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Wind driven transport of macroplastic debris in a large urban harbour measured by GPS-tracked drifters

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A R T I C L E I N F O

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A B S T R A C T

The transport pathways of floating plastic debris in Toronto Harbour, Ontario, Canada, were assessed using a series of GPS-tracked drifter bottles. The drifter trajectories were largely controlled by winds, and they could traverse the 2 km wide harbour within a day. The average ratio of drifter speed to wind speed (the wind factor) is consistent with values of 2-5 % used in modelling dispersion of marine debris. However, significant variability in wind factors meant some drifters travelled 2-5 times faster than expected in small waterbodies (Toronto Harbour), and as much as 7 times faster in large waterbodies (Lake Ontario). Importantly, based on our calculated wind factor equations and the coincident accumulation of our drifters with real plastic debris, we can justify the use of wind factors when studying plastic debris transport. Most (75 %) of the drifters that were released in the harbour, stayed within the harbour, accumulating downwind. However, 14 of all 66 drifters escaped Toronto Harbour, where ~70 % escaped through the West Gap while ~30 % escaped via the Outer Harbour. One drifter made a 290 km journey across Lake Ontario in a period of 14 days, demonstrating that Toronto is a potential source of plastic debris throughout Lake Ontario.

1. Introduction

Pollution from plastic debris is one of the defining features of the Anthropocene in aquatic environments because of the prevalence of everyday plastic-use, its common entry into the environment, easy long-distance transport via water currents travelling distances on the order of hundreds of kilometers, and slow degradation over hundreds to thousands of years (Barnes et al., 2009; Cozar et al., 2014; Eriksen et al., 2013). Weathering of macroplastics (particles >5 mm) leads to the fragmentation of plastic debris into smaller pieces, eventually becoming microplastics (particles <5 mm, Eriksen et al., 2013), and contribute to the long-term and pervasive problem of global plastic pollution (Ballent et al., 2013; Cable et al., 2017; He et al., 2018; Nava et al., 2023). Both plastics and their associated additives used in plastic production can cause harm to humans, environmental resources, and ecosystems (Cox et al., 2019; Chen et al., 2019; Cole et al., 2015; Rochman et al., 2013; Galloway et al., 2017; Gregory, 2009; Nakashima et al., 2012; Votier et al., 2011; Mohajerani et al., 2022). The ubiquity, magnitude, and collateral effects of plastic pollution suggest a new geological age, the Plasticene (Rangel-Buitrago et al., 2022). Since 50 % of people worldwide live within 3 km of a surface freshwater body (Kummu et al., 2011), plastic dispersal from land into freshwater systems is a monumental global problem. To better understand dispersal of macroplastics, it is critical to understand how plastics move through environments (Cable et al., 2017; Hoffman and Hittinger, 2017; Ballent et al., 2016; Mason et al., 2020).

The long-range transport of buoyant plastics across large, open water bodies has been previously studied through the use of hydrodynamic models (Ballent et al., 2013; Cable et al., 2017; Daily and Hoffman, 2020; Jalon-Rojas et al., 2019). A key unknown in modelling the fate of plastic pollution is in describing how and where plastic debris travels in aquatic environments. However, most plastic pollution research is focused on marine systems (Bucci et al., 2020), and there remains a large gap in the knowledge about plastic pollution sources, transport, hotspots of accumulation, and sinks of plastic debris in freshwater ecosystems (Earn et al., 2021; Hoffman and Hittinger, 2017; Zhu et al., 2024). In the Laurentian Great Lakes, a number of researchers have documented the presence of macroplastics along the beaches and coastlines, where plastics have been transported far from their urban and industrial sources (Arturo and Corcoran, 2022; Ballent et al., 2016; Driedger et al., 2015), but there remains a gap in understanding the actual transport patterns of plastic debris. This motivates us to understands the dispersal

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pathways of macroplastics within the lake environment. Here, we use GPS-tracked drifters to measure the transport and retention of buoyant plastic debris in Toronto Harbour and Lake Ontario.

Drifters have long been used as a tool for observing the movement of water currents; these "message in a bottle" studies were key in the earliest studies of Great Lakes circulation patterns (Harrington, 1895). Now with modern GPS technology, researchers can routinely record the positions of drifters in real-time at any time of day and in remote locations (Pickett et al., 1983). Most drifters typically look very different from plastic debris – they have a large underwater drogue that catches the water currents like a sail catches wind (Ohlman et al., 2005). When using GPS-tracked drifters to investigate the transport of floating plastic debris, it is important to design them to emulate natural plastic debris (e.g. water bottles) to be representative of real floating plastic debris transport. Although other researchers have used a similar approach of placing GPS-drifters or tags inside plastic bottles to track their movements in rivers and estuaries, and created probabilistic models of plastic transport and retention (Duncan et al., 2020; Newbould, 2021; Tramoy et al., 2020), we are not aware of any field studies that have sought to directly quantify macroplastic (plastic particles >5 mm) dispersion in lakes.

In lakes, the surface water currents are primarily wind driven, so the flow of lake water currents are different to water currents experienced in riverine and estuarine debris dispersal studies (Haines and Bryson, 1961). Often these wind driven surface currents are defined in terms of a wind factor, which is simply the ratio of surface water current speed to the wind speed. Specifically, Haines and Bryson (1961) posited a rational "wind-factor" equation where $V_{surface}/U_{wind} = 5.3\ \%/U_{wind} + 0.013\ \%$ with wind (U_{wind}) and surface water ($V_{surface}$) speeds in m s^{-1}. A number of studies have suggested that such wind factors are typically in the range of 1–6 % (George, 1981; Henderson-Sellers, 1988; Maximenko et al., 2018). Plastic dispersion patterns and accumulation on beaches in the Great Lakes are thought to be consistent with prevailing water currents (Driedger et al., 2015; Zbyszewski and Corcoran, 2011), however, the dispersal pathway from pollution sources in lakes are not known, and an important question remains as to whether the plastic pollution that enters the environment remains a localized problem near the source, or if plastic waste readily disperses throughout a lake? For this study, Toronto Harbour was chosen as the study site because it is a heterogeneous urban waterbody, easily accessible, and has an undeniable plastic pollution problem (Sherlock et al., 2023; Corcoran et al., 2015; Earn et al., 2021).

Plastic pollution from Canada's most populous city, Toronto, enters Toronto Harbour and greater Lake Ontario via many sources and pathways, but we have a limited understanding of how water currents and wind affect transport, dispersal, or accumulation patterns of plastic debris in Toronto Harbour (Hlevca et al., 2018). Typically, the prevailing westerly winds drive water flows from west to southeast in Toronto Harbour, flushing water out of the harbour roughly every week (Hlevca et al., 2018). In addition to this typical mean flow, water currents are also driven by seiches, upwellings, flood events from the Don River (which empties into the harbour), and short-term wind variability (Hlevca et al., 2018). The sources of plastic debris to the harbour include outflows from the legacy combined sewage system, general littering along the shoreline, and local storm drains (Sherlock et al., 2023). Another expected major source of plastic debris is the Don River, which has a large, urbanized watershed of 360 km^2 with 1.5 million residents. Given the large fetch of Toronto Harbour, it is expected that the transport of buoyant plastic debris, particularly debris with a high windage, will be heavily influenced and even dominated by wind-forcing. The overall objectives of this research are to estimate how far buoyant plastic debris will travel from potential sources throughout Toronto Harbour, help identify potential hotspots of plastic debris accumulation, and ultimately to inform remediation and plastic pollution management infrastructure in Toronto Harbour. The insight and methods of this research can be applied to other embayments, lakes, or seas to learn about plastic debris transport in aquatic systems.

2. Methods

2.1. Field site

The field site for this project was Toronto Harbour within Lake Ontario, Canada (Fig. 1). Lake Ontario is a large lake on the border between Canada and the USA, with a surface area of 18,960 km^2, and volume of 1639 km^3. It has many cities along its shores and is populated by >8 million people. Lake Ontario is hydrologically downstream from Lakes Superior, Michigan, Huron, and Erie, and upstream of the Saint Lawrence River and Atlantic Ocean. Toronto Harbour has been highly urbanized since the early 19th century and it is part of the City of Toronto which is populated by approximately 2.8 million people, and more broadly, the Greater Toronto Area has 6.2 million people (Statistics Canada, 2021). The harbour is visited by 27.5 million tourists annually (Tourism Toronto, 2019a, 2019b). This high population density produces a substantial amount of floating plastic waste (Sherlock et al., 2023). For example, if only 10 % of all 27.5 million annual visitors (Annie Ewing, personal correspondence, Oct. 2024) were to visit Toronto's waterfront, and 1 % of these visitors accidentally drop 1 piece of plastic into the water, that would introduce 27,500 pieces of plastic into Toronto Harbour every year. Generally, the water quality in Toronto Harbour has greatly improved in the last few decades due to the success of the remedial action plan that was established in 1985 for the Toronto and Region Area of Concern (Midwood et al., 2021). While population densities produce more plastic pollution, it was not originally considered for informing remediation efforts. As such, micro- and macroplastic contamination is an emerging issue in this urban water body (Ballent et al., 2016; Earn et al., 2021; Lapointe et al., 2022; Munno et al., 2022; Sherlock et al., 2023; Zhu et al., 2024).

