November 2018. [Online]. Available: https://www.newyorker.com/culture/on-and-off-the-avenue/the-optimized-anti-style-of-allbirds-shoes. [Accessed 18 March 2019].

[151] C. B. A/S, "Our revolutionary new Snap Pack," n.d.. [Online]. Available: https://carlsberggroup.com/pursuit-of-better/better-tomorrow/snap-pack/. [Accessed 26 March 2019].

[152] S. Hirsh, "Carlsberg's Beer "Snap Packs" Use 76 Percent Less Plastic Than Six Pack Rings," *Green Matters,* 18 March 2019.

[153] B. Rochman, "Straws are out, lids are in: Starbucks announces environmental milestone," *Starbucks Stories,* 9 July 2018.

[154] Starbucks Corporation, "Starbucks to Eliminate Plastic Straws Globally by 2020," 9 July 2018. [Online]. Available: https://stories.starbucks.com/press/2018/starbucks-to-eliminate-plastic-straws-globally-by-2020/. [Accessed 19 March 2019].

[155] Evergreen Packaging, "Plant-Based Identified as Important Trend, From Ingredients to Packaging," 2018.

[156] E. Rushe, "California Fog To Bottle Vodka Wins Best Alcohol Drink At World Beverage Innovation Awards, Germany," *Forbes,* 16 November 2018.

[157] L. Brehaut, "Going strawless: Starbucks is saying goodbye to its single-use plastic green straws," *National Post,* vol. 2019, no. March, p. 19, 9 July 2018.

[158] S. McNalty, "How Starbucks and A&W are addressing the plastic problem," *CBC News,* 8 March 2019.

[159] M. Newman, "Saltfleet high school teacher's petition takes aim at plastic food packaging," *Hamilton News,* 13 March 2019.

[160] Ocean Crusaders Foundation Ltd., "Ocean Crusaders: Plastic Statistics," Ocean Crusaders Queensland, 2019. [Online]. Available: http://oceancrusaders.org/plastic-crusades/plastic-statistics/. [Accessed 27 February 2019].

[161] A. Gray, "This plastic bag is 100% biodegradable," 4 May 2018. [Online]. Available: https://www.weforum.org/agenda/2018/05/this-plastic-bag-is-100-biodegradable-and-made-of-plants/. [Accessed 26 March 2019].

[162] W. Parker, "(2019 – 2024) Biodegradable Packaging Market Report – Industry Growth, Trends, Analysis and Forecasts," *The News Mates,* 21 March 2019.

[163] K. Kazda, "The Plastic Bag Problem," *Sustainable America,* 9 June 2014.

[164] M. Chester, "Reusable shopping bags cut pollution, wasted energy," *EnergiNews,* 26 September 2018.

[165] Research Nester, "Tote Bags Market," February 2019. [Online]. Available: https://www.researchnester.com/reports/tote-bags-market/566.

[166] Greenhandle, "Top 5 Alternative to Plastic Shopping Bags #Beatplasticpollution:," *Medium,* 4 June 2018.

[167] C. Thompson, "Paper, Plastic or Reusable?," *Stanford Magazine,* September 2017.

[168] D. Evans, "Top Alternatives to Disposable Plastic Shopping Bags," *Tern Goods,* 17 February 2018.

[169] M. o. E. a. F. Denmark, "Life Cycle Assessment of grocery carrier bags," 2018.

[170] N. D. Hall and B. C. Houston, "Law and Governance of the Great Lakes," *DePaul Law Review,* vol. 63, pp. 723- 770, 2014.

[171] Government of Canada, "Constitution Acts, 1867 to 1982," 12 03 2019. [Online]. Available: https://laws-lois.justice.gc.ca/eng/const/. [Accessed 20 March 2019].

[172] J. O. Saunders, "Law and the Management of the Great Lakes Basin," *Canadian Water Resources Journal,* vol. 25, no. 2, pp. 209-242, 23 January 2000.

[173] "Fisheries Act (R.S.C., 1985, c. F-14)," 5 April 2016. [Online]. Available: https://laws-lois.justice.gc.ca/eng/acts/f-14/. [Accessed 20 March 2019].

