Environmental Pollution 306 (2022) 119379

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

A record of microplastic in the marine nearshore waters of South Georgia☆

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ARTICLE INFO

Keywords:
Sub-antarctic
Plastic
Pollution
Marine
Contamination
Wastewater

ABSTRACT

The polar plastics research community have recommended the spatial coverage of microplastic investigations in Antarctica and the Southern Ocean be increased. Presented here is a baseline estimate of microplastics in the nearshore waters of South Georgia, the first *in situ* study of the north-east coast of the island. Our results show that the microplastic concentration in seawater at twelve stations in proximity to King Edward Point Research Station ranged from 1.75 ± 5.17 MP/L (mean ± SD), approximately one order of magnitude higher than similar studies of sea surface waters south of the Polar Front. Levels of microplastics in freshwater (sampled from Gull Lake) and precipitation (collected adjacent to the research station) were 2.67 ± 3.05 MP/L, and 4.67 ± 3.21 MP/L respectively. There was no significant difference in the microplastic concentration between seawater sites, and no significant bilateral relationship between concentration and distance from the research station outlets. We report an average concentration of 1.66 ± 3.00 MP/L in wastewater collected from the research station but overall, the counts of microplastics were too low to attach any statistical significance to the similarity in the microplastic assemblages of seawater and wastewater, or assemblages retrieved from penguin species in the region in other studies. Using a calculation described in contemporary literature we estimate the number of microfibres potentially being released from ships and stations annually in the region but acknowledge that further samples are needed to support the figures generated. More extensive research into microplastic distribution, characteristics, and transport in the region is recommended to fully compute the level of risk which this pollutant represents to the ecosystem health of this remote region.

1. Introduction

Of the nine billion metric tonnes (Mt) of plastic generated in the second half of the 20th century, an estimated 59% has been discarded as waste and is now in landfill or the natural environment (Geyer, 2020). In 2010, an estimated 12.7 million Mt of waste plastic entered the marine environment from coastal sources; a figure that was predicted to increase by an order of magnitude by 2025 (Jambeck et al., 2015). Microplastic pollution, whether produced as primary particles or secondarily via disintegration of larger plastics (Gewert et al., 2015; Jiang et al., 2021), causes multifarious challenges for marine ecosystem health, including reduced organism fitness following exposure (Rebelein et al., 2021; Richardson et al., 2021; Silva et al., 2021), chemical pollutant concentration and redistribution (Mai et al., 2018; Wang et al., 2019; Tang et al., 2020) and invasive species propagation (Frère et al., 2018; Naik et al., 2019; Bowley et al., 2020).

Coastal point sources, such as wastewater outlets, storm water runoff and riverine inputs are major contributors of microplastic pollution to the marine environment (Su et al., 2020; Naji et al., 2021; Werbowski et al., 2021; Yakushev et al., 2021). Positive correlation has been observed between urban coastal regions and marine microplastic concentrations (Naidoo et al., 2015; Song et al., 2018; Jang et al., 2020; Sugiura et al., 2021), though microplastic distribution is highly region-specific and requires in-depth local analysis to determine an accurate holistic picture (van Wijnen et al., 2019; Wang et al., 2020). Marine industries such as shipping, offshore resource extraction and mariculture constitute pelagic point sources (Chen et al., 2020; Lusher & Pettersen, 2021) and the oceans are an interconnected system, making it possible for MPs to be transported thousands of kilometres in their currents (Obbard, 2018; Bowley et al., 2020; Fraser et al., 2018). Remote

Abbreviations: FT-IR, Fourier Transmission Infrared; MP, microplastic(s); MF, microfibre(s); DI, deionised (water); SAP(s), suspected anthropogenic particles (i.e., particles thought to be microplastic prior to polymer analysis).

☆ This paper has been recommended for acceptance by Eddy Y. Zeng.

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https://doi.org/10.1016/j.envpol.2022.119379
Received 3 December 2021; Received in revised form 23 April 2022; Accepted 26 April 2022
Available online 29 April 2022

locations are not immune to microplastic incursion, as evidenced by the presence of microplastics observed in oceanic gyres (Egger et al., 2020; Jang et al., 2020), on uninhabited islands (Martins et al., 2020; Tan et al., 2020; Nichols et al., 2021) and at the bottom of submarine trenches (Jamieson et al., 2019; Peng et al., 2020; Abel et al., 2021). Nor is the transport and retention of microplastics limited to surface currents or horizontal transportation (Liu et al., 2020; Lobelle et al., 2021). It is also determined by the density of the polymer material (Mountford & Morales Maqueda, 2019; Daily & Hoffman, 2020), and the surrounding water (de la Fuente et al., 2021) as well as the level of algal growth on the plastics surface (Rummel et al., 2017; Saavedra et al., 2019; Semcesen & Wells, 2021).