Toronto Harbour (Fig. 1a) has a roughly rectangular Inner Harbour with dimensions of 3 km × 1.5 km with a maximum depth of 8.5 m, and a narrower Outer Harbour that is 4 km × 750 m in size. The Inner Harbour has two openings, one in the west, called the West Gap which leads directly to Lake Ontario (Fig. 1b), and one in the east, called East Gap, which opens into Toronto's Outer Harbour. Both of these channels are dredged to at least 8 m depth to allow use of the harbour by large "Seawaymax" freight ships that use the Saint Lawrence Seaway system of locks and canals to travel to the Atlantic Ocean. The man-made Leslie Street Spit flanks the eastern border of the Outer Harbour which opens onto Lake Ontario. On the Toronto Islands are many shallow channels with slow-moving water and are lined with tall trees, these islands bound the western and southern areas of the Inner Harbour. The Keating channel connects the mouth of the Don River to the northeast corner of the Inner Harbour. The Don River is expected to be one of the largest point-sources of plastic pollution in Toronto Harbour (Sherlock et al., 2023). Along the Northeastern side of the Inner Harbour are shipping channels for large freight ships, while the north shore has many small quays, piers, and boat docks. Also on the North shore of the Inner Harbour are tall buildings and skyscrapers of Toronto's downtown core. The tall downtown-Toronto buildings and trees on the Toronto islands contribute to wind differences between Toronto's Inner and Outer Harbours. The Toronto City Center (TCC) weather station at a local airport, located on the west side of the Inner Harbour, records wind and weather data. Toronto Harbour shorelines are either concrete walls, rubble/stone, sand beaches, or marshy with heavy vegetation. To the west of Toronto Harbour is Humber Bay, a broad embayment into which the large Humber River drains. For the purposes of this study, "Toronto Harbour" refers to the region containing the Inner Harbour, Outer Harbour, East and West Gaps, Shipping Channel, Don River Mouth, and Toronto Islands (see supplementary KML files).

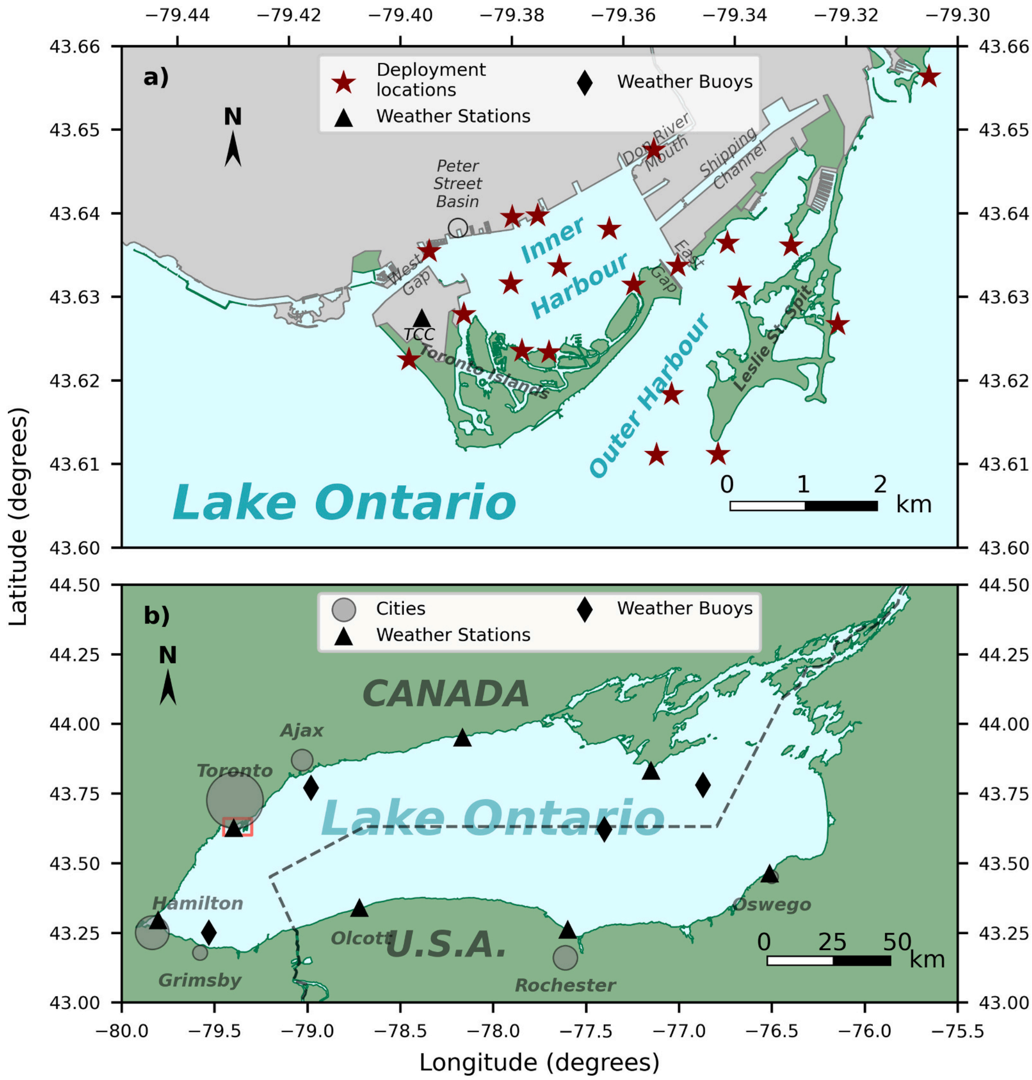

Fig. 1. a) Toronto Harbour is located within the city of Toronto, a city adjacent to b) Lake Ontario, as are other populous cities marked on the map by grey circles. Weather stations and weather buoys are marked with black triangles and diamonds, respectively. Deployment locations within and around Toronto Harbour are marked with dark red stars. (Google Earth 7.3.4.8248 (2021) Toronto Harbour, 43°38'20"N, 79°22'20"W). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. *Drifter deployments*

To measure the wind driven dispersion of floating plastics, we deployed and retrieved GPS-tracked bottle drifters (henceforth referred to as simply drifters) in Toronto Harbour. Up to 36 of these drifters were released from up to 21 different locations upon each deployment within and around Toronto Harbour during the summer of 2021 (Fig. 1a). Deployment locations were fairly evenly spaced throughout the harbour and selected because they were points of high person-traffic such as ferry terminals, lookout points, spits, docks, beaches, but also other points of interest like the middle of Toronto's Inner Harbour, Outer Harbour, and East Gap. Drifters were deployed in one pilot deployment in early April 2021, and 4 further deployments approximately every month on April 26, June 7, July 5, and July 26. Each of the 36 GPS drifters were deployed several times, for a total of 71 individual drifter path datasets (including the pilot deployments). Overall, 66 of the 71 recorded datasets were deemed usable for data analysis – 5 datasets were unusable because they did not record reliable data or recorded a single datapoint. The variable numbers of drifters deployed per deployment period was due to the loss of drifters during previous deployments. Multiple GPS-tracked bottle drifters were deployed in locations of hydrodynamic interest. Drifter retrieval was conducted on a drifter-by-drifter basis, where individual drifters were retrieved once they had become trapped or stranded for at least 7 days, then redeployed. While this retrieval method was not ideal for observing long-term transport patterns for individual drifters, it did allow us to increase redeployments, collect more datasets, and minimize drifter losses.

2.3. *Design of drifters*

The drifter design is shown in Fig. 2a, and is conceptually similar to drifters used in previous studies in rivers, such as Duncan et al. (2020). The proportion of the drifter that is floating above the water (i.e. freeboard) is shown in Fig. 2b. Our drifters were designed to behave similarly to plastic bottles that end up as floating debris in Toronto Harbour. The drifter bottle measures 22.5 cm long and has a maximum diameter of 9.5 cm. Each deployed drifter (Fig. 2) was a bright orange/pink primarily polypropylene "Blender Bottle® Classic™" (Trove Brands LLC, Lehi, UT, 84043 United States of America) that contained a GPS-tracker unit (Smart One C, Globalstar Canada, Mississauga, ON, L5R 3L1 Canada), a ballast weight made of plasticine (a synthetic and non-hardening modelling clay), and occasionally additional batteries. The few drifters

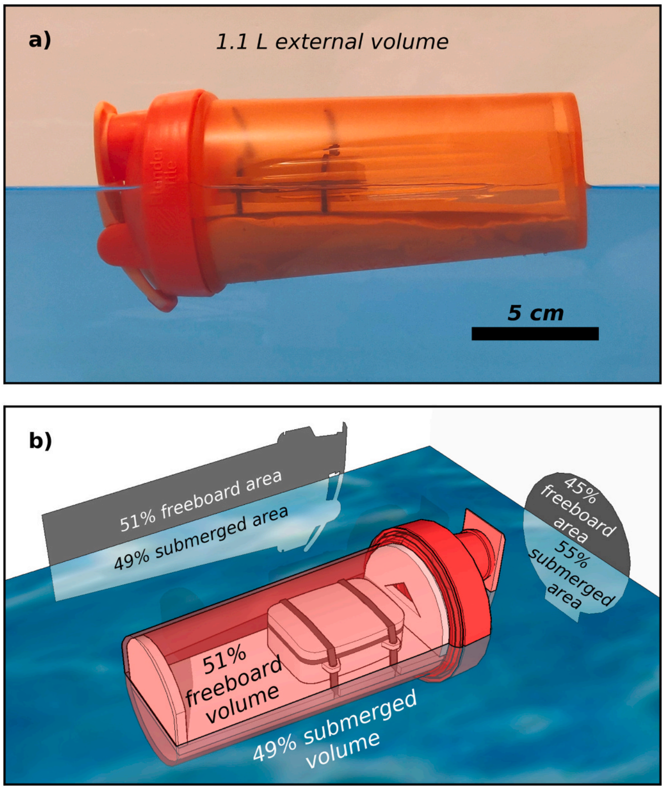

Fig. 2. a) A photograph of the standard configuration for the GPS-tracked bottle drifters floating in a still tank of water at 20 °C. A plasticine weight maintains the drifter in-plane with the water surface and directs the GPS-tracker unit toward the sky for optimal GPS signalling. b) The isometric view of the 3D modelled drifter (created using Sketchup Make 2017) visualizes and enumerates the freeboard and submerged volumes and trans-sectional areas contributing to direct wind and water transport effects.

that were deployed in locations where escape from Toronto Harbour was likely (e.g. Tommy Thompson Park, Outer Harbour, Beach Park) were modified to have extended battery capacities that would increase the length of time these drifters would send location coordinates. A drifter was considered to have escaped Toronto Harbour if it was deployed within the Toronto Harbour's boundary and managed to travel outside this boundary (see Supp. KML files). Each drifter was programmed to send a location message in World Geodetic System 1984 format (WGS84) of Latitude and Longitude every hour. A select few drifters deployed in areas of interest, like the East Gap, were programmed to communicate their location every half-hour to capture position data at a higher temporal resolution. The drifters were sealed with silicone sealant to keep them airtight when submerged in water.

