Inventory and transport of plastic debris in the Laurentian Great Lakes

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Abstract

Plastic pollution in the world's oceans has received much attention, but there has been increasing concern about the high concentrations of plastic debris in the Laurentian Great Lakes. Using census data and methodologies used to study ocean debris we derive a first estimate of 9,887 metric tonnes per year of plastic debris entering the Great Lakes. These estimates are translated into population-dependent particle inputs which are advected using currents from a hydrodynamic model to map the spatial distribution of plastic debris in the Great Lakes. Model results compare favorably with previously published sampling data. The samples are used to calibrate the model to derive surface microplastic mass estimates of 0.0211 metric tonnes in Lake Superior, 1.44 metric tonnes in Huron, and 4.41 metric tonnes in Erie. These results have many applications, including informing cleanup efforts, helping target pollution prevention, and understanding the inter-state or international flows of plastic pollution. *Keywords:* Microplastic, Great Lakes, Modeling, Plastic Pollution 2010 MSC: 00-01, 99-00

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1. Introduction

Plastic pollution has been an environmental concern in global oceans for many years. All of the major oceans are known to have large "garbage patches" where plastic debris from both marine and terrestrial origin collects [1, 2, 3].
Several numerical modeling studies have looked at the surface transport of plastic debris in the global oceans, and have typically concentrated on mapping the surface collection areas [4, 5, 6]. In the past few years, plastic pollution in the Laurentian Great Lakes has been recognized as a problem with several observational studies measuring concentrations in the open water, shorelines, and tributaries of the Great Lakes that are similar to those of the ocean [7, 8, 9].

Plastic debris account for around 80% of the litter on the shorelines of the Great Lakes and can adversely affect ecosystem services in many ways [7]. Larger plastic debris can harm wildlife through entanglement and can affect boating and other recreational activities by marring the beauty of the environ-

¹⁵ ment [10]. Smaller plastic debris can be ingested by aquatic animals, from fish and birds to plankton, and that plastic can be transferred up the food web to affect a larger section of aquatic or human life [7, 11]. Once ingested, toxins absorbed by the plastic can transferred to the ingesting organism and affect that organisms health [12]. In addition to ingestion, plastic debris can release toxic chemicals as it degrades in the aquatic environment. Both direct ingestion and

chemical release can be harmful to people, fish, and other wildlife in the Great Lakes system. There is much work to be done in understanding the scope of plastic pollution

in the Great Lakes. So far most of the knowledge about Great Lakes plastics
²⁵ comes from beach cleanup programs and several in situ samples [7, 13]. While this is vital information, it is not sufficient to characterize the problem over the scale of the entire Great Lakes. To our knowledge, no modeling studies have investigated the problem on an individual Lake basin, much less on the entire connected Lakes system. Modelling studies have the ability to derive estimates
³⁰ over time and spatial scales that are not possible for observational studies.

Moreover, an effective modeling study can advise future sampling efforts. This paper is a first attempt to estimate the total plastic input into the Great Lakes system and model the transport of the plastic debris over a several year period.

Several modeling studies have looked at the transport of plastic pollution in

- the global ocean with a focus on the presence of garbage patches. [4] used over 10,000 drifter trajectories from the Global Drifter Program to compute Markov transition probabilities between 1/2° latitude by 1/2° longitude grid cells. Particles were then released uniformly over the grid and five main aggregation regions (at the centers of ocean gyres) were found from multi-year simulations
- [4]. Global Drifter Program trajectories were also used by [5], who used similar methodology, but accounted for seasonal variation in currents by calculating six transition probability matrices between 1° latitude by 1° longitude grid cells using drifters in two month bins. Instead of homogenous idealized releases, particles were released along the coast according to population and longer sim-
- ⁴⁵ ulations were conducted. The same five accumulation regions were found with a sixth region identified in the arctic [5]. Coastal particle releases were also used by [6], but the particle trajectories were computed using velocities from a sixyear numerical global ocean hydrodynamic simulation. In addition to coastal releases proportional to population density and impervious surface area, ship-
- ⁵⁰ ping routes were used to define maritime release of particles. While beaching was not explicitly computed in the model, relative shore accumulation rates were estimated by counting particles in grid points adjacent to land [6]. Currents from a hydrodynamic model have also been used to model the transport of marine debris in the Mediterranean Sea [14]. Simulations were initialized with
- ⁵⁵ a uniform particle distribution and, unlike global studies, identify only short timescale retention zones [14].