There are records of microplastic pollution in Antarctica and the Southern Ocean (SO), including in the sub-Antarctic: latitudes north of 60°S Antarctic Circle but still within the cold polar waters of the Antarctic Circumpolar Current (ACC), as noted in review by Tirelli et al. (2020). Whilst these are key in advancing our understanding of MP distribution, records are difficult to compare due to the variation in sampling methods, a problem ubiquitous in microplastic research, despite calls for standardisation (SCAR Plastics Action Group, 2018; Hartmann et al., 2019). Notably, an estimation of the abundance of microplastics and synthetic microfibres in Antarctic water, based on the anthropogenic footprint of the region and estimated microplastic production per person was calculated to be five orders of magnitude lower than published observations from the field (Waller et al., 2017). This suggests some level of long-range transportation of microplastic particles to the SO and that our current understanding of microplastic distribution in the region is far from complete.

South Georgia is at the boundary between the South Atlantic and the SO, just south of the Polar Front. It is remote but has a human presence: in 2019, 10,000 tourists visited the island, a figure which is expected to rise in the future (GSGSSI, 2020). There are three notable fisheries with 40 registered vessels operating year-round and two scientific bases also staffed year-round. It is situated within the eastwards-flowing Antarctic Circumpolar Current, which may act as a buffer and potential holding zone for microplastics transported from lower latitudes (Fraser et al., 2018). Examples from elsewhere in the Southern Ocean, suggest that scientific research bases constitute a point source of microplastic pollution to their local environment but their relative contributions to local profiles have not yet been quantified (Cincinelli et al., 2017; Reed et al., 2018).

South Georgia is a biodiversity hotspot, a breeding site for five million seals and 65 million seabirds. Its waters also support a krill fishery, which in 2020 landed >110,000 Mt (Government of South, 2021 Trathan et al., 2021), a Patagonian toothfish (*Dissostichus eleginoides*) fishery which landed 1884 Mt in 2020 (CCAMLR Secretariat, 2021), and a mackerel icefish (*Champsocephalus gunnari*) fishery with a quota which has not surpassed 5000 Mt in recent years (CCAMLR, 2021). Krill and other zooplankton species, vital throughout the SO for their basal role in food webs, the biological pump, and carbon sequestration (Cavan et al., 2019; Shen et al., 2020), are susceptible to microplastic ingestion and in laboratory experiments exhibit resultant adverse impacts, such as reduced fitness and chemical toxicity (Dawson et al., 2018; Botterell et al., 2019; Wieczorek et al., 2019). *In situ* observations, show that pelagic amphipods in the SO may ingest microplastics even in regions of low microplastic concentrations and smaller population densities (Jones-Williams et al., 2020). In addition to impacting zooplankton, other ecological threats from microplastics include reduced primary productivity (Troost et al., 2018; Green, 2020), enhanced pathogenic bacteria reproduction (Eckert et al., 2018), altered feeding and social behaviour in fish caused by endocrine disruption (Rios-Fuster et al., 2021; Kim et al., 2021), and the exposure of higher predators to this pollutant (Nelms et al., 2018; Bessa et al., 2019; Le Guen et al., 2020), with as yet unknown consequences (Cunningham et al., 2021; Huang et al., 2021). Moreover, microplastic pollution in the SO is an additional stressor on a region already threatened by changing climatic conditions such as increase in ocean warming and acidification and populated by organisms which are often slow-growing and endemic which accentuates their vulnerability (Rowlands et al., 2021).

Here we assess the distribution, concentration, and characteristics of microplastics from the coastal region of South Georgia. We investigate microplastic distribution in seawater as well as in a local input (i.e., wastewater from the local research station). In addition, out of interest and for the sake of potential future comparisons, a sample of freshwater and a sample of precipitation were collected. We also estimate the number of secondary microfibres (a category of microplastic), generated from washing clothes consisting of synthetic textiles, being discharged into the South Georgia marine environment via ship and station wastewater, using the methodology of Waller et al. (2017) as a proxy for determining the anthropogenic impact on the region.

This study provides a first insight into microplastic pollution in the coastal waters of South Georgia, a baseline against which future observations can be compared and aims to contribute to research informing policy makers with jurisdiction over the South Georgia region.

2. Materials and methods

Samples of surface seawater were collected from 12 stations around South Georgia in the austral summer (December–March) of 2019 (Fig. 1). At each station a total of 9 L were collected (3 x 3 L replicates).

Ten of the seawater samples were collected from the coastline at 1-km intervals on foot from King Edward Point Research Station (Fig. 1c) using three 3 L glass jars, dipped horizontally below the surface of the water, and allowed to fill. Two seawater samples were collected on a research vessel offshore at locations removed from the research station (Fig. 1a), using 10 L plastic buckets. For consistency between samples only 9 L of water were used as a sample from the 10 L collected at these offshore stations.