[174] Environment Canada, "Frequently Asked Questions – Wastewater Systems Effluent Regulations," Government of Canada, 3 March 2017. [Online]. Available:

http://ec.gc.ca/pollution/default.asp?lang=En&n=9311E26E-1&pedisable=true&wbdisable=true. [Accessed 20 March 2019].

[175] Government of Canada, "Order Declaring that the Wastewater Systems Effluent Regulations Do Not Apply in Quebec: SOR/2018-194," *Canada Gazette,* vol. 152, no. 21, 1 October 2018.

[176] Environmental Law Centre, "A National Strategy to Combat Marine Plastic Pollution: A Blueprint for Federal Action," T. Buck Suzuki Foundation, Victoria, 2018.

[177] T. Maas and A. Curry, "Bill C-68: the clock is ticking on a historic opportunity to modernize the Fisheries Act," *The Hill Times,* 18 March 2019.

[178] P. Mazereeuw, "Chagger warns of more time allocation, but Conservatives say House cooperation conditional on Liberal 'transparency' over SNC-Lavalin," *The Hill Times,* 18 March 2019.

[179] Ministry of the Environment, Conservation and Parks, "Reducing Litter and Waste in Our Communities: Discussion Paper," Environmental Registry of Ontario, Toronto, 2019.

[180] "Ontario Water Resources Act, R.S.O. 1990, c. O.40," 3 April 2018. [Online]. Available: https://www.ontario.ca/laws/statute/90o40. [Accessed 20 March 2019].

[181] "Great Lakes Protection Act, 2015, S.O. 2015, c. 24," Government of Ontario, 3 Nov 2015. [Online]. Available: https://www.ontario.ca/laws/statute/15g24. [Accessed 20 March 2019].

[182] N. Kirmse, "Most toiletries with microbeads no longer for sale in Canada," *CTV News,* 2 July 2018.

[183] N. J. Schroeck, "Microplastic Pollution in the Great Lakes: State, Federal, and Common Law Solutions," *University of Detriot Mercy Law Review,* vol. 93, no. 2, p. 273, 2016.

[184] FDA, "The Microbead-Free Waters Act: FAQs," 11 March 2017. [Online]. Available: https://www.fda.gov/cosmetics/guidanceregulation/lawsregulations/ucm531849.htm. [Accessed 19 March 2019].

[185] "Microbeads in Toiletries Regulations (SOR/2017-111)," 2017. [Online]. Available: https://laws-lois.justice.gc.ca/eng/regulations/SOR-2017-111/index.html. [Accessed 19 March 2019].

[186] D. Shoe, "The U.K. Has Banned Microbeads. Why?," *The New York Times,* 9 January 2018.

[187] Government of Canada, *Microbeads in Toiletries Regulations SOR/2017,* 2017.

[188] P. Helm, Interviewee, *TEAM Group 4 Interview: Impact of Plastic Pollution on the Great Lakes System.* [Interview]. 19 January 2019.

[189] BASF, "Cegesoft® Peel," n.d.. [Online]. Available: https://www.carecreations.basf.com/product-formulations/product-highlights/product-highlights-detail/Cegesoft%20Peel/30718341. [Accessed February 2019].

[190] L. Whitehouse, "BASF offers biodegradable microbead replacement," *Cosmetics Design - Europe,* 17 October 2018.

[191] D. Diaczuk, "Province seeks feedback on a single-use plastic ban," *TBNewsWatch,* 17 March 2019.

[192] I. Calderwood, "16 Times Countries and Cities Have Banned Single-Use Plastics," *Global Citizen,* 25 April 2018.

[193] J. McAuley, "France becomes the first country to ban plastic plates and cutlery," *The Washington Post,* 19 September 2016.

[194] R. Lau, "Montreal plastic bag ban officially in effect," *Global News,* 12 July 2018.

[195] "Work created by Phizzy, distributed under under a CC Attribution-Share Alike 3.0 Unported license," 2008. [Online]. Available: https://commons.wikimedia.org/wiki/File:Great-Lakes-Basin.svg. [Accessed 26 March 2019].