To enable the recovery of beached or grounded drifters, the drifters were designed to float high in the water, which is also critical for the GPS units to receive accurate location data from satellites (Fig. 2a). This is one reason some drifters were lost, because they likely got stuck under piers or rocks and were no longer detectable. To prevent the general public from accidentally disposing drifters, each bottle was labelled with information on this project and included instructions with what to do if found (i.e. leave in place or contact the Tagging Trash Team if found after specific date). Including all the components, the mean density of each drifter was between 0.450 and 0.459 g cm^{-3}, which is less dense than Polypropylene (0.85–0.92 g cm^{-3}) but denser than expanded polystyrene (0.01–0.04 g cm^{-3}), both of which are common buoyant plastics found in aquatic systems (Driedger et al., 2015). Drifter density was calculated from volume and weight measurements. The total volume of a drifter was measured to be 1100 cm^3, calculated from the volume-displacement when submerged. Assembled drifters had weights of 500 g ± 5 g – the variability in quantity of silicone sealant used to seal each bottle contributes almost entirely to this variability in overall weight. Based on a 3-dimensional model of the drifter bottles in Fig. 2b (see supplementary drifter design files), approximately 51 % of the drifter volume (~524 cm^3/~1024 cm^3) floats above the water surface (total surface area = ~712 cm^2, floating surface area ~345 cm^2). Maximum crosswise trans-sectional area is ~74.8 cm^2, and 45 % of this area is above water (Fig. 2b). The maximum lengthwise trans-sectional area is 168.3 cm^2, 51 % of which is above the water (Fig. 2b). Drifters orient themselves such that the maximum trans-sectional area is approximately parallel to the direction of wave propagation and generally perpendicular to the wind direction - such that the lengthwise trans-sectional area is more relevant to wind and water transport rather than the cross-sectional area.

To maximize drifter retrieval for redeployment, we used bright orange bottles, as drifter freeboard visibility is important for retrieval since drifter GPS-location accuracy can be poor in near-shore areas. As the accuracy of the GPS location was 10 m under ideal circumstances, any obstruction of the GPS drifters, including submergence in the water, would lead to decreased accuracy – occasionally on the order of several hundred meters when the drifters were obstructed by docks or other structures. Thus, it was important that the GPS unit would be located at or above the surface of the water and remain skyward-facing. To reduce position scatter, the ballast weight made of plasticine was formed into the bottom of each drifter helped maintain the skyward-facing direction of drifters (Fig. 2) – the GPS drifters must have a clear view of the sky to maximize accuracy for position triangulation by GPS-satellites in Earth's orbit. Drifters with additional batteries that extended signalling duration had equal weight to the standard drifter configuration by means of removing excess plasticine ballast weight.

2.4. Drifter data processing

The raw drifter data was manually quality-controlled to determine when GPS drifters were truly travelling versus trapped near shore, then systematically filtered using Python to remove the position scatter for drifters trapped near shore. Quality-controlled drifter data was analyzed and processed using Python to calculate the distance travelled by each drifter in terms of the actual entire path distance travelled (cumulative distance) from the initial to the final or terminal position, while net distances were calculated as the distance between the initial and terminal drifter positions.

2.5. Meteorological data

Wind speed and direction data within Toronto Harbour was collected from the Toronto City Center (TCC) meteorological station located on Toronto Island at the local airport (Fig. 1.a). The meteorological station recorded standard wind speed in knots (at 10 m elevation), and wind direction in 10s of degrees from true north such that easterly winds blow from 90° and a southerly wind blows from 180°. TCC source data was inferred to be measured in whole-number knots (kt) due to rounding error artifacts stemming from conversion from knots to m s^{-1}; wind speed data was corrected to the nearest 0.01 m s^{-1} at regular 1-kt intervals to remove rounding-error artifacts. Due to the presence of TCC weather station within Toronto Harbour, and the sheltering effect of land, trees, and the city surrounding Toronto Harbour, it was assumed that the meteorological data measured at TCC weather station was representative of the weather within and around 1 km of Toronto Harbour.

Winds outside of Toronto Harbour over Lake Ontario are potentially much more expansive and spatially variable than winds within in Toronto Harbour, hence inverse-distance-squared weighted interpolation (ID^{2}W interpolation) was performed to estimate wind speeds for drifters that travelled >1 km outside of Toronto Harbour. Inverse-distance-squared weighted interpolation is a form of interpolation where the average wind velocity value is weighted based on the proximity of source data to the target datapoint, such that proximal wind data is weighted more strongly than distant wind data. The weather monitoring stations outside of Toronto Harbour are concentrated near Lake Ontario's shorelines, which leaves much ambiguity about wind and water currents in the open waters of Lake Ontario. ID^{2}W interpolation is performed by summing the inverse-distance-squared weighted wind speeds for each weather station, then dividing by the sum of inverse-distance-squared values for each weather station,

$$U_{10} = \left(\sum_s \frac{1}{d_s^2} * U_{10\ s}\right) * \left(\sum_s \frac{1}{d_s^2}\right)^{-1} \quad (1)$$

where U_{10} is the interpolated wind speed (in m s^{-1} at 10 m elevation) at a drifter location, s is the specifier for each weather station, and d is the distance (in km) between the drifter location and the specific weather station. Wind data used for estimating wind speed and direction was downloaded from the Government of Canada and National Oceanic and Atmospheric Administration (NOAA) buoys and weather stations (C45159, C45139, OLNC6, 45012, RPRN6, 45135, OSNG6). The height of wind speed measurement was variable between datasets; thus wind data was processed to normalize wind speeds to the standard 10 m elevation above the water or land surface, using the power law,

$$U_{10} = U_a * \left(\frac{z_{10}}{z_a}\right)^P \quad (2)$$

where U_{10} is the wind speed (in m s^{-1}) at z_{10} (10 m height), U_a is the reference wind speed (in m s^{-1}) measured at z_a (in m) the reference anemometer height for each specific weather station, and P is the wind-profile exponent for the atmospheric stability and surface roughness. Assuming near-normal atmospheric stability, based on results from Hsu et al. (1994), the wind-profile exponent is assumed to have a value of 0.11 for open water stations/buoys, and 0.143 for onshore stations. These ID^{2}W wind speeds were used for calculating drifter wind factors, which describe drifter speed as a percent of wind speed. Given the GPS minimum positional accuracy of 10 m, and hourly measurement frequency, drifter speeds below 10 m h^{-1} (0.27 cm s^{-1}) were excluded from wind factor calculations.

2.6. Calculation of net displacement of drifters

Net displacement analysis simply involves the change in position of each drifter from its deployment (initial position) location to its landfall or terminal location (final position) to provide insight into the retention and dissemination of plastic debris in Toronto Harbour. The initial position of a drifter is defined as the very first recorded position at deployment. Final positions are defined as either the position at which a drifter makes landfall or the last recorded position of a drifter before it was lost or retrieved. Net displacement information was then compared to general observations in wind data to find broad connections between plastic debris transport and weather.

2.7. Analysis of drifter paths

The observed paths of drifters were analyzed using the high-resolution position data to estimate drift velocities. Throughout their journeys, drifters were classified as having either "travelling" or "stationary" movement patterns. Only travelling drifter data was used in analyses of velocities, while processed data from stationary drifters was included for visualization. Stationary drifters were manually identified by large GPS position scatter on the order of tens to hundreds of meters and large directional changes or reversals occurring chaotically and without connection to observed winds. Drifters that were identified as stationary had their positions averaged for the entire duration of their stationarity, or if the scatter was on the scale of hundreds of meters, then the position data of the drifter was ignored to avoid spoiling the dataset with unreliable position data.

Drifter velocities were compared to wind velocities to investigate the relationship between wind velocities and plastic debris transport and accumulation. Drifter travel within Toronto Harbour was compared to Toronto City Center weather station wind data. Observed wind data from Lake Ontario weather buoys and stations were ID^{2}W-interpolated to drifter observations >1 km outside Toronto Harbour. Drifter velocity was calculated using directional distances and time intervals between consecutive drifter positions.

