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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 9887 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.

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 (Eriksen et al., 2013b; Law et al., 2010; Moore et al., 2001). 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 (Lebreton and Borrero, 2013; Maximenko et al., 2012; van Sebille et al., 2012). 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 (Driedger et al., 2015; Hoellein et al., 2014; Zbyszewski et al., 2014).

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 (Driedger et al., 2015). Larger plastic debris can harm wildlife through entanglement and can affect boating and other recreational activities by marring the beauty of the environment (Opfer, 2013). 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 (Driedger et al., 2015; Setälä et al., 2014). Once ingested, toxins absorbed by the plastic can transferred to the ingesting organism and affect that organisms health (Rochman et al., 2013). 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 comes from beach cleanup programs and several in situ samples (Driedger et al., 2015; Eriksen et al., 2013a). 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 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. Maximenko et al. (2012) used over 10,000 drifter

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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 (Maximenko et al., 2012). Global Drifter Program trajectories were also used by van Sebille et al. (2012), 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 simulations were conducted. The same five accumulation regions were found with a sixth region identified in the Arctic (van Sebille et al., 2012). Coastal particle releases were also used by Lebreton and Borrero (2013), but the particle trajectories were computed using velocities from a six-year numerical global ocean hydrodynamic simulation. In addition to coastal releases proportional to population density and impervious surface area, shipping 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 (Lebreton and Borrero, 2013). Currents from a hydrodynamic model have also been used to model the transport of marine debris in the Mediterranean Sea (Mansui et al., 2015). Simulations were initialized with a uniform particle distribution and, unlike global studies, identify only short timescale retention zones (Mansui et al., 2015).

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 (Lebreton and Borrero, 2013; Mansui et al., 2015; Maximenko et al., 2012; van Sebille et al., 2012). None of the studies convert the release or accumulation of particles into mass estimates of plastic pollution, but Sebille et al. (2015) computed estimates for these three models ranging from 96 to 236 thousand metric tonnes of floating plastic debris. To arrive at this estimate, over 11 thousand in situ observations of microplastic counts and mass from surface-trawling plankton nets were used to develop a regression model to convert the gridded model counts into g km^{-1}. These estimates were higher than previous estimates by Cózar et al. (2014)– which estimated between 7 and 35 thousand metric tonnes of plastic by averaging the observational data – and by Eriksen et al. (2014) — which used plankton net data to calibrate the Lebreton and Borrero (2013) 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 (Jambeck et al., 2015). 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, 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 Jambeck et al. (2015) 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 to 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.

2.1. 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 production 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 Area-level population data come from the 2011 census available at Statistics Canada (http://www12.statcan.gc.ca/census-recensement/2011/ref/index-eng.cfm). Boundary 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 10 km (Eq. (1)).

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

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 location 21 km away has one tenth the rate, and a location 30 km away from shore has 1% of the original generation rate. Eq. (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, Eq. (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 Fig. 1, where the population centers of Toronto, Chicago, Detroit, Buffalo, Cleveland, Rochester, and Milwaukee are clearly visible.

2.2. 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 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.

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