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Floating microplastics in a coastal embayment: A multifaceted issue

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ABSTRACT

Floating microplastic debris at the ocean's surface represents about 1% of all plastics found in the environment, with the remainder thought to be either deposited along the coast or sinks to the bottom of the ocean. This exploratory research on a coastal embayment in the Northeast Atlantic Ocean assesses floating microplastic densities and the potential influence of wind. A total of 1182 floating microplastic particles were retrieved from a total surface seawater volume of 2039.86 m^3. The average microplastic density (0.56 ± 0.33 MP m^{-3}) is based on a sample of 20 manta trawls. This study reports primary microplastics (microbeads) floating in Irish coastal waters for the first-time. Compared to similar bays in Europe, Galway Bay has a similar microplastic density range. Microplastics in surface waters are a multifaceted issue therefore, multiple types of sample collection along with associated environmental variables are recommended for coastal monitoring purposes.

1. Introduction

Plastic items of all shapes, colours and sizes are stockpiling globally in the marine environment at unprecedented rates (Jambeck et al., 2015; Lebreton et al., 2018), while global production continues to rise exponentially (PlasticsEurope, 2019). Plastic items are widely used in several industries and their physical and chemical properties contribute to the widespread distribution and residence time in the marine environment (Law, 2017). In fact, plastics have been reported in pristine environments from the Arctic (Kanhai et al., 2019) to the Antarctic (Lacerda et al., 2019), including the Swiss Alps (Bergmann et al., 2019), which illustrates the extent and ubiquity of the problem.

Among plastic marine litter, microplastics (MPs), defined by both Frias and Nash (2019) and Hartmann et al. (2019) represent an higher risk to marine wildlife and as such have been widely studied over the last decade, with the aim to map, identify and assess their sources, sinks and impacts (Jang et al., 2014; van Sebille et al., 2019; Maximenko et al., 2019). So far, MPs have been identified in every environmental matrix explored, including: ice cores (Kanhai et al., 2019), glaciers (Ambrosini et al., 2019), benthic sediments (Wang et al., 2019), lakes (Eriksen et al., 2013; Ballent et al., 2016), seawater samples (Collignon et al., 2012), and biota (Lusher et al., 2014; Markic et al., 2018). Their presence in the marine environment has negative effects to wildlife and human activities, with scientists even arguing that plastic debris should be classified as hazardous materials for their potential toxicological effects (Rochman et al., 2013).

Microplastics can either have primary or secondary origin, depending respectively on whether they have been purposely manufactured to have microscopic dimensions or whether they result from the fragmentation of larger plastic items exposed to weathering conditions in the environment (Cole et al., 2011). Most studies report mainly secondary microplastics such as fibres (Gago et al., 2018) and fragments, with only a reduced number of studies reporting primary microplastics, particularly resin pellets (Frias et al., 2010, Karlsson et al., 2018) and microbeads (Mani et al., 2019).

This exploratory work intends to assess the densities of floating microplastics in surface seawater in Galway Bay, and as a first step, to establish a representative baseline for this emerging pollutant.

2. Materials and methods

2.1. Study area

Located on the west coast of Ireland, Galway Bay (53 07.207 N, 9 29.048 W; Fig. 1) is a large semi-enclosed bay (62 km in length by 33 km in breadth) protected from the strong Atlantic Ocean swells by the Aran islands (Joshi and Farrell, 2020). The bay narrows to 12 km at the headland of Black Head resulting in a natural characterisation of the bay to Inner and Outer (Figs. 1, 2). The main freshwater input influencing the bay is the Corrib River (flow rate ~ 100 ± 60 $m^3 s^{-1}$; Joshi and Farrell, 2020) and the flow of oceanic water from the Atlantic Ocean also contribute to mixing effects (BIM, 2012). The seawater

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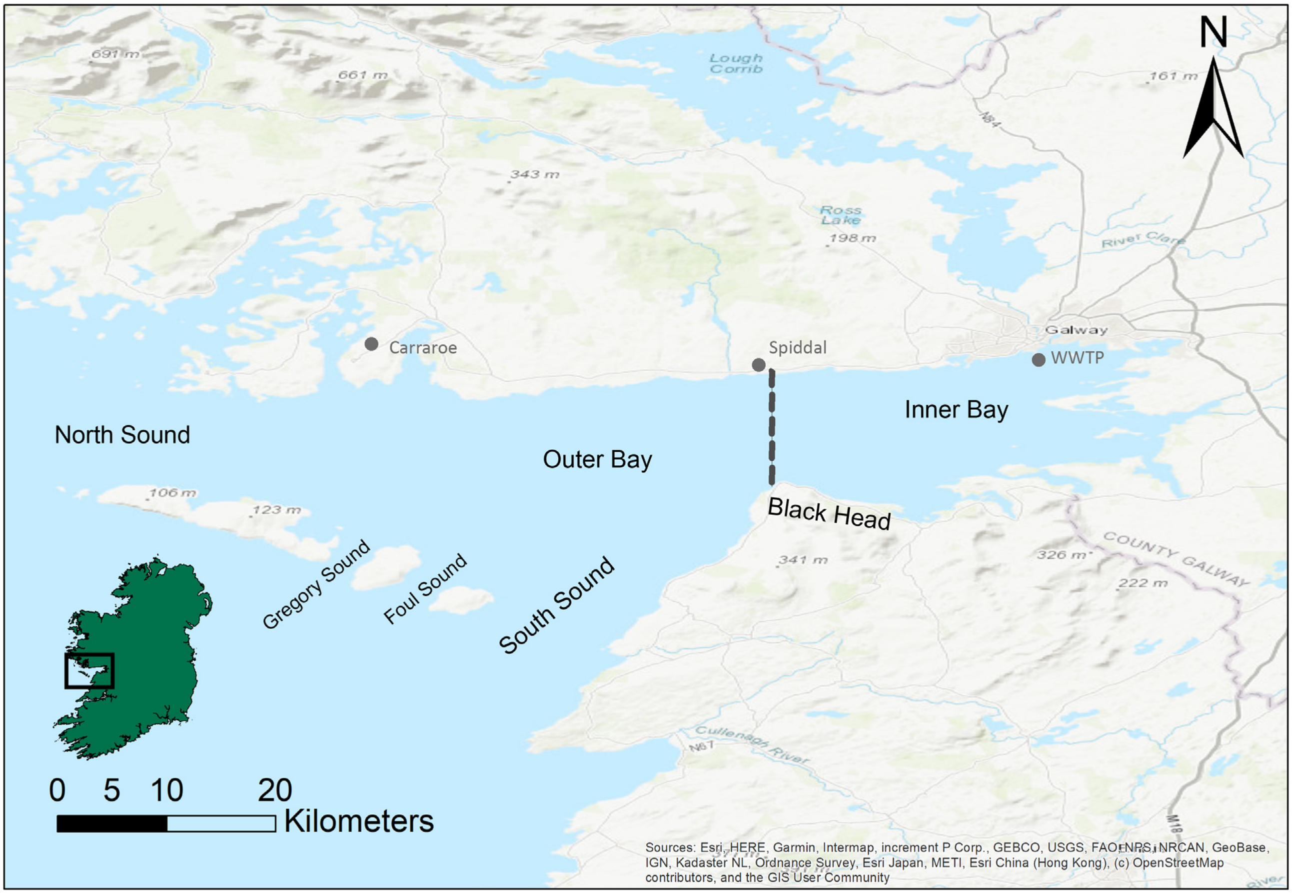