The filtered observed positions of drifters were mapped to highlight any areas of high-traffic transport and hotspots of accumulation to potentially identify specific sources which are more likely to lead to plastic debris accumulation or losses in Toronto Harbour. The data on areas of accumulation was used to inform the placement of trash capture devices (Sherlock et al., 2023) and waste-management infrastructure improvements within or around Toronto Harbour.

3. Results

The GPS-tracked drifters performed well in field deployments (Fig. 3a). The drifters used in this study were found to accumulate in the same locations as anthropogenic debris. Indeed, in Fig. 3a, several similar sized empty plastic bottles can be seen. In this photograph one of our GPS bottles is seen to accumulate at the back of dock on the north side of Toronto Harbour, along with other floating debris, including glass and plastic bottles, cans, branches, paper and assorted broken plastics. The image in Fig. 3a is typical of the sites monitored by Sherlock et al. (2023) in their audit of the efficiency of trash capture devices within the Toronto Harbour. The drifters were so like anthropogenic waste that several drifters were even mistaken for trash and discarded by members of the public despite the presence of informative drifter labels. One drifter managed to retain a connection to satellites after being collected by city waste management, and we observed its journey to Toronto's landfill site.

3.1. Drifter paths

In total, we recorded 66 separate informative drifter paths across all deployments (Fig. 4). Most (74 % of all drifters) travelled and became stranded within or just outside of Toronto Harbour. Drifters travelled for an average of 12.88 days before their journeys ended, however there was very large variation in the duration of travel (min = 3.12 h, max = 51.48 days, std. dev = 12.85 days). Note that these durations exclude the time spent stranded at the end of each drifter dataset prior to retrieval. Nearly half (42 %) of all 66 usable drifters had reached a shoreline and become stranded within 1 week of deployment, 24 % within 3 days, 8 % within 24 h, and 3 % within 6 h.

There were high-volumes of drifter transport in the Don River Mouth (Fig. 4a), Shipping Channel (Fig. 4b), East Gap (Fig. 4c), and West Gap (Fig. 4e), which have highly urbanized shorelines in line with the northeast-southwest axis of prevailing wind patterns. Urbanized northeastern and northwestern shorelines accumulated but generally did not retain drifters, rather the naturalized southwestern and southeastern shorelines of the Inner Harbour and naturalized shorelines of the Outer Harbour (Fig. 4d) had trapped drifters. Accumulation of drifters was observed in sheltered areas with slow moving water such as bays, slips, and channels throughout Toronto's Inner and Outer Harbours. Of the 63 drifters deployed within Toronto Harbour, 15.9 % travelled within The Don River Mouth, 12.7 % within the Shipping Channel, 14.3 % within the East Gap, 17.5 % within the West Gap, 77.8 % within the Inner Harbour, and 25.4 % within the Outer Harbour. Drifters travelled quickly and unimpeded through open water in Toronto's Inner and Outer Harbours, and Lake Ontario, whereas drifters travelled slowly once they reached complex shorelines with vegetation, beaches, docks, and channels or small embayments that were sheltered from wind. These

Fig. 3. Photos of a) drifter at its terminal position, showed that drifters were found where real floating plastic debris accumulates, demonstrating that our drifters emulate floating plastic debris well. This particular photo shows a GPS drifter just prior to recovery in Peter Street Basin (43°38′19.1″N, 79°23′22.7″W) on July 28, 2021. b) This drifter was found just outside Toronto Harbour and its West Gap (43°37′59.1″N, 79°24′12.5″W) on May 6, 2023, nearly two years after this project began. Additional photos are available in supplementary materials.

naturalized and complex shorelines can be found around Toronto's local wetlands, beaches, and islands. The 14 drifters that did manage to leave Toronto Harbour (Fig. 4f) tended to travel between 5 and 10 km, and most had exited through the West Gap (10 drifters) rather than the East Gap (2 drifters, via Outer Harbour) and Outer Harbour (4 drifters). Three drifters made journeys >100 km, with one travelling a meandering path east to Ajax, Ontario in 30.6 days, one heading rapidly south-west to Hamilton in 2.4 days, and one crossing the breadth of Lake Ontario toward Rochester, New York in 14 days (Fig. 4g).

Drifter paths can be briefly summarized by their general transport patterns. Of all 66 usable drifter datasets, 95.5 % (63 drifters) were deployed within Toronto Harbour's boundaries, while 4.5 % (3 drifters) were deployed external to these boundaries. Of the 63 drifters deployed throughout Toronto Harbour, which includes both the Inner and Outer Harbours, 77.8 % (49 drifters) travelled exclusively within its boundaries, 22.2 % (14 drifters) escaped Toronto Harbour, and 14.3 % (2 drifters) of these escaped drifters re-entered Toronto Harbour at least once. Of the drifters deployed within Toronto Harbour 11 drifters (17.5 %) travelled through the West Gap, none of which were deployed within the West Gap; 9 drifters (12.7 %) through the East Gap, 6 were deployed within; 8 drifters (12.7 %) in the Shipping Channel, 1 was deployed within; 10 drifters (15.9 %) in the Don River Mouth, 4 were deployed within; and 16 drifters (25.4 %) in the outer Harbour, 10 were deployed within. One of the three drifters deployed outside Toronto Harbour's boundaries managed to travel long distances, while two became beached on Toronto Harbour's external shorelines soon after deployment.

Cumulative drifter distances correspond to the distances of non-linear drifter paths shown in Fig. 4, while net distances are the linear distances from each drifter's start and end location, and are compared in Fig. 5. For cumulative drifter distances, a very small fraction ~5 %) of all drifters travelled between 100 m and 1 km; most drifters (67 %) travelled cumulative distances between 1 and 10 km – these distances support opportunities of escape/dissemination into Lake Ontario; 24 % of all drifters travelled between 10 and 100 km, ~5 % of all drifters travelled >100 km and travelled into Lake Ontario. When comparing cumulative distances to net distances, net distances show a similar peak at 1–10 km (54 % of all drifters), however, net distances are nearly an order of magnitude shorter than cumulative distances. A small percentage (6 %) of all drifters were only transported a net distance of <100 m from their deployment locations – these were often found to be stuck under boardwalks along with many other pieces of trapped litter (macroplastics like clothing, food containers, boating debris; and microplastics; see Fig. 3).

Drifters were recovered from sheltered areas like slips, bays, under piers, docks, boardwalks, from garbage cans (when discarded by the public), and occasionally from shore after storms or strong wind events. Non-recoverable drifters had either travelled too far from the harbour to be retrieved (i.e. near the cities of Ajax, Ontario and Rochester, New York) were presumed to have been discarded in garbage bins (13 drifters, ~20 % of all drifters), or were non-recoverable and considered lost or destroyed (14 drifters, ~21 % of all drifters). There were occasions where drifters would stop transmitting their positions after entering Toronto Harbour's shipping channel or West Gap which have frequent boat traffic – these drifters were presumed lost or destroyed. Anecdotally, this study was given a glimpse into longer-term resuspension of plastic debris since a drifter was observed just outside Toronto Harbour's West Gap nearly 2 years after this study was conducted (Fig. 3b). There was no consistent direction that drifters travelled between their start and end locations, but the drifters' movements did coincide with wind directions and speeds. Interestingly, wind conditions were occasionally strong enough to transport drifters upstream of the water currents in the Keating Channel at the mouth of the Don River such that the drifters would become trapped in the upstream trash-capture log-boom deployed to help prevent litter from the Don River into Toronto Harbour.

3.2. Wind data

Winds measured at the TCC weather station (Fig. 6) showed atypical trends from previous years with a higher proportion of winds blowing from the east rather than the typical strong dominance of southwesterly winds. Throughout May, June, July, and August, weak winds commonly blew in from generally western directions. Winds were observed to be stronger in April, May, and June when compared to July and August. Toronto's weather throughout this study (Fig. 6h) shows uncommonly weak prevailing winds coming from the west-southwest. Also uncommonly, there were very frequent strong winds coming from the east-northeast. However, the observed wind data that coincided with drifter measurements within and outside Toronto Harbour did show much stronger winds from the direction of typical southwesterly prevailing winds. Trigonometry was used to split winds into their north-