All of the modeling studies either use an idealized, uniform initial particle distribution or a release proportional to coastal population to identify regions having proportionally more plastic debris [4, 5, 6, 14]. None of the studies convert the release or accumulation of particles into mass estimates of plastic pollution, but [15] computed estimates for these three models ranging from 96-236 thousand metric tonnes of floating plastic debris. To arrive at this esitmate, over 11 thousand in situ observations of microplastic counts and mass from surface-trawling plankton nets were used to develop a regression model to

- ⁶⁵ convert the gridded model counts into $g \ km^{-1}$. These estimates were higher than previous estimates by [16]—which estimated between 7 and 35 thousand metric tonnes of plastic by averaging the observational data—and by [17]—which used plankton net data to calibrate the [6] model and arrived at an estimate of just over 66 thousand metric tonnes.
- All of these estimates of microplastic pollution are much lower than the global estimate of 4.8-13.7 million metric tons that was recently derived for input into the global oceans [18]. In this "top-down" model, coastal populations were scaled by country-specific estimates for per capita garbage production, percentage of garbage that is plastic, percentage of garbage that is mismanaged,
- ⁷⁵ and percentage of mismanaged garbage that enters the ocean. To the best of our knowledge, a similar estimate does not currently exist for any of the Great Lakes.

In this paper we use the methods of [18] to estimate coastal plastic input into the Great Lakes and then use currents from a numerical hydrodynamic model to calculate transport throughout the Great Lakes over the six-year period from 2009-2014. We search for accumulation zones in each of the Lakes and estimate nearshore accumulation regions. Using previously published in situ samples of microplastic in Lakes Superior, Huron, and Erie we then calibrate the model results to derive estimates for the total amount of floating plastic in those Great Lakes.

2. Methods

To estimate the transport of plastic debris in the Great Lakes we introduce particles as Lagrangian tracers and advect them using surface current fields from a numerical hydrodynamic model. The particles are introduced at model grid points that border land at rates that are based on the surrounding population.

Lake	Superior	Michigan	Huron	Erie	Ontario
Total input	4,353	707,531	87,477	350,854	224,419
From Shore	4,353	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	2,860
Pcnt. Leaving	6%	0.03%	14%	9%	1.3%

Table 1: Input and output from each of the Great Lakes (in particles)

Plastic Input Estimates

The rate of input of plastic debris into the Lakes is assumed to be a function of population near the shore. Unlike the studies of global ocean plastic debris mentioned above, which must account for very different waste produc-⁹⁵ tion and handling regimes internationally, we assume that the plastic waste generation rates are homogenous with population around the Great Lakes. In the US, population is divided by zip code while Canadian population is divided into Dissemination Areas, the smallest geographic area for which all census data are available. US zip code data were taken from the Zip Code

- Tabulation Area (ZCTA) data provided by the US Census, based on 2010 census data (https://www.census.gov/geo/reference/zctas.html). US zip code locations are taken from a zip code database. Canadian Dissemination Arealevel population data come from the 2011 census available at Statistics Canada (http://www12.statcan.gc.ca/census-recensement/2011/ref/index-eng.cfm). Bound-
- ary files were available for each Dissemination Area, and the calculated centroid of each Dissemination Area was taken as its location. After matching population data to location data for each zip code and Dissemination Area, there were 33,120 zip code areas and 56,203 Dissemination Areas in the sample. The rate of plastic input is assumed to be directly proportional to population and the

relationship between rate of plastic generation and distance follows a normal distribution with a mean of zero and a standard deviation of ten kilometers (Equation 1).

$$R_p = P * N(\mu = 0, \sigma = 10km) \tag{1}$$

By this equation, relative to a population area located right at the shore, a location 12 km from shore has half the rate of plastic debris generation, a

- ¹¹⁵ location 21 km away has one tenth the rate, and a location 30 km away from shore has 1% of the original generation rate. Equation 1 is applied to the 89,323 population areas in the US and Canada. Any population area centered more than 100 km from any Great Lakes shoreline is excluded from all calculations. Otherwise, Equation 1 is used to calculate the effect that each population area
- has on each shoreline grid point within 100 km. These are summed up over every combination of shoreline grid point and population area. Thus, the rate of generation of plastic debris for each shoreline grid point is the sum of the effect from all population areas within 100 km. The final output of these plastic input rate calculations is shown in Figure 1, where the population centers of Toronto, Chicago, Detroit, Buffalo, Cleveland, Rochester, and Milwaukee are
 - clearly visible.