In addition, a single freshwater sample was collected from Gull Lake, using the same method as the seawater samples, and samples of wastewater were taken from two of the outlet pipes at the research station on King Edward Point and the outlet pipe from the South Georgia Museum building at Grytviken (Fig. 1b). A sample of precipitation was collected by placing 3 L glass jars outside the research station (Fig. 1c) approximately 20 m from the nearest building during snowfall. The volume of snow was measured after melting and again, only 9 L were used for analysis.

2.1. Sample processing

Samples were filtered onto 55 μm-pore size Whatmann GF filter papers (47 mm diameter), 1 L per filter paper. All filter papers were examined under an Olympus SZX10 microscope, with an Olympus UC30 camera, and visualised using CellSens software (Olympus) to identify suspected anthropogenic particles (SAPs). Principles outlined in Jones-Williams et al. (2020) were used as guidelines for identifying candidate plastic debris: the colour, shape, texture, brittleness, and presence of organic or lithic characteristics were all factors taken into consideration. The maximum feret length (the largest distance between two parallel tangential lines in any plane direction of a particle) of each SAP was measured using CellSens software. The frequently cited criteria of microplastic = 1–5000 μm was employed during optical sorting (Hartmann et al., 2019). The size, colour and abundance of each SAP was recorded.

SAPs were examined using the Fourier Transmission Infrared (FT-IR) spectroscopy method, using a Thermo Fisher Scientific iN10 Nicolet spectrometer equipped with the OMNIC Picta software (Thermo Scientific OMNIC Series Software). The spectrometer was operated in transmission mode for all SAPs and a standard resolution of 4 cm^{-1}, scanning between wavelengths of 800–6000cm-1, was used. Twelve scans were collected for each particle or fibre and a baseline correction was applied to each first derivative spectrum. For material identification, spectra