Fig. 1. Location of Galway Bay, West coast of Ireland. Dash line, adapted from O'Donncha et al. (2015), shows an arbitrary boundary between Inner and Outer bay at the constriction of the Bay.

circulation pattern within Galway Bay is anticlockwise and the seawater enters the bay mainly through the South Sound and exits through the North Sound (BIM, 2012; Joshi and Farrell, 2020). The depth within the bay is variable, with the inner bay ranging between 0 and 20 m, and the outer bay ranging between 20 and 60 m (Joshi and Farrell, 2020). The bay includes a shipping port in the inner bay, the 7th busiest in the country, with approximately 180 vessels passing through the port in 2017 and carrying almost 856,300 t of cargo (Central Statistics Office, 2019a). In 2016, Galway City and suburbs had a population of approximately 80,000 inhabitants (Central Statistics Office, 2019b). The inner bay also has a wastewater treatment plant (WWTP) (Mutton Island - domestic and industrial sewage 91,600 population equivalent (PE)) (Monaghan et al., 2009) that discharges to the Bay, and two untreated urban wastewater discharge points off Spiddal and Carraroe (EPA, 2019).

2.2. Sample collection, storage and processing

Seawater surface samples were collected on board of the R/V *Celtic Voyager*, in October 2017 (CV17026) and December 2017 (CV17039) (Fig. 2). A total of 20 surface trawls were carried out within the bay using a manta trawl. Stations were selected taking into consideration potential inflow sources of microplastics into the bay (e.g. the River Corrib). Sampling stations followed transect lines: in the Inner Bay the transect went from Galway City towards Blackhead, Co. Clare; and in the Outer Bay several transects were made following circulation patterns within the bay. Trawls M1 to M5, in bold, were surveyed in October 2017, and the trawls 1M1 to 12M1 were surveyed in December 2017 (Fig. 2). All trawls are independent and were dependent on weather conditions.

Galway Bay is known to have consistent rainfall throughout the year. The driest month is April, which has an average rainfall of 60 mm. The highest rainfall season is associated with Autumn/Winter period (Oct–Jan). Average rainfall for October (112 mm) and December (122 mm) is similar. As all sampling was conducted within this period, the flow of the Corrib river was also strong, which might have contributed to a microplastic load dilution in the first sampling stations.

The manta trawl frame used is made of aluminium and has two hollow long wings on each side to allow flotation. The frame has a rectangular aperture of 15 cm high and 61 cm wide, to which a 2 m long, 300 μm mesh size nylon net with a 30 × 10 cm^2 cod end was attached. The cod end was made of 3-mm thick grey PVC tubes with a total length of 23 cm and a diameter of 11 cm. The trawl frame was also equipped with a Hydro-Bios mechanical flowmeter with back-run stop, whose revolutions were registered prior to and after each tow, as well as the initial and final GPS coordinates.

The manta net was deployed from the starboard side of the vessel, in order to prevent collecting water affected by turbulence inside the wake zone, at an average speed of 2 knots for approximately 20 min.

Retrieval of surface seawater samples was conducted following an adapted methodology from Viršek et al. (2016), briefly: on attaining a sample, the manta net was thoroughly rinsed from the outside, from manta mouth to the cod end, using a freshwater hose connected to the vessel water reservoir. As such, all particles and organisms adhered to the net were now concentrated in the cod end. The cod end was detached and brought inside the wet lab where airborne contamination was being monitored using control filters. The cod end was then thoroughly rinsed with ultrapure water from the outside, and the sample washed through a set of previously decontaminated stainless-steel sieves (100 and 300 μm), to capture microplastics particles ≥100 and