NOAA GLCFS Models

To compute the propagation of plastic pollution, we use model output from NOAAs Great Lakes Coastal Forecast System (GLCFS). GLCFS provides operational nowcasts and forecasts of the five Great Lakes plus Lake St. Claire on its website (http://www.glerl.noaa.gov/res/glcfs/). All of these models are three-dimensional hydrodynamic simulations based on the hydrostatic, primitive equations Princeton Ocean Model (POM). Lakes Michigan, Huron, and Erie all have uniform 2 km horizontal grids, while Lake Ontario has a 5 km grid and Lake Superior has a 10 km grid. All of the models have terrain following sigma

vertical coordinates. Three-hour fields are available for each of these models for the years 2007-2014 and the velocities from these model results are used here. Brief descriptions of the important properties of the models for each basin are



Figure 1: Relative population in each of the shore grid points of the model that are used to define modeled input along the shores of the Great Lakes.

Lake	Resolution	Grid Size	Rivers?	Export Time Delay
Superior	$10 \mathrm{km}$	61x30	No	1 dy to Huron
Huron	$2 \mathrm{km}$	201x188	Yes	9 dys to Erie
Michigan	$2 \mathrm{km}$	131 x 251	Yes	3 hrs to Huron
Erie	$2 \mathrm{km}$	193x87	Yes	1 dy to Ontario
Ontario	$5 \mathrm{~km}$	61x25	No	N/A

Table 2: Properties of the Great Lakes Hydrodynamic Models

presented in Table 2, but more information about each of the models and the full system can be found at http://tidesandcurrents.noaa.gov/ofs/glofs.html.

Advection Scheme

Propagation of particles would ideally be completed within the model itself, but due to model availability and computational time this is not possible. Even so, Lagrangian studies have been completed based on relatively sparse gridded currents by using interpolation. Here we follow the work of [19, 20] and use bicubic interpolation in space and third-order Lagrange interpolation in time. Bicubic interpolation requires a uniformly spaced grid [20] and the GLCFS models all use Lambert conformal grids which are non-uniform in latitude and longitude. They do, however, have uniform 2 km, 5km, or 10 km

- spacing depending on the lake, so all computations are done in the space where (x, y) gives the km distance from the northeast corner of the grid. These are converted to latitude and longitude only at the end of the simulation for the purpose of plotting. GLCFS model velocities are given every 3 hours, so notationally we assume that for a given time, t_i , time t_{i-1} is 3 hours previous.
- Velocities at times t_{i-1} , t_i , t_{i+1} , and t_{i+2} are used to interpolate to half-hour velocities in the interval (t_i, t_{1+1}) . These velocities are then used to advect the particles according to the dynamical system

$$\frac{dx}{dt} = u(x, y, t),\tag{2}$$

$$\frac{dy}{dt} = v(x, y, t),\tag{3}$$

using the Runge-Kutta 4th order solver with a timestep of one hour. One hour was chosen as a good compromise between accuracy and computational cost.

Lake Coupling

River flow is thought to be an important factor in plastic discharge to marine systems, and is likely responsible for transport of plastic litter between the Great Lakes [9, 21]. Although majority of observations have occurred on the Lakes themselves, [9] have observed significant plastic accumulation in the Chicago river, and plastic debris has been seen in Lake St. Claire between Lakes Huron and Erie [8]. The GLCFS models are not coupled and so do not track water flow between lakes. In order to model inter-lake transport, particles near the mouths of major river connectors are "manually" removed from one lake and placed into the adjoining lake. The models of Erie, Michigan, and Huron all have major rivers included, so the locations of those rivers are used here and are represented in the flow. Lake Superior does not have rivers included in Marys river. Lake Ontario also does not have GLCFS modeled rivers, but an

insertion point is added at the Niagara River mouth and a removal point is added at the head of the St. Lawrence River. Whenever a modeled particle enters the grid cell defined as a river head, it is removed from the current lake and inserted at the corresponding location of the river mouth in the adjoining lake after a specified time delay. This time delay is intended to represent the transport time of the given river. Lakes Michigan and Huron are the exception as they are more closely connected and are actually a single large lake. Flow