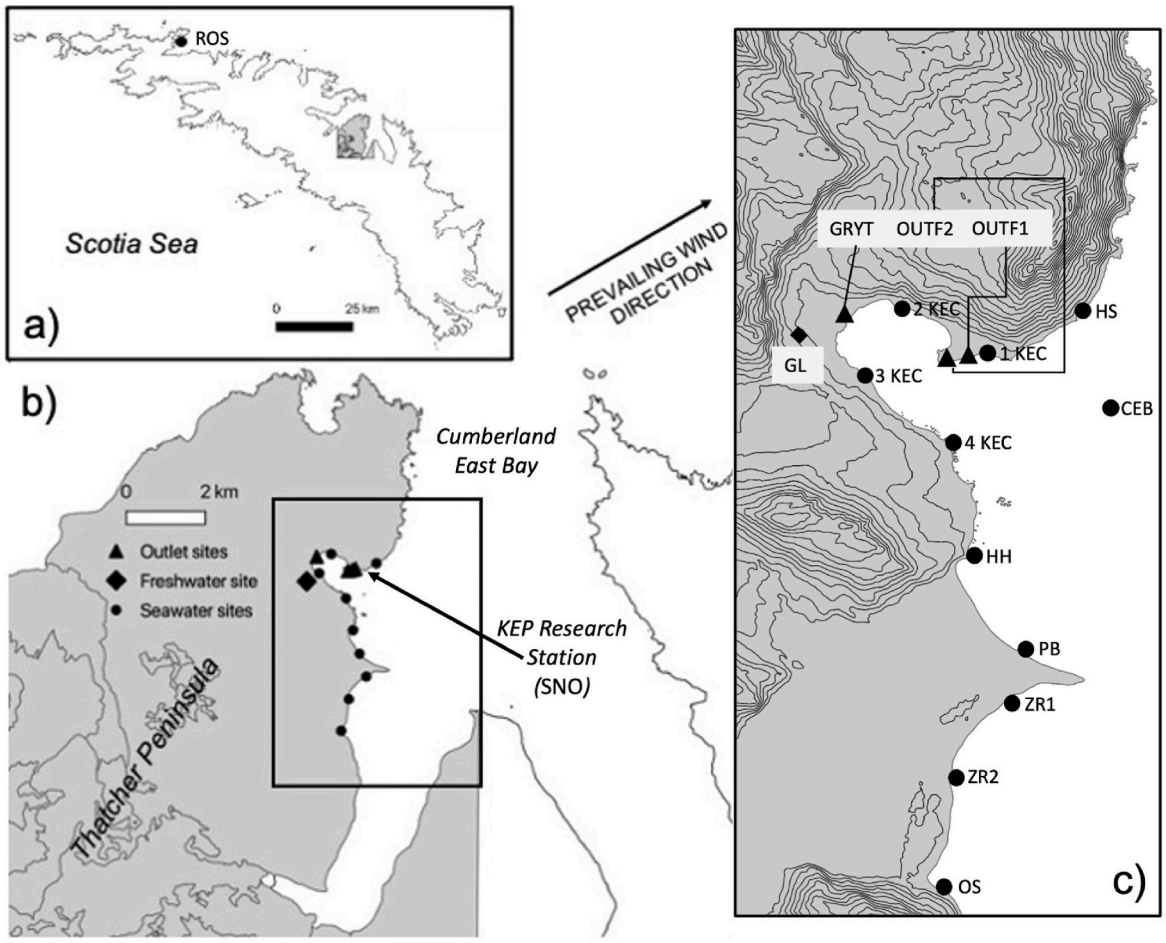

Fig. 1. Study area and sampling stations around a) South Georgia (inset top left), b) the Thatcher Peninsula (bottom left), and c) within the accessible coastline as designated partly by British Antarctic Survey travel limits, and partly by topography i.e., north of Sooty Bluff (HS) and south of Mt. Osmic (OS) the coastline is inaccessible on foot (inset right). Seawater sampling sites (circles) are shown in relation to wastewater outlets sampled (triangles), and the location of freshwater Gull Lake (GL) and where precipitation (SNO) was sampled. Sampling stations were named after geographical locations as follows: HS = between Hope Point and Sooty Bluff, 1–4 kEC = sequential samples in King Edward Cove, HH = Horse Head, PB = the beach by Penguin River, ZR1-2 = sequential samples along Zenker Ridge, OS = at the base of Mt. Osmic, CEB = Cumberland East Bay, ROS = Rosita Harbour.

were compared to several industry standard reference libraries (see Supplementary Material for full list) as well as a library of potential contaminants built up during the survey process (see below "Contamination control"). Matches of ≥70% with spectra from a reference library were considered positive. Where possible, every fragment and fibre recovered underwent spectral FT-IR analysis, though in the case of multiple appearances of the same SAP (same colour and shape), a subsample of at least 25% were tested. The state of particles taken for FT-IR analysis was not specifically examined i.e., buoyancy of the particles or the level of weathering were not denoted.

2.2. Contamination control

Any plastic item which was in proximity to a sample during fieldwork or laboratory processing was judged to be a contamination hazard and was therefore sampled to build a library of contaminant items in the FT-IR software, against which environmental samples could be compared.

During fieldwork, samplers positioned themselves downwind from the open sample jar to reduce the chance of atmospheric contamination from clothing fibres. Jars were not opened until they were submerged beneath the water's surface and were closed and sealed before being exposed back to the air. In this way the chance of airborne contamination from the atmosphere during sampling was reduced to zero and therefore no blank samples were collected in the field.

During laboratory work, optical sorting and the FT-IR polymer analysis, atmospheric controls were taken by exposing a damp filter paper (Whatmann 55 μm-pore size, GF), placed in a glass petri dish that had been washed with deionised water (DI water) and ethanol-rinsed, within the working environment which then went on to be examined for SAPs using identical optical and FT-IR methods.

Any items which contacted the sample (jars for collection, forceps for handling filter papers etc.) were rinsed three times with DI water and three times with filtered 70% ethanol prior to being used. All DI water and ethanol used for rinsing samples or cleaning equipment was filtered (Whatmann 55 μm-pore size, GF) prior to use.

During filtration, blanks were taken by running DI water, the water used for washing the equipment between samples, through the same filtration processes. For every 3 L sample, a litre of DI water and 500 ml of 70% ethanol was run through the system and examined for SAPs in a protocol identical to that of environmental samples as blanks.

Any SAPs which were confirmed to be microplastic after FT-IR analysis were added to the contamination library which was used during the examination of SAPs from environmental samples.

2.3. Elimination of contaminants

When it came to determining the level of contamination, each plastic

particle in the environmental sample was reviewed individually and compared with contamination from the contamination library. Having separate controls for each filter paper at each stage of processing allows for specific correction of each sample, although this only applies at the processing stage and not during the sampling stage. Particles were considered a match based on their material, the percent confidence of material identification (as produced by the FT-IR), spectral similarity, colour, and the shape of the particle. Any sample particle that was identified as matching a particle from the controls was removed. Total MP counts were corrected by subtracting the sum of contaminant plastic particles found on air contamination filters and number of particles isolated from procedural blanks. Any particles that matched (≥70%) with the contamination library (i.e., particles which would have contaminated the sample pre-processing) were eliminated from final counts.