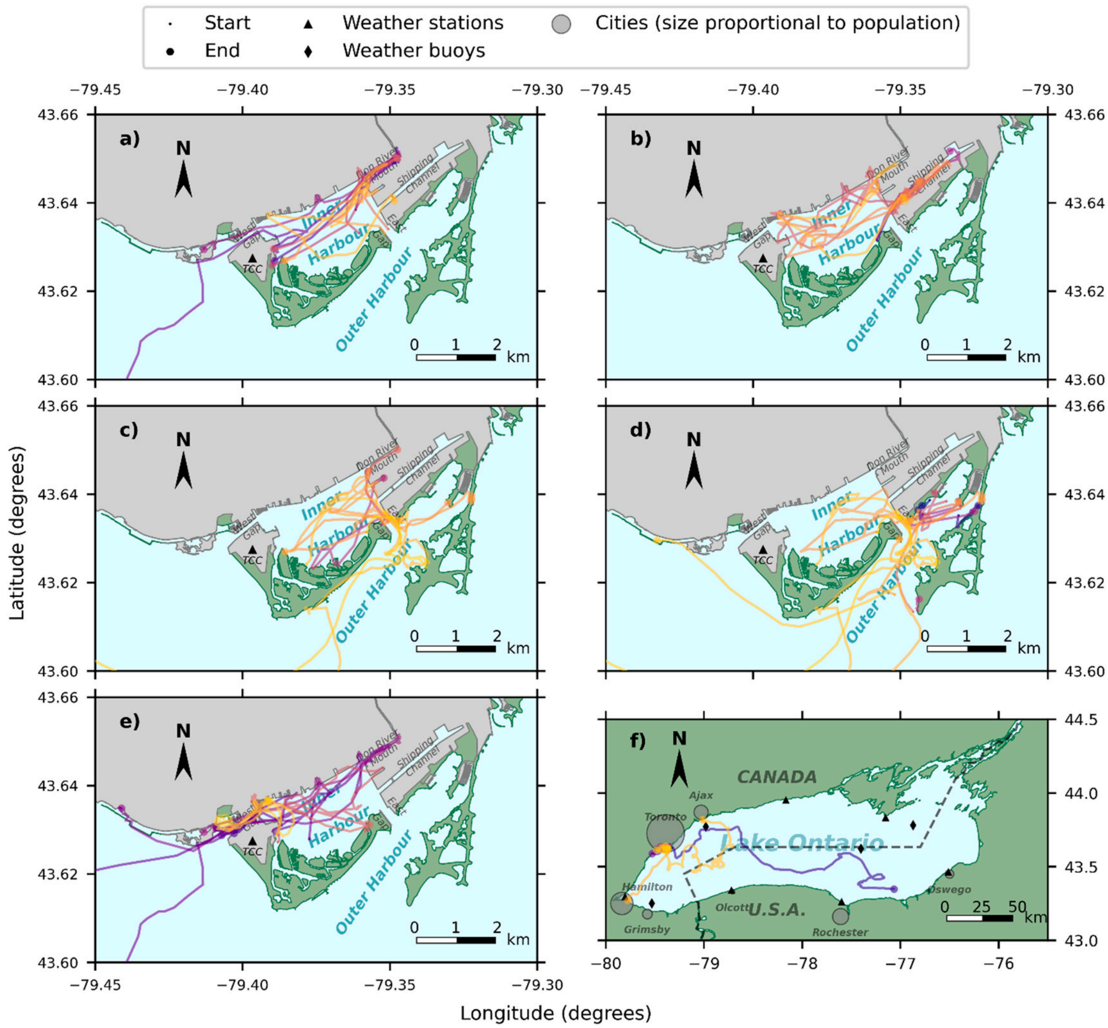

Fig. 4. Map of observed drifter paths within grouped by on transport patterns for the following locations a) Don River Mouth, b) Shipping Channel, c) East Gap, d) Outer Harbour, and e) West Gap within the vicinity of Toronto Harbour. See supplementary information for a time-lapse animation showing all drifter paths within Toronto Harbour (https://youtu.be/yfE9pLOog5g). All drifters that travelled outside Toronto Harbour and into Lake Ontario are shown in f). Most drifters that managed to escape Toronto Harbour became stranded within 10 km of the harbour, but 3 drifters managed to travel hundreds of kilometers in Lake Ontario. Each individual drifter path is consistently represented by a unique colour between plots and the timelapse animation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

south and east-west component vectors used in data analysis.

3.3. Wind and drifter relationships

Drifters showed strong wind-dependent transport. Easterly winds pushed drifters against the shores of Toronto's Centre Island while westerly winds blew drifters toward the Keating Channel, shipping channel, and deep into outer harbour's most northeastern shorelines. Northerly and southerly winds, while also uncommonly frequent, were much weaker than easterly or westerly prevailing winds and as such the net displacements of drifters were dominated by west and east transport. One drifter (see supplementary file 0-4334637_Dep4_0.png) oscillated in Toronto Harbour's West Gap coinciding with observed winds, except once when winds were calm and the drifter travelled back into Toronto Harbour presumably under the influence of water currents alone. Occasionally, westerly winds were strong enough to blow drifters and plastic debris upstream into the mouth of the Don River.

The observed drifter speeds and directions are correlated to the wind, both within and outside of Toronto Harbour, as summarized in Fig. 7. Drifters that travelled through open Lake Ontario have much faster speeds (mean = 24.2 cm s^{-1}) than drifters within 1 km of the relatively sheltered Toronto Harbour (mean = 3.5 cm s^{-1}). Wind speeds are generally 15–30 times faster than drifter speeds, although drifter speeds can exceed wind speeds due to the presence of water currents. The high proportion of drifters travelling at near-zero speeds corresponds to the stranding or trapping of drifters – approximately 20–30 % of all observed data. Common (base 10) log-normal drifter speeds show a bimodal distribution – when this bimodal distribution is split into 2 unimodal components, the average drifter speeds in open water are approximately 13.57 cm s^{-1} (10^($\mu = 1.13$, $\sigma = \pm 0.34$) cm s^{-1}), while average drifter speeds at shorelines are 0.78 cm s^{-1} (10^($\mu = -0.108$, $\sigma = \pm 0.504$) cm s^{-1}).

The drifter-to-wind direction differences have a broad distribution that is centered at 0°, indicating that drifters generally travel in the same direction as the wind (Fig. 7c, f). If the drifters travelled directly downwind, we would expect a narrow and tighter distribution in the histograms. The broad histograms are a result of the complex water currents in finite basins. For example, in a large open body of water we might expect drifters to travel directly downwind, although it is expected that Coriolis forces due to Earth's rotation will deflect surface currents to the right of the wind direction in the northern hemisphere. Toronto Harbour is relatively small, and the direction of the wind often

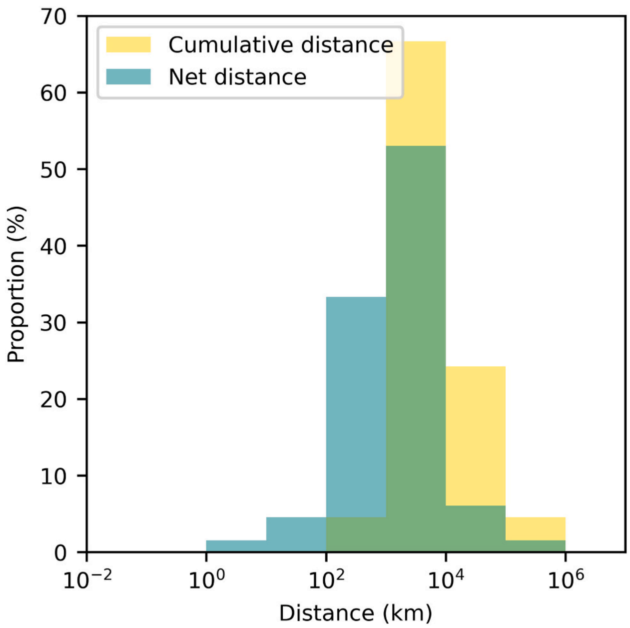

Fig. 5. Histogram of cumulative (yellow) and net (teal) distances travelled by drifters between initial and terminal (final) positions. Cumulative distances show a fairly normal (logit) distribution, with a peak of approximately 67 % of the drifters travelling cumulative distances between 1 and 10 km. Net distance results show similar trends to cumulative distance results, but net distances are nearly an order of magnitude smaller than cumulative distances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

does not align with the shorelines, resulting in water currents at an angle to the wind. There will also be recirculation patterns that set up return flows flowing against winds. Perhaps most importantly water currents take time to set up, and they persist after the wind stops, so that drifter velocity is often lagging behind wind velocity changes.

3.4. Wind factor analysis

One way to quantify the drift speed of our drifters is to calculate the wind factor – how fast the drifters move relative to the wind speed (Fig. 8). The short-term variability of currents in the Toronto Harbour is thought to be largely wind driven (Hlevca et al., 2018) so we expected a fair correlation between drifter speed and direction, and wind speed and direction. Wind factors describe drifter speed as a percentage of wind speeds. The observed mean wind factors of our drifters within 1 km of Toronto Harbour reinforce the findings of Haines and Bryson (1961) for the values of the wind factors. They also align with typical water current speeds in lakes being 2–5 % of wind speeds. However, there is a lot of variability in drifter wind factors where drifter wind factors within 1 km of Toronto Harbour can easily be between 2 and 5 times greater than expected from the Haines and Bryson (1961) equation ($WF_{Haines\&Bryson} = 5.3\ \%/U_{wind} + 0.013\ \%$, with U_{wind} in m s^{-1}), and up to 7 times greater outside 1 km of Toronto Harbour. Wind factor equations for our observations within 1 km of Toronto Harbour ($WF_{\leq 1km\ TH} = 4.1\ \%/U_{wind} + 0.014\ \%$) and without 1 km of Toronto Harbour ($WF_{>1\ km\ TH} = 12.0\ \%/U_{wind} + 3.188\ \%$) were rational equations calculated from lines fitted to our drifter speed versus wind speed observations using linear regression. Additionally, there are clusters of many near-zero wind factor observations which lowered the observed mean wind factors and coefficients of determination (R^2 values; $1.85 \times 10^{-5} < 1$ km outside TH; $0.11 > 1$ km outside TH) for the linear equation fits used for calculation of wind factor rational equations. Hence, their equation is a great foundational tool, but the variability, outliers, and the effects of confounding factors (e.g. shoreline complexity) should be recognized and considered when modelling plastic debris transport.