- through the Straights of Mackinaw reverses direction, with the result being amean flow from Michigan to Huron that is only a fraction of magnitude of atypical flow. To simulate this, instead of moving all particles in the Straight of
- Mackinaw from Michigan to Huron only 1/15th of the particles are moved after a delay of 3 hours (1 time step). The specified transport times for the rest of the Lakes are shown in Table 1. These are calculated by giving a time of one day to each river. Thus there is a one day delay for travel from Superior to Huron through the St. Marys River and for transport from Erie to Ontario through
- the Niagara River. For transport from Huron to Erie, one day is allocated for each of the rivers and seven days is given for Lake St. Clair based on estimates of the residence time. In reality, all plastic debris entering a river will not be transported completely through as some will be beached or sink along the way. This is not modeled in this study, which represents a first attempt to investigate the impact of inter-lake transport.

3. Results

200

Transport Model Results

A total of 1,374,634 particles are released into the particle transport model of Great Lakes system over the six-year period from 2009-2014 and advected using 3-hour hydrodynamic nowcast fields. More than half of those particles (707,521) are released into Lake Michigan, while Superior has the fewest with 4,553 (Table 1). Superior and Michigan also have the fewest particles leaving to other lakes, with 264 and 243 respectively. There are three reasons for this. First, Superior and Michigan have the longest hydraulic residence times of the

- ²⁰⁵ Great Lakes (173 years for Superior and 62 years for Michigan) [22]. Second, the St. Marys River mouth in not included in the model of Lake Superior so it is likely that the circulation in the neighborhood of the river mouth will be more parallel to the shore in the model than in reality. Third, the total plastic input into Lake Superior is two orders of magnitude lower than any other lake
- ²¹⁰ due to low adjacent populations. In contrast, 14% of the particles that were placed in Lake Huron are transported to Lake Erie and 9% of the particles that enter Erie leave to Ontario (Table 2). Several particles travel in three of the lakes, with 83 particles that started in Huron ending up in Ontario and a single particle that started in Michigan making it to Erie.
- To check for the presence of accumulation zones, we compute the average particle density in each grid box over the six-year simulation. The average particle densities in the open water show no evidence of garbage patches similar to those in the global ocean gyres (Fig. 2). The lack of visible accumulation zones is interesting, because the average current structures of some of the Great Lakes have gyre patterns. Looking at the simulation, particles do accumulate in these gyre patters at some times, but this structure gets periodically pressed towards the shore by sustainded wind events. As a result, plastic does not accumulate in the middle of any of the Lakes for a long period of time.
- Instead of gyres, the highest particle densities are in the neighborhoods of large population centers with high releases. In Lake Michigan, the particle releases from Chicago remain largely trapped in the southern part of the Lake. In Lake Erie, particles exiting the Detroit River congregate in the western basin, while particles released from Cleveland mainly stay along a thin strip of the southern edge of the Lake. Finally, the particles released from Toronto appear
- to stay in the western basin of Lake Ontario before being transported along the southern part of the Lake with particles released from Buffalo (that have been transported from Erie to Ontario) and Rochester. The highest particle density in Lake Huron is in Saginaw Bay, while Superior has the highest densities in the



Figure 2: Modeled average particle density in the open water over the years 2009-2014.

central part of the Lake and in the neighborhood of Marquette, MI.

235

- While no beaching model is in place, some particles do tend to become trapped near the shore for long periods of time. These can be used as a way of approximating shoreline accumulation, although we emphasize the need for developing a beaching model in future work. By looking at the difference between the particles released in grid cell bins along the shore and the amount of particles in those bins after the six-year simulation, we can estimate sources 240 and sinks of plastic pollution (Fig. 3). As discussed above, major population centers are the primary sources, with Chicago, Toronto, Cleveland, and Detroit all releasing several thousand more particles than accumulated on their shores (Fig. 3). Most of the particles from Chicago (and Milwaukee) end up accumu-
- lating on the eastern shores of Lake Michigan, while the particles from Detroit 245 and Cleveland end up along the southern coast of the eastern basin of Lake Erie. Particles released from Toronto, on the other hand, appear to accumulate on the southern coast of Lake Ontario, including around Rochester and Sodus



Figure 3: Difference between the number of particles released between 2009 and 2014 from shore locations and the number of particles at those locations at the end of simulation. Areas in blue are where more plastic is released into the system than accumulated and red indicates more plastic accumulates than is released.