2.4. Statistical analyses

The concentration of microplastics in this study is count data with a non-normal distribution, and of values too low (~<5) to lend statistical credibility to comparisons of concentrations or microplastic characteristics, between stations (von Friesen et al., 2020; Karlsson et al., 2018). Stations were therefore pooled into their respective water types, therefore increasing the count of microplastics and the number of replicates. Comparison of the microplastic concentration between water types was examined using a non-parametric Kruskall-Wallis test. Stations were also pooled by collection method, jars or buckets and a one-way ANOVA was used to examine the variation in microplastic concentration between these groups. Finally, a simple linear regression was applied to determine the influence of distance from an outlet on the microplastic concentration also. Multivariate analyses were attempted on square root transformed abundance (MP/L) or presence/absence (1/0) data using PRIMER-E with the PERMANOVA + extension using Bray-Curtis similarity however the non-metric multi-dimensional scaling (nMDS) plots showed no signs of clustering which confirmed the assumption that microplastic concentration values were too low for statistical comparison.

A polymer richness index was calculated to show the number of

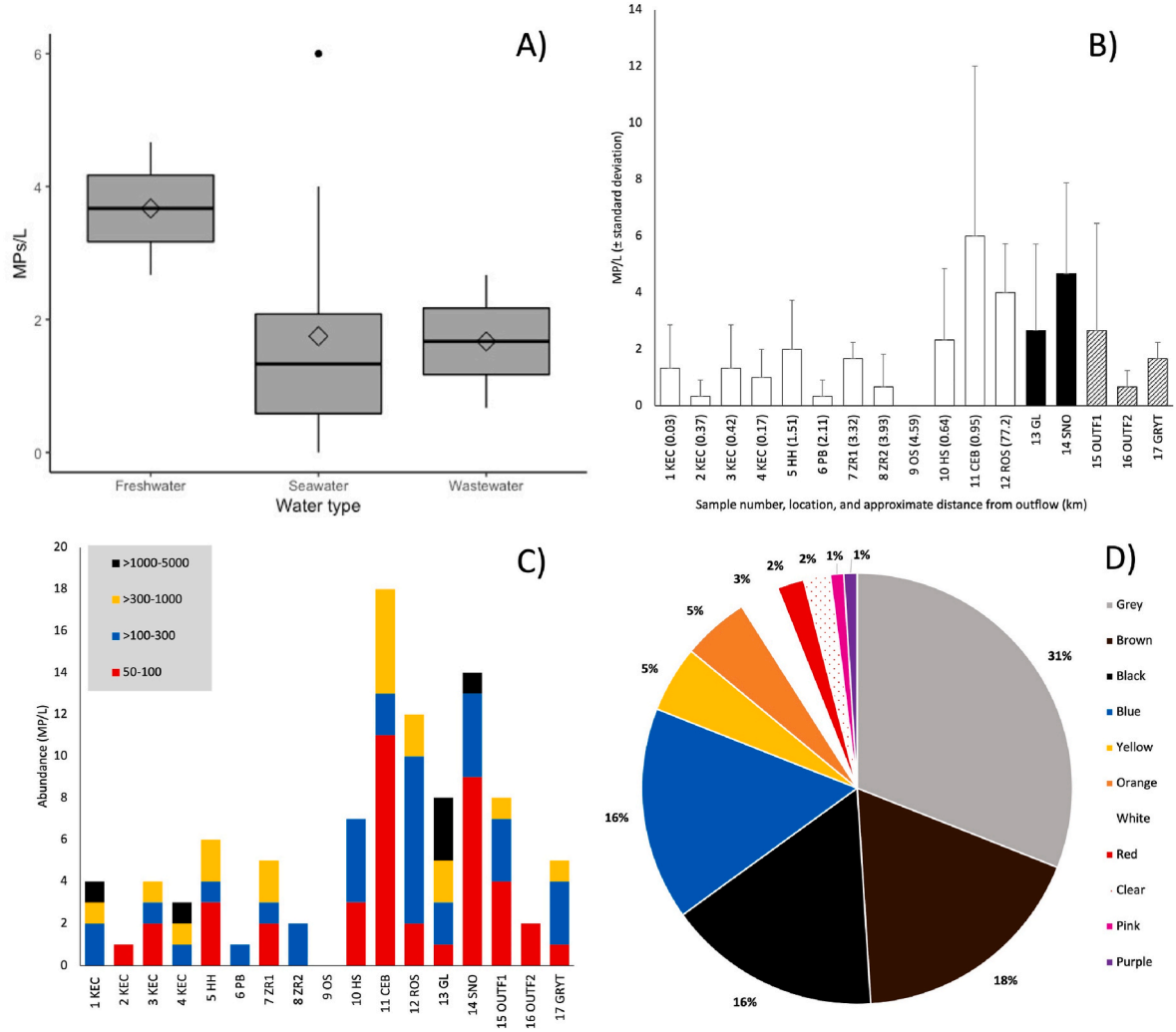

Fig. 2. (Top to bottom, left to right): A - Concentration of microplastic (MP) particles (≥50 μm, MP/L) in freshwater (Gull Lake and precipitation combined), seawater and wastewater samples from South Georgia. The diamond represents the mean, the line the median, whiskers the minimum and maximum, bottom of the box the 25th percentile, top of the box the 75th percentile, the dot an outlier. B – Concentration of microplastic particles (≥50 μm, MP/L) at each individual station sampled around South Georgia, including seawater (white), freshwater (black) and wastewater (crosshatch), plus standard error; for seawater stations "straight line" distances to nearest outlet are shown in parentheses. C – Microplastic (MP) particle size distribution and abundance is all samples of water from South Georgia. X-axis = sample number and location. Samples 1–12 represent seawater, 13 represents freshwater from Gull Lake (GL), 14 the sample of precipitation (snow, SNO), and 15–17 wastewater outlets. D - Relative proportion (% of total across all stations) of various colours of particles in water sampled from South Georgia. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

different microplastics in each group (categorised by size, colour, and shape) which provides an indication of which polymers were the most frequently occurring over the entire site and how diversity varied between stations and water types.

It must be noted that the limited counts of microplastics in the present study may limit the veracity of the probability calculated in polymer richness equations (von Friesen et al., 2020).

3. Results

Of the total SAPs tested, just over 7% were a positive match (≥70% match for plastic polymers in the reference library) and therefore considered microplastics. The average concentration of microplastic in seawater across all 12 stations sampled was 1.75 ± 5.17 MP/L. Concentrations are presented as the mean number of microplastics per litre with the standard deviation (±) unless otherwise stated. Of total microplastics in seawater, 50.8% were fragments and 49.2% were microfibres. Less than 1% were categorised as films and therefore were included in the total of fragments. The average concentration of MP in wastewater was 1.66 ± 3.00 MP/L, 46.7% fragments and 53.3% microfibres. In Gull Lake the concentration was 2.67 ± 3.05 MP/L 25% fragments and 75% microfibres, and in the precipitation sample the concentration was 4.67 ± 3.21, 78.6% fragments and 21.4% microfibres.