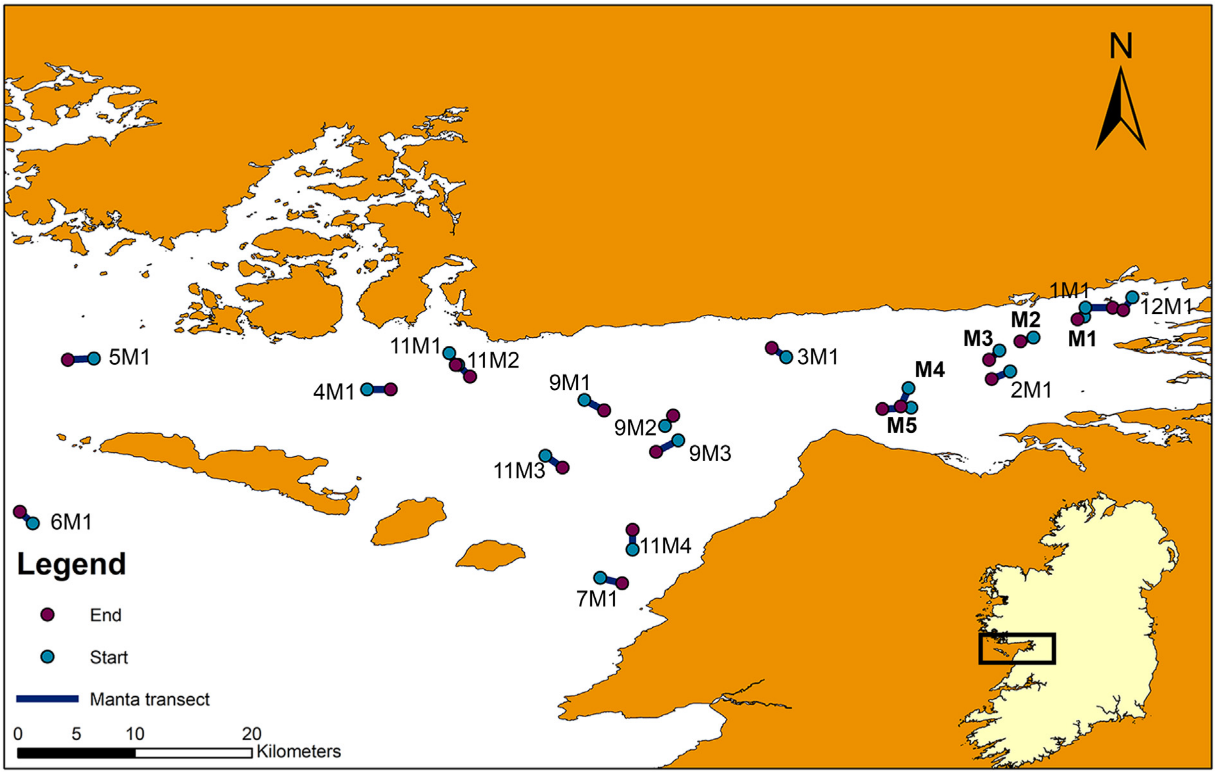


Fig. 2. Sampling sites in Galway Bay, including the starting (purple dot) and ending (blue dot) points of each trawl. Stations in bold (M1–M5) correspond to October cruise, the remaining stations correspond to the December cruise (1M1–12M1), all in 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

≤300 μm. All natural (wood/algae) or artificial litter (fragments) visibly larger > 5 mm (macro and meso litter) were carefully removed using metal tweezers, and not accounted for here. The contents of the sieve were gently washed into a decontaminated glass jar with a labelled metal lid. The sieve was rinsed with filtered seawater three times and the contents were added to the jar. Samples were immediately frozen −20 °C, without adding fixing solutions, until further analysis.

2.3. Microplastic analysis

In the laboratory, samples were defrosted in the glass jar. A 10% potassium hydroxide (KOH) solution was then introduced to digest the zooplankton, for 24 h at room temperature (~20 °C). The resulting digestate was filtered using a vacuum pump (VWR VCP 130) through a 47 mm Whatman® GF/C glass microfiber filter membrane. This filter was transferred onto a labelled petri dish which was then used for visual examination and sorting of microplastics under a stereomicroscope (Olympus SZX7). Microplastics were counted, photographed and measured using Olympus CellSens® software. Polymer identification was carried out in a subsample (n = 37) of micro particles, using a Bruker Hyperion 2000 series μ-FTIR microscope, on transmission mode, within the wavenumber range 4000–400 cm^{-1} using a spectral resolution of 4 cm^{-1}, using 128 scans per sample. The background spectrum was measured with the same parameters prior to scanning other samples. The subsample selected was based on the suspected microplastic which was commonly found throughout the sample processing.

2.4. Contamination control and reduction of cross-contamination

Preventive contamination and cross-contamination measures, particularly targeted at vessel cross-contamination and airborne microplastic particles was carried out during sample collection, handling and processing following recommendations from Frias et al. (2018) and Hara et al. (2020). Vessel contamination was assessed through the removing of a small paint sample from the outside of the vessel for later comparison and by accounting for airborne cross-contamination during collection. Inside the vessel's wet lab, airborne control was accounted for using glass microfiber filters.

During laboratory handling and processing, the methodology followed was the one described by Hara et al. (2020), briefly: 100% cotton lab coats and nitrile gloves were worn at all times; all work surfaces, benches, tools and equipment were thoroughly cleaned with ethanol prior to and after use; all glassware was decontaminated using a nitric acid (HNO_3) (0.05%) bath wash, followed by rinsing with ultrapure water. Colours of clothing items worn underneath the lab coats were daily registered and operator tried to use natural fibres (e.g. cotton and wool) underneath. All open jars and beakers were covered with aluminium foil.

Working stations were subjected to airborne contamination controls using clean glass microfiber filters. To ensure quality assurance and quality control (QA/QC), procedural blanks using ultrapure water and digesting solutions (KOH) were evaluated simultaneously during digestion processes. All solutions, including seawater, distilled water and KOH were filtered prior to use, and blank jars with the solutions were also used to assess the cleanliness of the acid wash.

2.5. Statistical analysis

All statistical modelling was performed in R version 3.6.3 (R Core Team, 2020). Descriptive statistics, histograms and box plots were generated, and tests of normality were conducted on all data sets to determine whether parametric or non-parametric statistical analyses were appropriate.

A generalised linear mixed model (GLMM) was developed (R package *Lme4*, Bates et al., 2015) to determine whether there were differences between the inner and outer Galway Bay regarding microplastic density, and to understand the influence of wind speed and direction in the microplastic density. Windrose maps were made in Python version 3.6.5 (van Rossum, 1995).