4. Discussion

While most drifters released in the harbour remained exclusively within the harbour, 22.2 % of drifters deployed within Toronto Harbour's boundaries had escaped the harbour. Two of these escaped drifters had re-entered the harbour on at least one occasion through the West Gap and demonstrated the potential for infiltration of debris into Toronto Harbour from elsewhere in Lake Ontario. Two of the three drifters deployed outside of Toronto Harbour's boundaries quickly became beached on Toronto Harbour's external boundary but had not quite entered Toronto's Inner or Outer Harbours. Overall, three drifters had travelled long distances of >100 km across Lake Ontario (Fig. 9a), the first was deployed just outside Toronto Harbour's eastern boundary and travelled through Lake Ontario toward the city of Rochester; the second was deployed in Toronto's Outer Harbour and travelled through Lake Ontario toward Hamilton; the third was deployed near the shoreline of the southwest corner of Toronto's Inner Harbour, then travelled through the East Gap, Outer Harbour, and Lake Ontario to the City of Ajax. These observations demonstrated that Toronto Harbour's plastic pollution can disseminate throughout Lake Ontario.

Most notably, under the same wind conditions, drifters travelled faster in the open waters of Lake Ontario relative to drifters travelling in the less expansive and shallower waters of Toronto Harbour (Fig. 8). The high shoreline complexity of Toronto Harbour can redirect or retard surface water currents, particularly in nearshore areas. Meanwhile, land topography affects surface water currents by funneling or acting as a barrier to winds. Our drifters are directly affected by winds because they are approximately half-submerged in the water, and half-exposed to winds – meaning that they are approximately 50 % influenced by water currents and 50 % influenced by wind currents. The direct interaction of our drifters with winds had occasionally elevated the wind factors for our drifters relative to expected water current speeds. The wind factor values observed in Toronto Harbour were very similar to those described by Haines and Bryson (1961), where their drifters travelled approximately at expected surface water current speeds. Given the similarity of scale between Toronto Harbour (13 km length, 1.5 km width, 6 m mean depth) and Haines' and Bryson's study site, Lake Mendota (9 km length, 6.6 km width, 12.8 m mean depth), this similarity in wind factors was expected (Hlevca et al., 2018). The implications of these relatively small basin dimensions are that surface wind-driven water currents are fetch-limited, and bottom drag of these shallow basins have a greater importance on slowing the flow of water currents when winds stop blowing. It is important to note that our observed near-zero wind factors (i.e. smaller than the expected wind factors) are likely attributed to the effects of shoreline complexity and basin morphometry. Meanwhile, where observed drifter wind factors are larger than the expected wind factors, they are likely attributed to the direct interaction of our drifters with winds. When comparing our results to previous field work by Haines and Bryson (1961), George (1981), and Wells and Troy (2022), they are in agreement that drifter speeds are fastest for the strongest winds. Our results also agree with their observations where wind factors are highest for slower winds, such that wind factors can be described as being inversely proportional to wind speeds. These various field-study estimates of wind factor have substantial variability, which may arise due to the effects of drifter size and shape. However, these studies all find wind factors of <5 % for low-windage drifters. We can anticipate that wind factors will be greater for very buoyant plastic debris, like our relatively high-windage drifters, for which a large fraction of the debris sits above water and can directly interact with winds.

The effects of direct wind-to-drifter interaction are more apparent for drifters that travelled into Lake Ontario's open waters, i.e. they had larger wind factors than drifters within Toronto Harbour. These wind factors for large open lakes were as much as 7 times larger than the expected surface water current speeds; drifters could sometimes move at

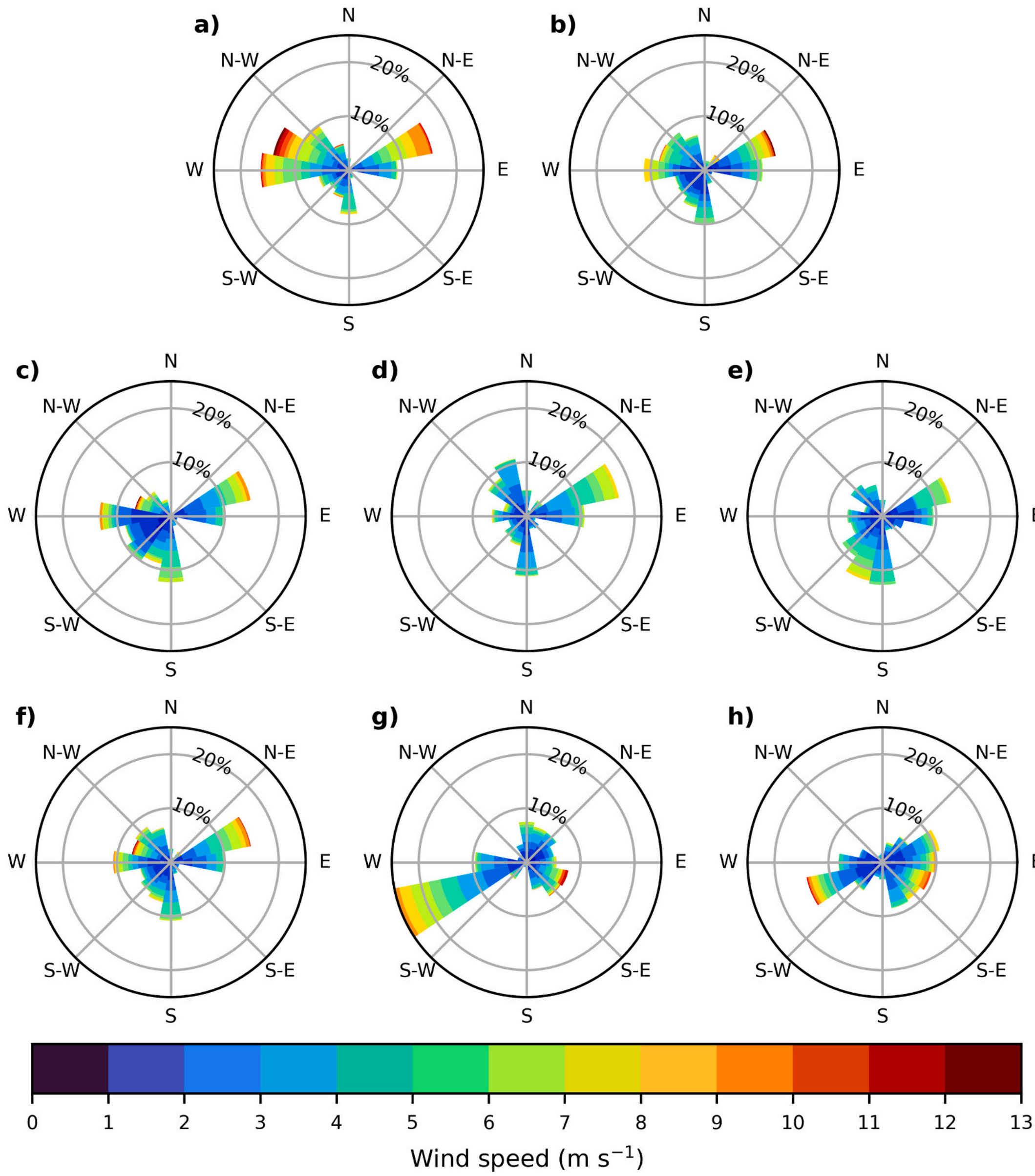

Fig. 6. Wind roses showing radial wind velocity histograms (in m s^{-1}) observed at Toronto City Center weather station during the months a) April, b) May, c) June, d) July, and e) August, f) the entire 2021 sampling season (April 16–August 18, 2021) from the Government of Canada Historical Weather data archive (Government of Canada, 2021), g) winds coinciding with observations of drifters within 1 km of Toronto Harbour, and h) winds coinciding with observations of drifters outside 1 km of Toronto Harbour. The size of each of the bars on the wind rose indicates more wind coming from that direction while the colour corresponds to wind speed; blues indicate slower speeds and reds indicate faster speeds. Atypically, southwesterly prevailing winds were weak during the entire 2021 sampling season. Occasional storms occur that bring in strong winds from the north, east, and south. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

speeds approaching 50 % of wind speeds, particularly when wind speeds are slower. Additionally, concurrent wind and water currents can interact with the drifter constructively such that a drifter can reach very fast transport speeds. This can be explained by the persistence of water currents in the much deeper and larger Lake Ontario, since there is less fetch limitation and less importance of bottom drag slowing currents. When the wind stops in the open waters of thermally stratified lakes, like Lake Ontario, the upper layers of water are buffered from the effects of bottom drag at the lower layers, meaning that surface water currents persist in absence of wind (Choi et al., 2020). These persistent and large water currents can transport drifters long distances during periods of low wind. Another feature seen in these deep open waters of Lake Ontario is the clockwise spiralling of water currents, so-called "inertial waltzes" (Choi et al., 2020), whereby water currents and our drifters travel in clockwise motions when winds stop. This occurs due to Coriolis forces, caused by the Earth's rotation, which lead to a continuous force toward the right-hand side (clockwise). For instance, a current moving at 0.1 m s^{-1}, will execute a circular motion with a radius of approximately 5–10 km by this process. Such inertial motions are frequently visible in Fig. 9b, and these persistent motions at low wind speed can influence the wind factors.