Bay (Fig. 3).

250 Comparison with Published Sample Data

Since the model predicts spatial distributions of plastic debris throughout the Great Lakes, we can compare the modeled results to open water and beach sample data. In particular, we look at the relative distribution patterns found in in situ samples. For the open water, we compare the average modeled dis-²⁵⁵ tribution to the 2012 samples taken at 21 locations over three weeks in Lakes Superior, Huron, and Erie by [13]. To compare the relative abundances, we normalize both the model and in situ samples in each Lake by dividing the values in each data set by the respective mean value for that Lake. In the case of Lake Erie, there is a significant mismatch in the eastern basin (locations 20 and ²⁶⁰ 21) where observed particle densities are significantly higher than the relative



Figure 4: Comparison of modeled average particle densities (red circles) with 2013 samples from [13] (blue circles). The size of the circles is proportional to the amount of plastic debris in that location. The larger circle is plotted below the smaller one, so when only one circle is visible it indicates close agreement. All values are normalized by dividing the data sets in each Great Lake by the lakewide average.

modeled densities, so these are treated as outliers and excluded from the mean calculations of both the model and observations. By scaling in this way, we can compare the spatial patterns of relative abundances of microplastic in the different Great Lakes (Fig. 4).

265

While the comparison of average particle density over 6 years with an instantaneous sample is potentially noisy, the agreement is good at most of the sample locations (Fig. 4). The agreement is excellent at seven of the twenty remaining locations, with the circles from the two data sets almost completely overlaid. At another six locations there is a small disagreement, typically that the model

²⁷⁰ underestimates the in situ density. The largest mismatch is a significant underestimation of the relative distribution in the in situ samples in the eastern basin of Lake Erie (Fig. 4). [13] found the highest plastic particle counts in the eastern basin of Erie, but the model average distribution has higher densities in the western basin. There are several possible explanations for this disagreement.

- It is possible that it is the result of the difference between instantaneous and averaged distributions or by a discharge of plastic that is not evenly distributed in time (as is assumed in the model). When examining the time-series particle density data, available as a movie file in the Supplimental Material, it is clear that high-density "packets" of particles collect against one shore then drift to-
- gether across the lakes when the prevailing surface currents shift. This means that the measured particle density at any central point may diverge widely from its time-averaged value. The discrepancy between modeled and measured values could also be due to errors in the particle model—either due to errors in the modeled currents or due to the lack of three-dimensional particle transport in the model. Despite these mismatches, the agreement between the model and the in situ samples is surprisingly good overall.
- The samples from [13] are reported in three sizes—0.355-0.999 mm, 1.000-4.749 mm, and > 4.75 mm—and five plastic types—fragments, pellets, film, line, and foam. To convert the open water average model densities to basin-wide ²⁹⁰ mass estimates we use a similar process to the global estimates of [17], [16], and [15]. First we assume that the modeled particles distributed across size and type in the same propotions as the samples from [13]. Masses of the samples are not reported, so we use conversions from counts to weight density derived from the ratios of the global ocean samples reported in [3]. [3] have data for ²⁹⁵ fragments, pellets, film, and line, but do not report counts of foam. Foam mass is not reported, so it is assumed to be negligible and is set to zero. Since foam is both less dense than pellets or fragments and is less abundant (by an order of magnitude) this will not have a huge effect on the mass estimates. After the modeled average densities in the open water are scaled to the [13],
- they are converted to mass to arrive at an estimate for surface microplastic in Lake Superior, Lake Huron, and Lake Erie. This process yields estimates of 0.0211 metric tonnes of microplastic in Lake Superior, 1.44 metric tonnes



Figure 5: Comparison of modeled average particle densities at the shore of Lake Huron (and thus assumed to be beached) with beach sample data from [8]. All values are normalized by dividing the data sets by the lakewide average, so the bar chart values are proportional to the amount of plastic debris in that location.

in Lake Huron, and 4.41 metric tonnes in Lake Erie. This methodology also allows the conversion of the between-lake particle transport counts in Table 1
to mass transports of 0.00071 metric tonnes per year from Superior to Huron, 0.16 tonnes per year from Huron to Erie, and 0.95 tonnes per year from Erie to Ontario.