There was no significant difference in the concentration (MP/L) of microplastics in seawater, wastewater, and freshwater ($p > 0.05$, Fig. 2A) but notably, the two stations with the highest concentrations of microplastics were CEB (East Cumberland Bay) and ROS (Rosita Harbour), the two stations sampled offshore via vessel, 6.00 ± 6.00 and 4.00 ± 1.73 MP/L respectively (Fig. 2B); and when stations were grouped by the collection method, there was a significant difference between samples collected via jar from the coast and those collected in a bucket from a vessel ($p = 0.001$).

Linear regression revealed no significant relationship between the concentration of microplastics in seawater and the distance from the nearest outlet pipe.

The minimum cut-off size (MCS) of microplastics in the present survey was 50 μm despite the filters used having a pore size of 55 μm, many particles smaller than this were present on the filters presumably due to clogging. However, as it was not possible to manually transfer particles smaller than 50 μm from the filter to the diamond pane for FT-IR analysis, the cut-off was set at this size. 38.1% of microplastics in seawater, 45.5% in freshwater and 46.7% in wastewater were 50–100 μm in size (Fig. 2D). In seawater, wastewater, and the sample of precipitation there was negative correlation between the number of microplastics and the size category in question. In Gull Lake water, 37.5% of microplastics were in the largest size category ≥1000–5000 μm, though it should be noted that the count of microplastics in all samples is too low to draw meaningful conclusions from said corelations.

When grouped by material or type (colour, size, and shape) seawater had the most diverse assemblage, with counts of 19 different materials and 24 particle types, with PET/grey fibres being the most prevalent (Fig. 2C). Bearing in mind the varying volumes of water types sampled however, seawater is arguably the least diverse with 0.52 materials per litre compared to wastewater which contained 0.88 materials per litre (with eight materials overall, most commonly PET, and 12 particle types, most commonly blue fragments 50–100 μm in size). The microplastic assemblage in the single precipitation sample contained eight materials and 11 particle types.

3.1. Contamination

64 microplastic particles were removed from the final count, from across all stations due to matches (≥70%) with the contamination library. An additional particle was removed from the final count due to a match with a contaminant from the samples corresponding atmospheric filter. In total, 39.4% of all particles sampled were deemed to be contamination. 96.9% of contamination from all sample combined consisted of black PET fibres. There was little difference in the proportion of microplastics that were removed as contamination from seawater (44.2%) and wastewater (37.5%), though freshwater was noticeably lower (21.4%). The sample of precipitation had the lowest rate of contamination of any sample analysed (17.6%), apart from two seawater samples (2 KEC and 2 ZR) where zero contamination was detected, although in these seawater samples only one and two microplastics were recovered across the whole samples respectively.