[196] Government of Canada, "Canada-US boundary waters treaty," Feb 2017. [Online]. Available: https://www.canada.ca/en/environment-climate-change/corporate/international-affairs/partnerships-countries-regions/north-america/canada-united-states-boundary-waters-treaty.html. [Accessed 20 March 2019].

[197] "Great Lakes Water Quality Agreement," 7 September 2012. [Online]. Available: https://www.canada.ca/content/dam/eccc/migration/main/grandslacs-greatlakes/a1c62826-72be-40db-a545-65ad6fceae92/1094_canada-usa-20glwqa-20_e.pdf. [Accessed 26 March 2019].

[198] International Joint Commission, "Pollution of Lake Erie, Lake Ontario and the International Section of the St. Lawrence River," International Joint Commission (IJC) Digital Archive, 2017.

[199] L. Botts and P. Muldoon, "Using the Boundary Waters Treaty for the 21st Century: Revitalizing the Great Lakes Governance Regime," *Wayne Law Review,* vol. 54, no. 1, p. 1553, 2008.

[200] International Joint Commission, "Microplastics in the Great Lakes Workshop Report," Stratos Incorporated, Windsor, ON, CAN, 2016.

[201] PICS, "What's the G7's 'Charlevoix Blueprint' all about?," *The Climate Examiner,* p. 2018, 13 June 2018.

[202] G7, *Charlevoix Blueprint for Health Oceans, Seas, and Resilient Coastal Communities,* Charlevois, Quebec: Government of Canada, 2018.

[203] ICTSD, "G7 Summit in Charlevoix Sees Intense Debate on Trade, Climate Action," *Bridges,* vol. 22, no. 21, 4 June 2018.

[204] Richmond News, "Canada officially bans products containing plastic microbeads," 4 July 2018. [Online]. Available: https://www.richmond-news.com/news/canada-officially-bans-products-containing-plastic-microbeads-1.23136634. [Accessed 19 March 2019].

Appendices

Summary of current research related to microplastic pollution in the Great Lakes and/or other marine environments.

Title	Author	Affiliated Organization	Year	Summary
The pollution of the marine environment by plastic debris: a review	Jose G.B. Derraik	University of Otago, New Zealand	2002	Overview on plastic pollution in marine environments, not specifically on the Great Lakes
Anthropogenic Litter in Urban Freshwater Ecosystems: Distribution and Microbial Interactions	Timothy Hoellein, Miguel Rojas, Adam Pink, Joseph Gasior, John Kelly	Loyola University Chicago	2014	Review of the effects of anthropogenic litter (AL) in urban freshwaters, terrestrial, and marine ecosystems; quantified from Chicago River and Lake Michigan Chicago shoreline
Microplastics in the Great Lakes Workshop Report	Various Authors	International Joint Commission	2016	Workshops led by experts in the field with recommendations for IJC to propose to Canadian and US governments;
Microplastic pollution in the surface waters of the Laurentian Great Lakes	Marcus Eriksen, Sherri Mason, Stiv Wilson, Carolyn Box, Ann Zellers, William Edwards, Hannah Farley, Stephen Amato	Gyres Institute (Los Angeles), State University of New York College at Fredonia	2013	Using SEM to analyze plastic debris collected from Laurentian Great Lakes; most were microbeads from consumer products, likely from nearby urban effluent
Plastic debris in the Laurentian Great Lakes: A review	Alexander Driedger, Hans Durr, Kristen Mitchell, Philippe Van Cappellen	University of Waterloo	2015	Overview of current state of knowledge on plastic pollution in Great Lakes, pollution sources, identifying knowledge gaps, and suggesting future research directions
Microplastics in freshwater	Martin Wagner, Christian	Environmental Sciences Europe	2014	Discussion on sources of microplastics, impact of