Beach samples have also been collected for Lakes Huron and Erie—in 2008 and 2010 respectively—and the modeled average density fields again match the qualitative distribution of the observed counts (Fig. 5) [8]. In Lake Huron, the highest counts were along Sarnia Beach at the very southern tip near the Detroit River mouth, with lower counts along the eastern shore of the southern basin, and no plastic debris along the western shore of the southern basin [8]. This distribution is almost exactly what is seen in the model, with an average

of over 2000 particles at the southern tip of Lake Huron and in the hundreds along the eastern shore. There are few modeled particles along the western



Figure 6: Comparison of modeled average particle densities at the shore of Lake Erie (and thus assumed to be beached) with beach sample data from [8]. All values are normalized by dividing the data sets by the lakewide average, so the bar chart values are proportional to the amount of plastic debris in that location.

City	Input Range	Best Estimate	Model Input	Conversion
	(tonnes/yr)	(tonnes/yr)	(particles/yr)	(kg/particle)
Chicago	1,425-3,800	2,850	63,756.8	44.7
Rochester	78-208	156	2,403.3	64.9
Oswego	6.75-18	13.5	179.5	75.2

Table 3: Model Particle to Plastic Conversion Estimates using Different Cities

shore, although more than the zero that were observed in [8]. In Lake Erie the available beach samples qualitatively match the modeled higher accumulation of particles along the southern shores than the northern shores, though the fit is not as good as in Huron (Fig. 6). The model overestimates the particle abundance in the far eastern part of Erie and underestimates the abundance along the northern shore. This is possiblly due to the circulation patterns of Erie combined with the lack of a beaching model

Estimated Plastic Releases

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The output from this modeling effort produces relative rates of plastic debris generation along the shore. To scale these relative rates to absolute rates, we apply the assumptions from [18] to calculate the estimated annual plastic input into the Lakes from three coastal communities of various sizes: Chicago, IL; Rochester, NY; and Oswego, NY. These estimates of total annual plastic input are compared to the relative input rates along the coast adjacent to each city to estimate a scaling factor that can convert the calculated relative rates into absolute rates (Table 3). From [18] we take the estimates that coastal populations in the US produce 2.58 kg of municipal waste per person per day, that 13% of

this waste is plastic, and 2% of this waste is "mismanaged". Of the mismanaged
waste from coastal US communities, 15-40% ends up in the lake (we take 30% as the central figure), meaning that 0.078% of all waste and 0.6% of all plastic waste from coastal areas ends up in the lake.

When these assumptions are applied to the three sample communities, we

Lake	Low Bound	High Bound	Best Guess
Superior	16.0	42.7	32.0
Michigan	$2,\!635.3$	7,027.5	$5,\!270.7$
Huron	312.6	833.7	625.3
Erie	1,260.1	$3,\!360.3$	2,520.2
Ontario	719.3	$1,\!918.3$	$1,\!438.7$
Total	4,943.4	13,182.4	9,886.8

Table 4: Estimates for Plastic Input in each of the Great Lakes (in tonnes)

find that the greater Chicago area releases 1425-3800 tonnes (best estimate = 2850 tonnes) of plastic into the lake annually, Rochester releases 78-208 tonnes (best estimate = 156 tonnes) annually, and Oswego releases 6.75-18 tonnes (best estimate 13.5 tonnes) annually. When these estimates are compared to the relative rates for the three communities, they result in similar scaling factors: using the Chicago estimate, each modeled particle of debris represents 44 kg of

³⁴⁵ plastic, the Rochester results imply that each particle represents 62 kg of plastic, and Oswego results suggest 75 kg per particle (Table 3). We use the Chicago ratios as our best estimate of the quantity of plastic represented by each particle, which means that our model has a total annual plastic input into the Great Lakes of 9,887 metric tonnes per year (Table 4), which can be compared against the

estimate in [18] that total US plastic debris into the ocean is 40,000 to 110,000 tonnes annually. We elect to use the Chicago number because Chicago has a larger population that is closer to Lake Erie than the Rochester population, in addition to the fact that the Lake Michigan model has finer resolution than the Lake Ontario model (Table 2). All of the conversion rates yield estimates of the

same order of magnitude, which is reasonable considering that these estimates are highly uncertain, based on somewhat speculative assumption in [18], and therefore should be taken only as rough "order of magnitude" estimates anyway.