The classic picture of water circulation in Lake Ontario is described by Beletsky et al. (1999), and is compared to our drifter paths outside Toronto Harbour (Fig. 9b). The depictions of water circulation by Beletsky et al. (1999) appear to suggest the Great Lakes have a system of steady gyres driven by the prevailing westerly winds, but it is important to remember that these figures show only the mean flows as a summary of water circulation, and that there is actually considerable variation in

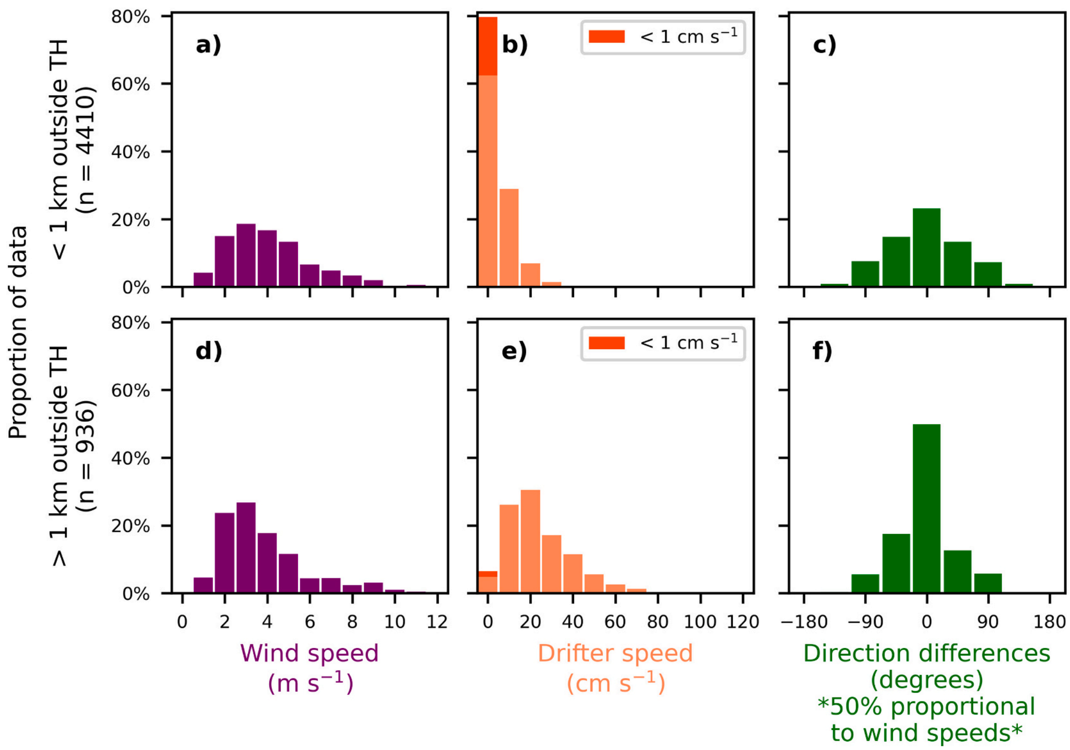

Fig. 7. A comparison of the histograms of wind speeds (purple) concurrent with drifter speeds (orange), and drifter-to-wind direction differences (green), for the region within 1 km of Toronto Harbour (a, b, c) and regions >1 km outside of Toronto Harbour (d, e, f). Histograms of concurrent wind speed distribution (purple) were measured at Toronto City Center Station for the region within 1 km of Toronto Harbour, while inverse-distance-squared weighted interpolated wind data was used for regions >1 km outside Toronto Harbour. Drifter speeds are shown a much stronger right-skewed distribution relative to wind speeds, particularly within 1 km of Toronto Harbour. Direction differences are roughly centered at 0°, implying that on average plastic debris is blown downwind.

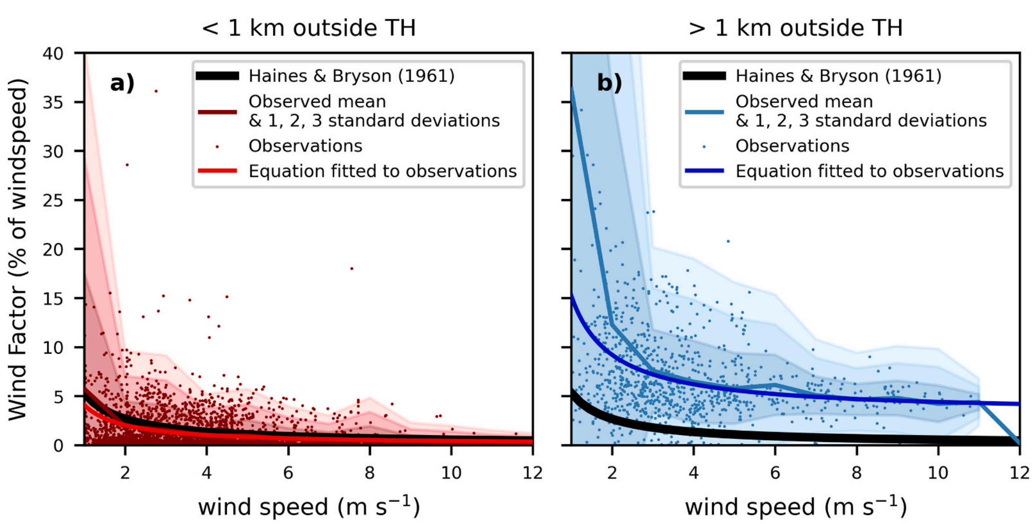

Fig. 8. Wind factor (drifter speed expressed as % of wind speed) vs wind speed (m s^{-1}) with line fitted for wind factor equation from Haines and Bryson (1961). a) Wind factors plotted for drifters travelling within 1 km of Toronto Harbour (red). The observed mean calculated wind factor (dark red line) is slightly lower but follows the expected wind factors defined by the equation from Haines and Bryson (1961) (black line) nearly exactly. Nearly all (99 %) of datapoints are within 3 standard deviations from the mean (red shaded area). b) Wind factors for drifters travelling outside of 1 km of Toronto Harbour (blue). The observed mean calculated wind factor (dark blue line) is >2-fold higher than expected wind factors. Wind factors within 1 km of Toronto Harbour boundaries (red) are approximately 5-fold lower than those outside 1 km of Toronto Harbour boundaries (blue), and all observed wind factors show high variability. Note: Winds outside of 1 km of Toronto Harbour were estimated using inverse-distance-squared weighted interpolation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water currents around this mean. For instance, our drifters that escaped Toronto Harbour had travelled in different directions; most travelled west before becoming stranded within 10 km of Toronto Harbour; one travelled directly southwest to end up near Hamilton, Ontario; one circuitously headed east toward Ajax, Ontario; and one headed to the south-east to end up near Rochester, New York. Since we collected very few datasets for drifters travelling in Lake Ontario, the coincidence of mean circulation patterns and our observations can only be considered

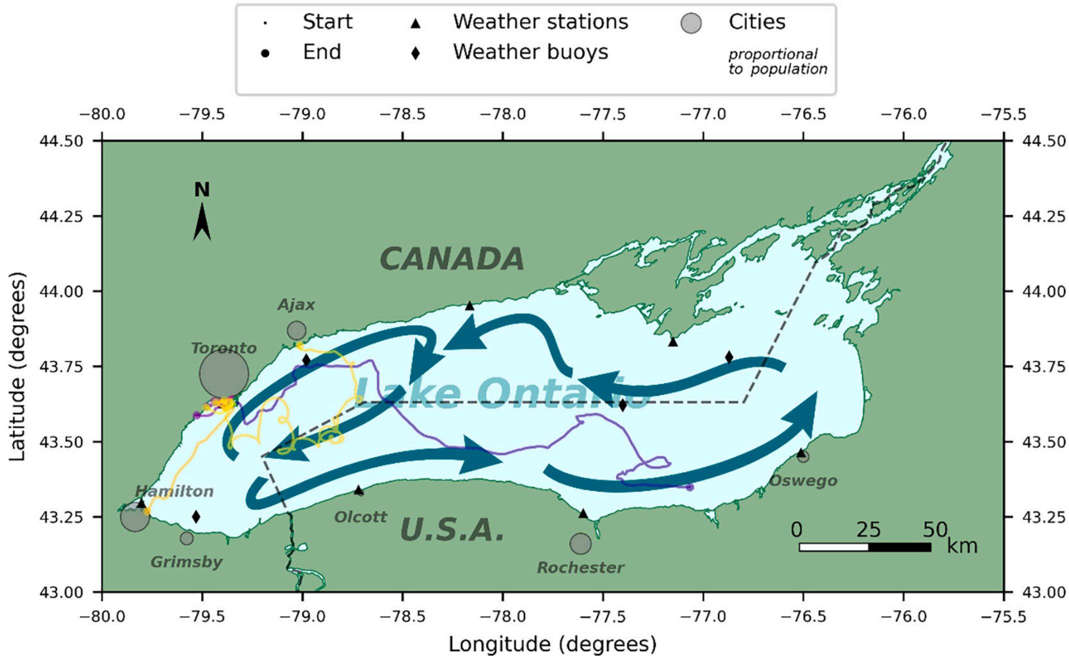

Fig. 9. Observed drifter paths in Lake Ontario compared to the generalized surface water circulation patterns from Beletsky et al. (1999). Lake Ontario water currents are generalized to have an anti-clockwise (cyclonic) circulation pattern, but instantaneous surface water currents are highly variable and constantly changing due to their heavy dependence on winds blowing on the lake surface. Surface currents can change direction rapidly due to shifting air masses and storms.

to be anecdotal rather than a reinforcement of the Beletsky et al. (1999) proposed mean circulation pattern. In fact, the drifter that travelled to Ajax actually happened to travel opposite of the expected mean circulation. It would be hypothetically possible for high-windage drifters to be blown into different water currents, which could result in a sharp directional change. Unfortunately, the data collected in this study is not enough to answer these questions. Using current meters, Beletsky et al. (1999) reported minimum, maximum, and average mean water current speeds of 0.1 cm s^{-1}, 2.5 cm s^{-1}, and 1.0 cm s^{-1} in summer. All these speeds are much slower than our instantaneous observed average drifter speeds of approximately 3.5 cm s^{-1} within 1 km of Toronto Harbour's boundaries, and 24.2 cm s^{-1} outside 1 km of Toronto Harbour's boundaries, respectively (Fig. 7b, e). The surface water current data used by Beletsky et al. (1999) was measured at 15 m depth, so we expect that actual surface currents could be much larger, given that surface currents generally decay with depth (Wells and Troy, 2022). For instance, in Lake Ontario, Swatridge et al. (2022) used a well-tested numerical model to predict that the mean water currents can reach 60 cm s^{-1} in the coastal jets during storms, and at some locations in their model the water currents reached speeds of 80 cm s^{-1}. While the picture of water circulation in Lake Ontario as described by Beletsky et al. (1999) is powerful, it does not illustrate the large variability in water current directions and speed caused by wind forcing. The average water currents in Lake Ontario can be relatively fast (10–20 cm s^{-1}), and due to the great depths of the lake, the currents persist even when the wind stops. Taken together, these features mean that plastic debris can travel much faster and farther in the vast open waters of the Great Lakes relative to a smaller waterbody of similar size to Toronto Harbour.