4. Discussion

This is the first South Georgia-based survey of microplastics in the coastal waters of the region and the first to collect samples from potential *in situ* anthropogenic point sources of microplastic pollution. The results of the present survey suggest the mean concentration of microplastics in the nearshore surface water of South Georgia is 1.75 ± 5.17 MP/L, with the highest concentration at Cumberland Bay (CEB, 6.00 MP/L, the outlier in Fig. 2a) and the lowest on the shoreline at the base of Mt. Osmic (OS, zero MP/L).

There have been records of microplastic in the marine environment of South Georgia, but these were either a single sample as part of a study in the wider Southern Ocean region (Barrows et al., 2018; Suaria et al., 2020), or else not specifically analysing seawater (Thompson et al., 2009; Bessa et al., 2019; Le Guen et al., 2020).

We found the concentration of microplastics in surface seawater to be higher than from elsewhere in the Southern Ocean (Cincinelli et al., 2017; Isobe et al., 2017; Kuklinski et al., 2019; Lacerda et al., 2019; Suaria et al., 2020), in some cases one order of magnitude higher or greater. However, the design of this study was dictated by logistics in the field which resulted in a limited spatial coverage and a small number of samples and further investigations are necessary to validate the discrepancy in the amount of microplastic observed in this study compared to the previous investigations. Further, this discrepancy is not explained by the sample collection strategy. Like Barrows et al. (2018) the method in this present survey is essentially grab sampling and would not have excluded particles on any size, however, unlike Barrows et al. (2018), who used filters with a pore size of 0.45 μm, the filters in this study resulted in a MCS of 50 μm which means that the high counts observed here cannot be attributed to the grab-sampling technique. Although the higher count of smaller particles reported here suggests that a similar result may have been possible given a reduced MCS. Vessel-based surveys may have an MCS dictated by the mesh size of the net used in the surface tow, such as the 300 μm net used by Suaria et al. (2020), but if the present dataset is edited to report only microplastic particles which are ≥300 μm in size, similar concentrations are still not achieved. Moreover, Cincinelli et al. (2017) was able to retain particles down to 1 μm in a ship-based net-tow survey and still reported concentrations at least one order of magnitude lower than in the present study.

The location of our study may perhaps in part account for the high concentration of observed microplastics. Whilst statistical analysis found no significant relationship between distance to outlets and microplastic concentrations in seawater in this instance, the pattern is generally well-described (Browne et al., 2011; Kazour et al., 2019; Liu et al., 2021), including in polar regions (Munari et al., 2017; Reed et al., 2018 Granberg et al., 2019). Moreover, although the geographical spread of sampling stations was limited, the location in question, Cumberland Bay and King Edward Cove, are subject to a high level of vessel traffic: 151 vessels (tourism, scientific, and fishing) visited during the same austral summer in which sampling took place (Government of South Georgia and the South Sandwich Islands, 2020). Using a calculation described by Waller et al. (2017) and data regarding the number of people present in the region on ships and stations (person days), the

amount of microfibres produced during clothes washing (Napper & Thompson, 2016), and bearing in mind the tendency for polar clothing to be made of insulating synthetic materials (Tirelli et al., 2020), we estimate the number of microfibres being released into South Georgia waters to be between 8.6 and 36.8 million per year. This is including allowing for the assumption that 90% are removed by wastewater treatment prior to discharge, which will vary between vessels and research stations (for calculation details, see Supplementary Material). This influx of wastewater may account for the higher microplastic concentrations observed here than elsewhere in the Southern Ocean (Waller et al., 2017), and indeed 40% of particles recovered from wastewater in the present study consisted of microfibres made of materials which may have come from clothing (i.e., PET), and made up 36% of total particles in seawater. However, it should be noted that ships are prohibited from expelling wastewater into the marine environment within 12 nautical miles of the coastline (Annex IV, INTERNATIONAL MARITIME ORGANIZATION, 2011), therefore no ship-based wastewater discharge would be taking place directly in the sampling locations. Suaria et al. (2020) found zero microplastics in their sample of surface seawater just offshore from South Georgia so perhaps the high concentrations in Cumberland Bay cannot be attributed entirely to wastewater discharge. Additionally, the counts of microplastics in the present study were not high enough to attach significance to any similarity in particle materials or types between seawater and wastewater (Alomar et al., 2016; Munari et al., 2017; von Friesen et al., 2020).