4. Discussion

This is the first modeling study of plastic transport in the Great Lakes system and presents the first estimates of plastic input and inventory of microplastic debris. Our estimate of an input of around 10,000 metric tonnes per year of plastic debris for the Great Lakes is reasonable when compared to the 40,000 to 110,000 tonnes estimated to enter the oceans from the coastal US, especially when considering that the plastic input into the Great Lakes comes from both the US and Canada.

The stock estimates were then used to prescribe input locations of particles which are then propagated around the Great Lakes using hydrodynamic model nowcast fields. This allows for the modeling of the spatial distribution of plastic debris. In spite of gyre structures in the mean current fields in several Great

Lakes, there do not appear to be any stationary garbage patches like those found in the ocean. The circulation does have gyre-like motion at times and this does lead to the collection of particles, but strong, persistent wind events break up these structures and send the debris onto the shore, often into a different state or country than the one generating it.

The modeled average particle distributions have good qualitative agreement with in situ samples taken in the middle of Lakes Superior, Huron, and Erie. This indicates that the particle transport model and the input fields are relatively realistic.

The modeling results can be used in many applications, including informing cleanup efforts, helping target pollution prevention, and understanding the inter-state or international flows of plastic pollution. They can also help to interpret and extrapolate the results of sampling efforts. To that end, surface microplastic inventories of Lakes Superior, Huron, and Erie were derived by using preiously published sampling data to calibrate the modeled results. As

compared to the stock estimates, the inventory estimates are two to three orders of magnitude smaller. This several order of magnitude discrepency is consistent with what has been found in estimates of global microplastic inventory [15, 17, 16]. As [15] point out, this is reasonable when you consider that the stock estimates include plastic debris of all size and densities while the inven-

tory estimates is based on floating microplastic captured by trawl nets. Dense plastic pollution will presumably sink and be deposited on the lakefloor and much of the plastic will end up on the shores instead of the middle of the Lakes. In fact, if the calculaton of the floating microplastic inventory of the lakes is modified to include the plastic in cells adjacent to land (which were assumed to be beached), the estimates of microplastic debris rise from on the order of 0.1%-1% of availible plastic waste to 1%-10%.

It is possible that a larger fraction of plastic pollution in the lakes ends up in the shore than it does in the ocean system due to the scale, the circulation differences, and the higher ratio of shoreline to open water. While much of the plastic in the ocean accumulates in mid-ocean garbage patches far from human population, the plastic pollution in the lakes is frequently brought to coastal

400

- areas where it can be beached. Often, these are low polluting areas that are expected to see higer-concentrations of debris wash up on shore. An example of this is in Lake Michigan, where the model shows large amounts of plastic from the Chicago area ending up on the Michigan shores. This has important
- implications for policy aimed at reducing plastic debris on beaches, as the source may be across state or—in the case of Toronto plastic ending up on New York shores—international boundaries.

In addition to plastic on the lakefloor, these estimates do not take into account microplastic distributed in the water column. Plastic could travel vertically through the water column either through vertical mixing or through changes in density. The vertical mixing part of this could be addressed by including three-dimensional hydrodynamic fields in the simulation. These fields are availible and can be incorporated in future work. As for density changes,

while all of the particles in this study are assumed to stay at the surface, several studies have found that marine plastics can undergo density changes due to biofouling that can lead to plastic sinking after some time [23, 24, 25]. In principle, density could be included in the particle modeling and if rates of density changes through biofouling are determined in laboratory settings they could be modeled

⁴²⁰ as well. Taking into account this three-dimensional movement of plastic debris would be challanging, but could be crucial in reconciling the gap between stock and inventory estimates.

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