ecosystems: what we know and what we need to know	Scherer, Diana Alvarez-Munoz, Nicole Brennholt, Zavier Bourrain			microplastics on freshwater species
Distribution and Degradation of Fresh Water Plastic Particles Along the Beaches of Lake Huron, Canada	Maciej Zzbyszewski, Patricia L Corcoran	University of Western Ontario	2011	Detailed examination of the distribution, types, and physical and chemical degradation processes of plastic particles in a fresh water setting
Plastic and Priority Pollutants: A Multiple Stressor in Aquatic Habitats	Chelsea M Rochman	University of Toronto	2013	Focuses on the hazards of plastic materials and debris, current viewpoint, and future directions
Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps, and prioritisation of research needs	Dafne Eerkes-Medrano, Richard Thompson, David Aldridge	University of Cambridge, UK	2015	Microplastics widely distributed in waters and sediments of rivers and lakes, human density and activities influence the types of microplastics present, influence of physical forces. Review of the issue of microplastics in freshwater systems to summarize current understanding, identify knowledge gaps and suggest future research priorities
Contributing to marine pollution by washing your face: microplastics in facial cleansers	Lisa Fendall, Mary Sewell	University of Auckland, New Zealand	2009	Educates the public on immediate and long-term threats to the heath of oceans and food from using products that contain microplastics
Hidden plastics of Lake Ontario, Canada, and their potential preservation in the sediment record	Patricia Corcoran, T Norris, T Ceccanese, MJ Walzak	University of Western Ontario	2015	report the amounts of microplastics from various sites of Lake Ontario and evaluate their potential for preservation in the sediment record

Assessing and Mitigating Plastic Pollution in Lake Huron	Reed Froklage, Chris Lant, Amel Misbah	Lake Huron Centre for Coastal Conservation		Determination of microplastic pollution sources, specific effects on aquatic and terrestrial wildlife, and chemical effects of plastic in freshwater environment
Microplastics research- from sink to source	Chelsea M Rochman	University of Toronto	2018	Prevalence of plastic fragments and microplastics in both freshwaters and oceans
Microplastics are not important for the cycling and bioaccumulation of organic pollutants in the oceans- but should microplastics be considered POPs themselves?	Rainer Lohmann	University of Rhode Island	2017	The role of microplastic particles in the cycling and bioaccumulation of persistent organic pollutants (POPs) is discussed. Five common concepts, sometimes misconceptions, about the role of microplastics are reviewed. Microplastics accumulate POPs relative to their surroundings and act as passive samplers; scant evidence that microplastics are important in transfer of POPs in animals, but possibly for plastic additives
Current opinion: What is a nanoplastic?	Julien Gigault, Alexandra ter Halle, Magalie Baudrimont, Pierre-Yves Pascal	Universite de Rennes	2018	Proposed definition of nanoplastics as basis for discussion; misuse of prefix "nano" may lead to misrepresentative results
Microplastics: What are the solutions?	Marcus Eriksen, Martin Thiel, Matt Prindiville, Tim Kiessling	Gyres Institute (Los Angeles)	2017	Freshwater and oceanic marine debris solutions, stakeholder costs and benefits of mitigation; provides analysis and framework to create solutions to plastic pollution for public and private leadership to use

Microplastics Are Contaminants of Emerging Concern in Freshwater Environments: An Overview	Scott Lambert, Martin Wagner	Goethe University Frankfurt	2017	overview of the issues that may be of concern for freshwater environments
Analysis, Occurrence, and Degradation of Microplastics in the Aqueous Environment	Sascha Klein, Ian Dimzon, Jam Eubeler, Thomas Knepper	Hochschule Fresenius University of Applied Sciences, Germany	2017	Summary of degradation pathways for synthetic polymers in environment; different strategies for the sampling of water and sediment and sample treatments, including the separation of plastic particles and removal of natural debris that are necessary prior the identification of microplastics; and the techniques used for the identification of plastics particles are presented in this chapter
Plastic Debris in 29 Great Lakes Tributaries: Relations to Watershed Attributes and Hydrology	Austin K. Baldwin, Steven R. Corsi, and Sherri A. Mason	United States Geological Survey	2016	Characterizes the quantity and morphology of floating micro- and macroplastics in 29 Great Lakes tributaries in six states under different land covers, wastewater effluent contributions, population densities, and hydrologic conditions