Multivariate analysis of variance (MANOVA) was used to investigate whether microplastic length and width and microplastic colour and type were different between inner and outer Galway Bay. The significance level for all statistical test was set at $\alpha = 0.05$.

3. Results

Samples from 20 manta trawl, collected in two different research cruises (Fig. 2), retrieved a total of 1182 microplastics from 2039.86 m^3 of surface seawater in Galway Bay, in October and December 2017. Despite being sampled in different months, there are no statistical differences between microplastic density between months. Microplastics collected from samples were divided into different types, with the most dominant MP, at 86.1% being fibres (n = 1017), followed by fragments 12.5% (n = 148). The remaining 1.4% corresponded to fishing line (n = 9), beads (n = 3), films (n = 2) and foams (n = 2). Size ranges differed depending on the MP type, i.e. fibres ranged from 102.8 to 20,760 μm in length and from 1.5 to 74.4 μm in width, while fragments ranged from 100.6 to 6510 μm in length. Microplastics identified here as fishing lines ranged from 485.7 to 19,850 μm in length and from 55.8 to 311.9 μm in width. The films and foams, ranged in length, from 1900 to 3900 μm and from 679.7 to 832.9 μm, respectively. Some of the upper size ranges for fibres, fragments and lines here are > 5 mm, but the authors still classified them as microplastics based on their width/thickness. In relation to microplastic length, 19% ranged from 100 to 350 μm while the majority were > 350 μm (81%).

The colours of the MPs recovered involved three predominant classes i.e. black (n = 462), blue (n = 393), red (n = 120). Other colours (n = 208) represented 18% of the total. The MANOVA analysis shows that there are no statistically significant differences between inner and outer bay for MP colour and type. Three microbeads were collected in this study, of which two were blue and one was green, and ranged in diameter from 413.8 to 551.5 μm (Fig. 3).

Results from μ-FTIR analysis showed that about 8% of MPs were either semi-synthetic (hydroxypropyl methylcellulose) or natural (cellulose acetate and wool), while the remaining 92% were synthetic. Although semi-synthetic and natural polymers were identified in our FTIR analysis, they were not included in the statistical analysis. The most common polymers identified were polypropylene (~24%), polyethylene (~14%), nylon 6 (~14%) and polyamide (~10%). The μ-FTIR analysis also identified 2 polyethylene terephthalate (PET, 5.4%), 2 polyvinyl alcohol (5.4%) and 1 polystyrene microplastics (2.7%).

The range of microplastic densities in Galway Bay, expressed in number of microplastic particles per cubic metre, is represented in Fig. 4. All manta trawls in this study had microplastics in the cod-end (100%), with the densities ranging from 0.16 to 1.67 MP m^{-3}.

The average microplastic density within the bay was 0.56 ± 0.33 MP m^{-3}, with the inner bay recording 0.46 ± 0.16 MP m^{-3} and outer bay having 0.62 ± 0.40 MP m^{-3} (Table 1). The highest density of 1.67 MP m^{-3} was recorded in station 7M1 at the South Sound where Atlantic water enters the bay. Fig. 5 shows microplastic densities by location within the bay, taking into consideration the arbitrary division from Fig. 1. The outer bay has a higher microplastic density, although not significantly different from the inner bay (*p*-value 0.375 Wilcoxon test). The MANOVA analysis shows that there are statistically significant differences between inner and outer bay for MP length and width. Both physical characteristics were higher in the inner bay.

Fig. 6 shows microplastic densities (A) and dominant wind speed and direction (B) while sampling. Most inner and outer trawl sites are influenced by SW winds. There are five stations that do not exhibit influence by the dominant wind, three of them (M1, M5, 6M1) displayed in the 1st quadrant (NE) and two stations (7M1 and 11M3) in the 4th quadrants (SE).

4. Discussion

The dominant MP type in this study was fibres, which is in accordance with similar studies in this field (Gewert et al., 2017; Henry et al., 2019; Mao et al., 2020). In addition, the most common MP colours (black, blue, and red) in this study are similar to findings in other relevant studies (Gewert et al., 2017; Anderson et al., 2018). While there were no significant differences microplastic colour and type between locations, as highlighted in the MANOVA test, there were higher number of fibres and fragments of all colours in the outer bay, apart from blue fragments. The MANOVA test for length and width by location identified statistically significant differences between inner and outer bay. Inner bay microplastics were both longer and wider.

There are several environmental factors (wind speed, wind direction, currents, etc.) that might influence the distribution of microplastics in Galway Bay and environs. This exploratory work examined microplastic densities in the inner and outer bay. Because the GLMM showed no significant differences by location within the bay (Fig. 5), the potential influence of wind speed and direction was considered (Fig. 6). Most stations in the study were influenced by SW winds, however there were 5 stations that did not followed that trend. This may be related to the strong hydrodynamic influence of the currents in the bay (Joshi and Farrell, 2020), which may play a more important