While there are emerging models for plastic transport in the Great Lakes (Daily and Hoffman, 2020), the transport of plastic debris in lakes in general is not nearly as well understood as that in oceans. For example, Maes and Blanke (2015) modelled international oceanic transport of floating plastic bottles to explain their observation of stranded plastic bottles in New Caledonia that likely originated from the Solomon Islands and Papua New Guinea. Conceptually similar studies include models of the dispersion of debris across the Pacific from the Japanese tsunami (Maximenko et al., 2018), dispersion of buoyant pumice from a volcano in the south pacific (Bryan et al., 2004), and dispersion of wreckage in Indian Ocean from the lost Malaysia Airlines flight MH370 (Durgadoo et al., 2019). A key variable used in such debris dispersion models is the windage of buoyant debris - if a large fraction of an object is out of water, it will catch more wind than a fully submerged object, and can be transported faster than surface water currents (typically 2–6 % of the wind speed, Maximenko et al., 2018). For small to medium lakes where the Coriolis effect from earth's rotation is negligible, studies consistently find water currents with wind factors in the range of 1.5–3 % (Henderson-Sellers, 1988).

4.1. Implications for movements of floating debris in Toronto Harbour

It is widely acknowledged that large urban centres are overwhelmingly the sources of most aquatic plastic pollution (Nava et al., 2023; Baldwin et al., 2016). Zhu et al. (2024) estimated that approximately 3.5–3.9 thousand tonnes of plastic debris is emitted by Toronto annually. Our field observations show that plastics can easily travel several kilometers in a day within Toronto Harbour, and thus the transport and accumulation of plastics at a particular location depends on basin morphometry and spatial variation of loading and transport. Our drifters that managed to escape Toronto Harbour and travelled into Lake Ontario tended to travel distances approximately an order of magnitude larger than drifters travelling within Toronto Harbour, and all drifters demonstrated large variability in travel distances ranging from 581 m to 290 km. Similarly, an estuary and river drifter study by Tramoy et al. (2020) showed large variability in total cumulative distances ranging from 0.7 km to 360.1 km, where more variability was observed in the estuary. Their drifters also tended to travel longer distances in the open waters of the estuary relative to the river. Fortunately, most of Toronto's plastic pollution is expected to remain local, which allows for localized interception of Toronto's plastic pollution and prevention of widespread plastic pollution transport.

Plastic pollution must be intercepted within Toronto Harbour through various means, and interception should be prioritized where there is rapid transport, high-volume transport, and natural accumulation of plastic pollution. Areas of rapid and high-volume drifter transport at the openings of the East Gap, West Gap, and the Shipping Channel would be best suited for the installation of passive trash-capture devices like Seabins, since there was little to no accumulation of plastic debris in these areas and constant manual cleanups of these areas are infeasible. High-volume transport and accumulation of drifters was observed at the mouth of the Don River, where regular cleanups and an active trash capture device like a trash wheel, which pulls floating plastic debris out of the water with a conveyor belt (Lindquist, 2016), are recommended. Trash capture devices should be prioritized at the West Gap to address the relatively high proportion of escaped drifters at this location. Our drifters were observed to naturally accumulate in slips and embayments, along piers, and under boardwalks, bridges, and docks. Accumulation was more transient along urbanized shorelines rather than naturalized vegetated or sloping shorelines; urban shorelines would require more frequent cleanups to maximize plastic pollution collection.

A visual audit by Sherlock et al. (2023) in Toronto Harbour during the summer of 2021, found plastic debris accumulation to be variable throughout the harbour where counts of anthropogenic debris items collected ranged from 10 to 276 items per site. Overall, Sherlock et al. (2023) ranked plastic bottle caps as the 1st most common (837 total pieces) and plastic water bottles the 8th most common (190 total pieces) types of anthropogenic debris. The presence of many bottlecaps and relatively few bottles suggest the potential for a larger loading and removal of plastic bottles into Toronto Harbour than observed through the visual audit. Drifters from our Tagging Trash project were not included in the visual audit nor captured by Seabins (passive trash capture devices – see https://seabin.io/). Given the small number of our drifters observed at the study sites of Sherlock et al. (2023), and the total number of our deployed drifters, the actual amount of plastic pollution that could be travelling through Toronto Harbour is staggering.

The western regions of Toronto Harbour, particularly Peter St Basin, accumulated more anthropogenic debris than eastern regions (Sherlock et al., 2023), which can be attributed to the dominance of wind-driven transport. Based on the typical southwesterly prevailing wind pattern in the Great Lakes, plastic debris was expected to accumulate along eastern shorelines, as observed from previous beach-cleanup studies throughout the Great Lakes (Zbyszewski and Corcoran, 2011; Driedger et al., 2015). However, considering the atypical wind patterns of 2021 (Fig. 6) with weak and infrequent southwesterly winds and frequent strong northeasterly winds, it was unsurprising that floating plastic debris accumulated along the western regions of Toronto Harbour. Sherlock et al. (2023) did not find a positive correlation between wet weather events (i.e. rain) and increased plastic debris counts, as would be expected if storm water were major source of plastics, which further supports the dominance of wind-driven transport of plastic debris in Toronto Harbour.

5. Conclusion

This paper is, to our knowledge, the first to quantify how fast and how far plastics can travel from their urban sources in a lake. As the largest city in the watershed of Lake Ontario, Toronto is likely one of the major sources of plastic debris into Lake Ontario. Our drifter results suggest that most floating macroplastics in Toronto Harbour (~3/4 of all drifters) will become stranded very close to their sources, but some (~1/4 of all drifters) can leave the harbour and travel hundreds of kilometers in Lake Ontario (~5 % of all drifters). While floating plastic pollution appears to be mostly localized, a sizeable fraction of plastic pollution is far reaching, making Toronto Harbour an urban upstream source of plastic pollution for Lake Ontario. These findings reinforce the need for waste-management infrastructure near plastic pollution sources to prevent debris transport into remote areas that are not feasible to remediate.

Our drifters demonstrated where plastics were transported and accumulated, which informs waste-management infrastructure improvements within and around Toronto Harbour. Drifters displayed natural accumulation zones in embayments, under boardwalks and docks, near piers, and within slips. Areas of temporary accumulation are good candidates for passive trash capture devices (e.g. Seabins), particularly along the urbanized northwestern and northeastern shorelines. Regular cleanups are the best option for removing plastic debris from naturalized shorelines like those of the Toronto Islands. Areas with high-volume debris transport at the Mouth of the Don River should have infrastructure that can manage very large amounts of debris, like a trash-wheel. Manual cleanups and trash capture devices at the periphery of high-volume transport areas like the Shipping Channel, and West and East Gaps would prevent plastic debris from escaping Toronto Harbour.

A key result of this study is that the transport paths of plastic debris in open water were largely wind-driven. Floating plastic debris emulated by our drifters demonstrated that the dissemination of plastic debris is much faster and expansive than expected from water currents alone. Floating plastic debris can easily be transported 7 times faster than expected, and plastic emissions from Toronto leaves a spatial footprint throughout Lake Ontario. It is important to note that variability in wind direction will also lead to variability in water currents and thus plastic debris transport paths. For instance, the drifters that travelled outside of the harbour travelled in different directions; most escapees travelled west before becoming stranded within 10 km of Toronto Harbour, one travelled 50 km southwest toward Hamilton, Ontario, one headed 30 km east toward Ajax, Ontario, and one headed 190 km south-southeast toward Rochester, New York. This intrinsic variation in wind-driven water currents means caution should be remembered when interpreting the gyre-like mean circulation patterns in the Great Lakes as described by Beletsky et al. (1999). Fortunately, if plastic pollution emissions from Toronto are reduced, these actions would also reduce plastic pollution throughout all of Lake Ontario.

CRediT authorship contribution statement

P.O. Semcesen: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.G. Wells:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. **C. Sherlock:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **R.F. Gutierrez:** Writing – review & editing, Methodology, Conceptualization. **C.M. Rochman:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mathew Wells reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Has patent pending to. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.marpolbul.2025.118034. These data include the Google maps of the most important areas described in this article.

Data availability

Source data has been included in supplementary information. Select code will become available in a future MethodsX article, or can be requested from the corresponding author.

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