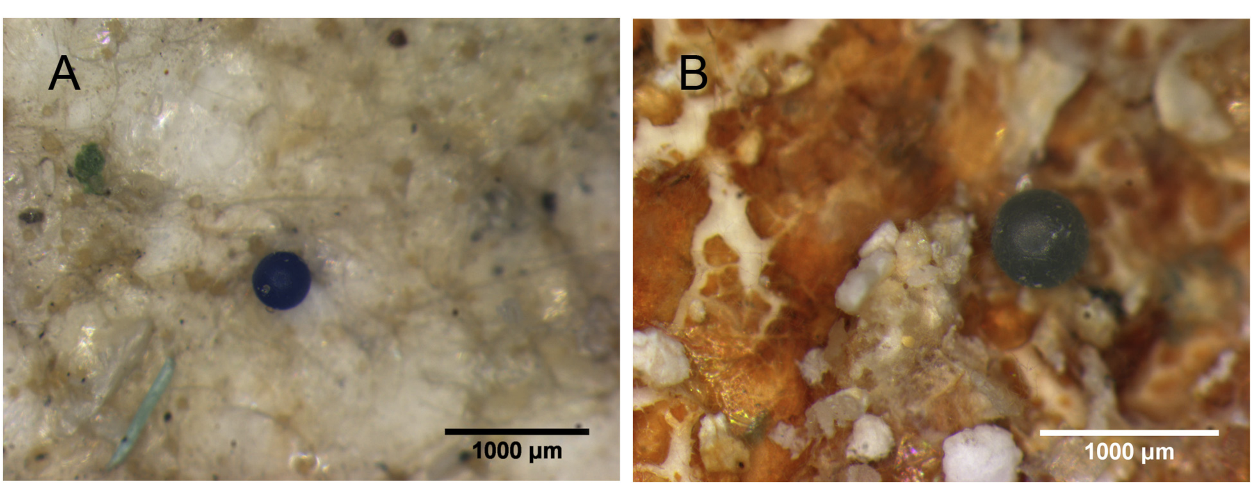


Fig. 3. Examples of two microbeads collected from surface waters from Galway Bay: A) blue and B) green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

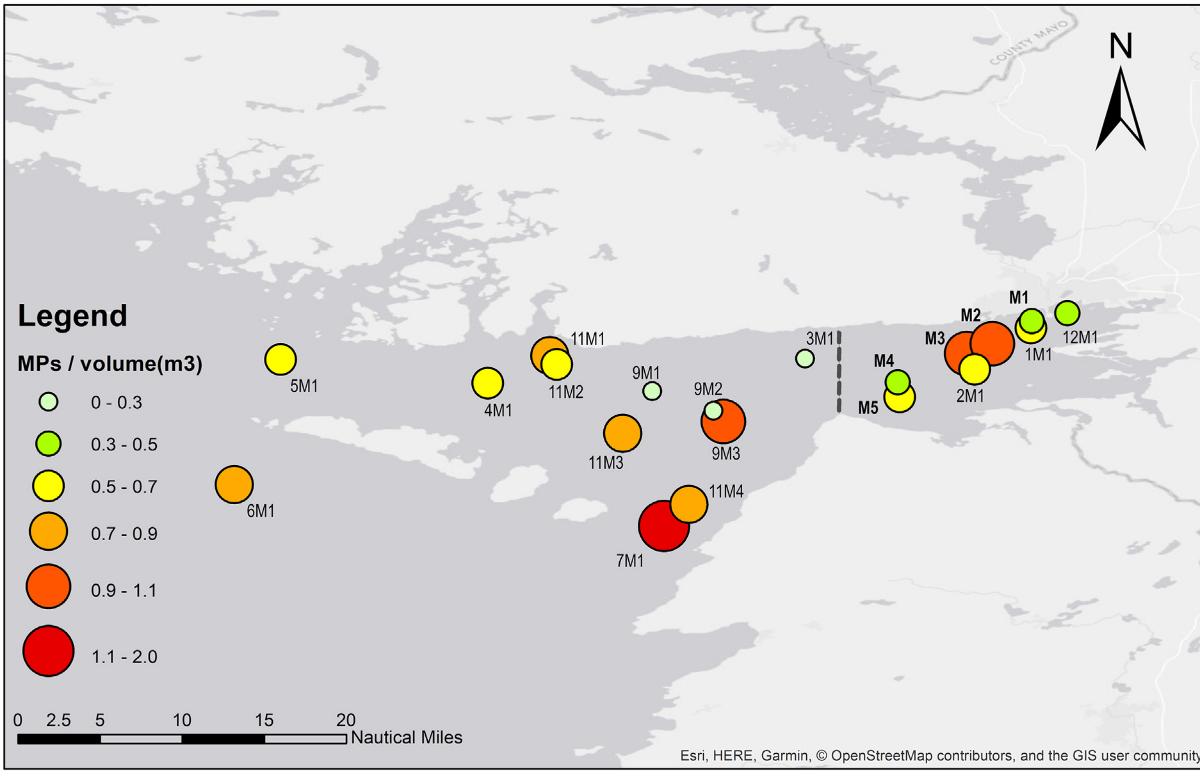


Fig. 4. Microplastic densities in Galway Bay and environs. Incremental size in circles shows increasing densities.

Table 1
Density comparison with similar bays and estuaries around the world.

Reference	Microplastic density (MP m^{-3})	Sampling area	MP particle size (μm)	Mesh size (μm)	Location	Nearby human population[a]
This study	0.46 ± 0.16 (Inner bay) 0.62 ± 0.40 (Outer bay)	Surface haul	> 100– < 300	300	Galway Bay, Ireland	80,000
Ramírez-Álvarez et al., 2020	0.19 ± 0.21 (in 2016) 0.20 ± 0.24 (in 2017)	Surface haul	> 250	333	Todos Santos Bay, Mexico	523,000
Aliabad et al., 2019	0.49 ± 0.43 (Chabahar Bay)	Surface haul	> 100– < 5000	333	Makran Coasts, Oman	107,000
McEachern et al., 2019	3.8 ± 1.5 (Old Tampa Bay) 5.8 ± 7.1 (Lower Tampa Bay)	Surface and subsurface hauls	< 5000	330	Florida, U.S.A.	393,000
Figueiredo and Vianna, 2018	1.3 4.8	Surface and subsurface hauls	100– > 5000	200 64	Guanabara Bay, Brazil	15,000,000
Tunçer et al., 2018	12.63	Surface haul	> 1000– < 50,000	333	Sea of Marmara, Turkey	15,000,000
Gewert et al., 2017	0.19 7.73	Surface haul	290–27,000	335	Stockholm archipelago, Sweden	974,073
Frère et al., 2017	0.24 ± 0.35 (Bay of Brest)	Surface haul	> 335– < 5000	335	Britany, France	140,000
Song et al., 2015	12,600 (Jinhae Bay)	Surface haul	< 50– > 1000	2000	Gyeongsangnam-do, South Korea	1,100,000
Cole et al., 2014	0.26 (Penlee, Western English Channel) 0.31 (L4, Western English Channel)	Surface haul	25–250	200	Plymouth, United Kingdom	235,000
de Lucia et al., 2014	0.01 ± 0.00 (Caletta) 0.35 ± 0.11 (Minerva/off-shore)	Surface and subsurface hauls	< 500	500	Sardinia, Italy	1,652,000
Lima et al., 2014	0.2604 ± 0.04	Surface haul	> 45– < 300	300	Goiana, Brazil	257,300
Doyle et al., 2011	0.004 (Southeast Bering Sea) 0.19 (Southeast Bering Sea)	Surface haul	< 1000– > 10,000	505	Alaska, U.S.A.	3500
Nóren, 2009	2400 (Lysekil, Southern Harbour) 0.01–0.140 (Gullmar Fjord)	Surface haul	1000–30,000	80 450	Lysekil, Sweden	10,000

[a] Based on the most recent census for each country.

role than the wind speed and direction. Wind by itself cannot serve as a proxy for oceanographic data on surface currents. A residual current model produced by Joshi et al. (2017), for maerl beds (Fig. 7), identified the predominant currents for winter in Galway Bay. Results provided here combined with the data in Fig. 7 help to explain the gradient of microplastic densities in the inner bay and the high density recorded at station 7M1. Stations within the bay are influenced by the output of freshwater of the River Corrib, which might explain the higher numbers in stations M2 and M3 (Fig. 4). In fact, the currents model by Joshi et al., 2017, even explains the higher densities in stations 6M1 (West of

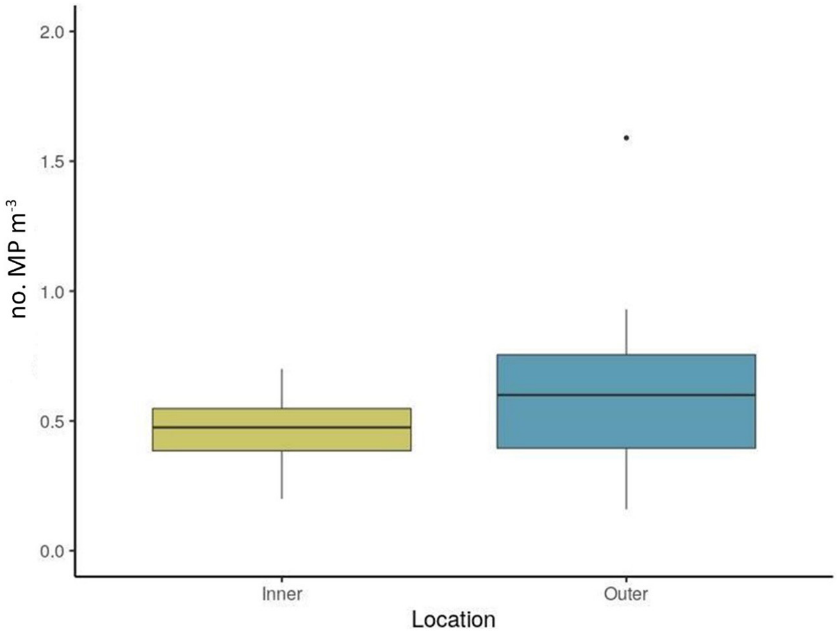


Fig. 5. Microplastic densities as defined by their location within the bay.

the Aran Islands) and 7M1 (South Sound). As previously mentioned, sampling took place in October and December 2017, two of the months with higher rainfall in the study site. Rainfall might contribute to more microplastics being introduced in the bay, but at the same time also contributes to dilution throughout the water system. Despite of higher rainfall in these months, no significant differences were recorded between October and December. Stations 4M1 and 5M1 in the North Sound do not reflect an accumulation of MPs despite being located where the anticlockwise circulatory patter of surface water leaves the bay. Initially the authors had hypothesised that water circulation pattern would cause densities to be lower at the South Sound and higher at the North Sound, which is not verified. The authors assume that the relatively higher MP densities in the South Sound are probably due to the combination of water from the Atlantic Ocean entering the bay alongside with the easterly winds. Overall, there is no obvious pattern in density distribution as low and high levels are recorded close to Galway City, making the interpretation of resulting data a multifaceted issue.

An important aspect of this study is the collection and identification of plastic microbeads in Irish surface waters. Despite their low number (n = 3), these primary non-essential microplastics introduced to personal care products (Habib et al., 2020), have been previously recorded elsewhere, mainly in Asia (Cheung and Fok, 2016; Cheung and Fok, 2017). In Europe, microbeads have been recorded in the Rhine River in Germany (Mani et al., 2019) and the English Channel (Cole et al., 2014). A recent study on Wastewater Treatment Plants (WWTP) revealed a predicted concentration of 21 microbead particles m^{-3} released into freshwater systems (Kalcíkova et al., 2017), which could also be a theoretical explanation as to why microbeads were found in Galway Bay. Further research efforts need to be conducted to verify this assumption.

Although MP densities in this study are slightly higher than similar bays around the world (Table 1), e.g. Todos os Santos bay in Mexico, Britany in France, Sardinia in Italy and the Western English Channel, they are within the same order of magnitude. In contrast, when compared to Guanabara Bay in Brazil, Jinhae Bay in South Korea or Tampa Bay in Florida, U.S.A., the MP densities are significantly lower. Physical properties and oceanographic dynamics are highly variable around the globe and should be taken into consideration for local studies.

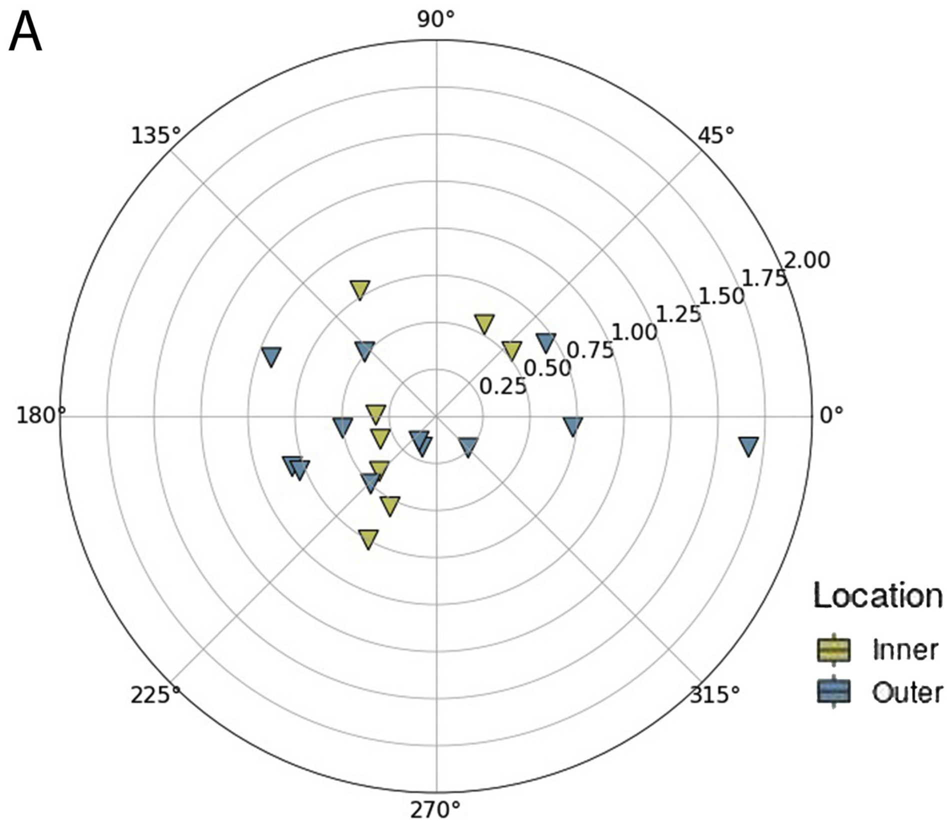
Table 1 also shows the wide range of sampling methodologies based on the mesh size and reported particle size. It is of vital to have standardised methodologies for sampling, processing and analysing in order to accurately allow comparisons. In this study 19% of the retrieved microplastics were between 100 ≤ 350 μm (Frias and Nash, 2019), even though a 300 μm sampling mesh was used, which highlights that the mesh size used is only a theoretical limit to what can be recovered.

However, even with the variability in sampling methods worldwide there is further complication when trying to compare data, as Table 1 demonstrates. Not all bays are the same, and their geographic location and environmental weather conditions alongside with population density and other aspects might contribute to higher or lower microplastic densities. For example, Galway Bay has strong hydrodynamics and weather conditions which are assumed to contribute to a relatively short residence time of microplastics at the surface levels. In addition, there are other factors that this study did not take into consideration and that are likely to affect microplastic distribution such as, ingestion by biota, degradation, fragmentation, and bottom deposition. Results in this study often relate to microplastic concentration deposited in bottom sediments (Pagter et al., submitted).

Monitoring is a fundamental requirement and assessment tool that not only feeds European regulations, but also drives scientific progress. However, as this study highlights, multiple microplastic surface samples are required to provide a snapshot for a given area and time. Because of the complexity of microplastic monitoring, the authors would like to emphasise the importance of establishing a monitoring protocol that includes several environmental matrices (e.g. sediment, air, water, biota, soil, etc.), to have overarching and comprehensive monitoring data. Having a holistic approach and including environmental variables (e.g. precipitation, wind and currents data) and a record of storms and extreme events (e.g. floodings or draughts) might contribute to a better assessment over time.

5. Conclusion

This study provides a snapshot of microplastic density in Galway Bay. Results show no obvious pattern of microplastic density distribution based solely of wind speed and direction. In fact, other factor such as currents plays a significant role in their distribution. This study also provides the first record of floating plastic microbeads in surface seawaters of Galway Bay. Although their source it is not obvious, further



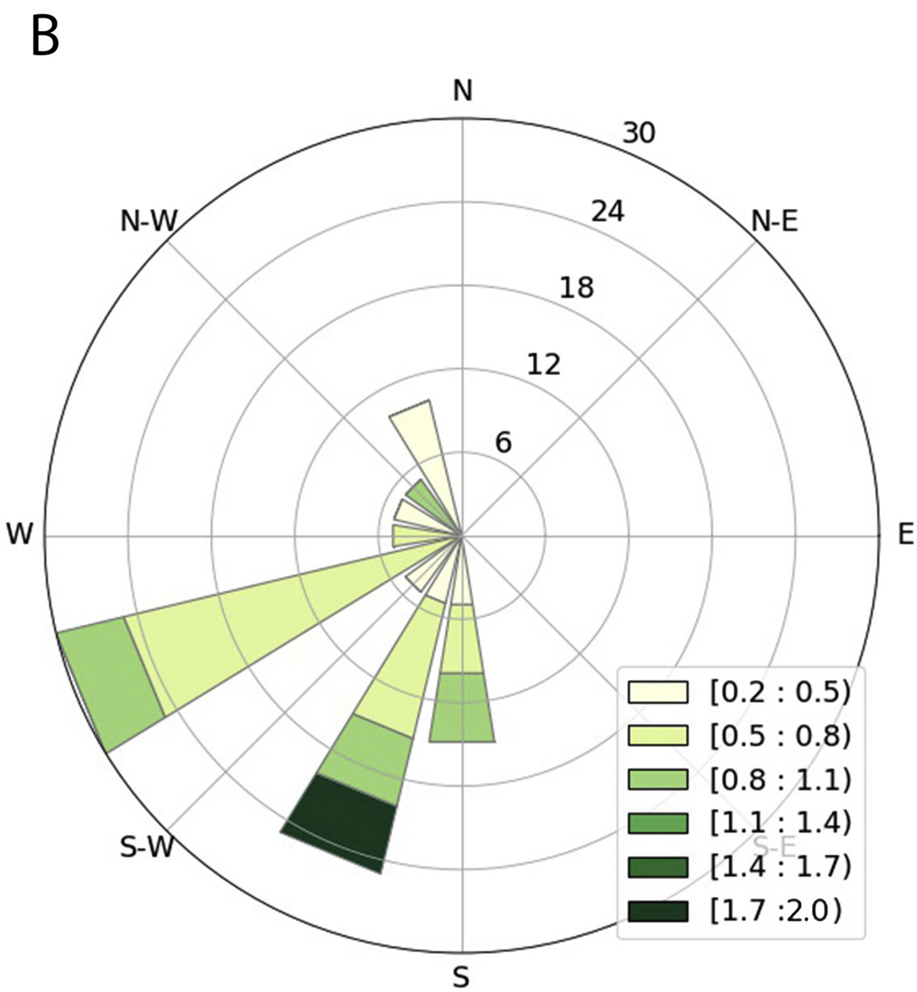


Fig. 6. A) Microplastic density (MP m^{-3}) azimuths for the 20 manta trawls and B) stacked wind rose with dominant wind speed and direction ($m\ s^{-1}$).

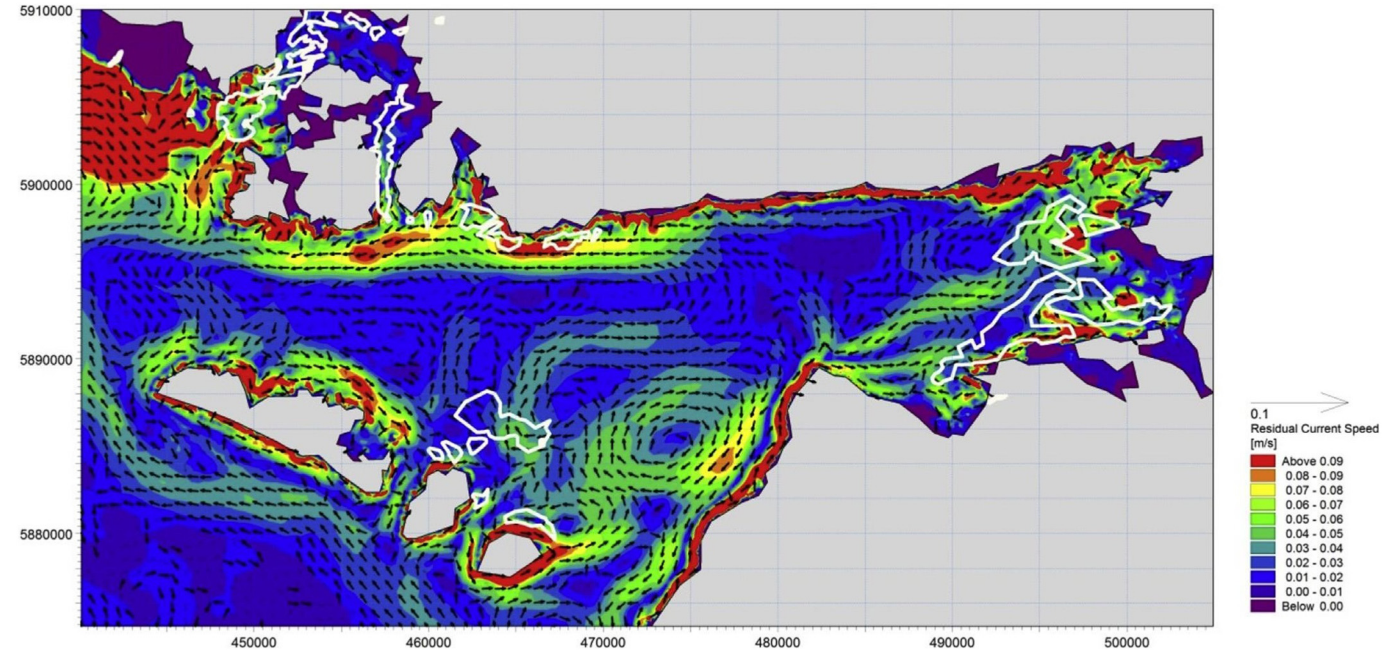


Fig. 7. Combined wave-current induced residual current distribution under storm conditions in Galway Bay and environs, in winter of 2017. (*Reproduced from Joshi, S., and Farrell, E., 2020, Physical oceanographic drivers of geomorphology of rhodolith/maerl beds in Galway Bay, Ireland, Fig. 12.4, with permission license from the authors and Elsevier publishing.*)

research into this need to be conducted. The densities of microplastics in Galway Bay are comparable to similar bays around the world, and for some cases are even in the same density range.

Monitoring of microplastics in surface seawater, particularly in bays, should rely on at least 6 to10 different sampling sites in the case study bay to allow for various influential factors, such as river input, population density and economic activity in the coastal zone. Thus, the authors recommend that research also follow a more holistic approach where data from several environmental variables (wind speed, direction, precipitation, current speed, current direction, etc.) are also collected.

CRediT authorship contribution statement

João P.G.L. Frias: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft.**Olga Lyashevska:**Methodology, Writing - review & editing, Formal analysis.**Haleigh Joyce:**Writing - review & editing, Investigation.**Elena Pagter:**Writing - review & editing, Investigation.**Róisín Nash:**Writing - review & editing, Supervision.

Declaration of competing interest

The author(s) declare(s) that there is no conflict of interest.

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