Microplastics in precipitation, or which have been transported via the atmosphere may also contribute to the high concentrations observed here. That the sample with the second highest concentration of microplastics in this study (4.67 ± 3.21 MP/L) is the precipitation (snow, SNO) sample lends credence to this suggestion. Recent discoveries of microplastics in an isolated Antarctic stream and within the planetary boundary layer suggest that MP particles can be transported thousands of kilometres in the atmosphere (González-Pleiter et al., 2020; González-Pleiter et al., 2021). Long-range atmospheric transport has been suggested as a source of microplastics retrieved from isolated locations in the past, generally for smaller particles approximately ≤100 μm (Bergmann et al., 2019; Zhang et al., 2019), though it is possible for larger particles (~300 μm) to be transported (Allen et al., 2019; González-Pleiter et al., 2021). Microplastic in the precipitation sample in the present study ranged in size from 50 to 830 μm, with a majority (64%) in the 50–100 μm size category, suggesting smaller particles are more likely to be transported via the atmosphere in greater quantities. South Georgia lies at 54°S, in the path of strong westerly winds which can reach speeds of up to 40 ms^{-1} (Bannister & King, 2015), which may be capable of transporting MP long distances potentially making the island a sink for MP from a wider geographical source. The sample size in the present study is too small to state definitively the concentration of microplastic being input into the system by precipitation, indeed the fact that this observation is in the same order of magnitude as atmospheric microplastic fallout over Paris, Hamburg, and Dongguan (Dris et al., 2016; Cai et al., 2017; Klein & Fischer, 2019) raises a serious question mark, despite every contamination control measure being taken; although similar concentrations have been noted in snow in the European Alps (Bergmann et al., 2019; Parolini et al., 2021) so it is not entirely improbable. Further research is recommended, and in addition, investigation into the proportion of microplastic found in seawater which may have come from atmospheric deposition.

It must be acknowledged that the concentration of microplastics in wastewater is notably low compared to other studies, including ones from remote locations (Granberg et al., 2019; Hidayaturrahman & Lee, 2019; Wei et al., 2020). In fact, it is more similar in concentration to wastewater which has undergone tertiary treatment (Blair et al., 2019; Turan et al., 2021; Azizi et al., 2022), though no such treatment is carried out at KEP which deploys only coarse filters on washing machines and sub-surface settlement tanks. It may be that microplastic concentration in wastewater varies daily depending on the activities at the research station, and that the day of sampling was not representative of any longer-term output. The system is also flushed continuously in winter months or on cold days in other months to prevent freezing of the pipes which may have been taking place prior to the day of sampling. Finally, it may be that a large subsection of particles in wastewater are being identified as cellulose following FT- IR analysis. Rayon, viscose, and cotton microfibres, which will be generated from washing clothes from clothes, all yield similar spectra and may not be in the reference libraries utilised which mainly contain plastics. Following spectral analysis, across all stations 74% of fibre SAPs proved to be cellulosic, potentially indistinguishable from cellulose-based synthetic materials (e.g., cotton, rayon etc.), or else from planktonic algae (Kuklinski et al., 2019), and were therefore eliminated from final MF counts (Jones--Williams et al., 2020; Stark, 2019). The percentage of particles, which proved to be cellulosic in wastewater (47.1%), was higher than that of seawater (32.8%) but as the actual material of these cellulosic particles is unknown, no definitive conclusion can be drawn.

4.1. Recommendations

Further samples of microplastics from seawater are required to statistically compare with potential sources be they wastewater outlets from ships or stations, local macroplastic debris, or other anthropogenic-related particles (i.e., from clothing or equipment). This information would help to determine how much microplastic pollution is being produced locally and how much is transported from afar. Additionally, further sampling of wastewater is required to build up an accurate picture of microplastic flux from this source. Microplastics have been discovered in two species of penguin in South Georgia (Bessa et al., 2019; Le Guen et al., 2020) in both cases, in populations which inhabit the same marine area that was sampled in the present study, in proximity to the zone of greatest anthropogenic presence. The physiological effects of ingesting microplastic on higher predators is relatively unknown, but knowledge of whether organisms in remote, pristine regions are threatened by microplastics being transported from afar, and if so, to what degree, is vital to species conservation. Fine-scale mapping of the hydrological regime around South Georgia would also contribute to this knowledge.

More extensive examination of the particles recovered is also recommended. It is customary law that a spectral match of ≥70% is the minimum required for a positive identification, however in this case the spectral libraries utilised contained only virgin plastics therefore any microplastic particles from the environment that have undergone weathering, aging, biofouling, or chemical adsorption are unlikely to meet this ≥70% threshold. The aging and roughing of a microplastic's surface, plus adsorption of unknown chemicals, can cause up to 40% possible variation in the carbonyl region of plastic and subsequent spectral variations (Dong et al., 2020; Liu et al., 2019; Prata et al., 2020; Chen et al., 2021). Lowering the threshold for a potential match is not recommended but comparison with more diverse libraries that potentially contain spectra from weathered materials may counter this problem (La Daana et al., 2018; Lindeque et al., 2020).

The buoyancy of particles should also be considered. Mountford and Morales-Maquada (2021) postulate that the majority of microplastics present in the Southern Ocean will be neutrally buoyant. The transport of microplastics from surface waters to other ocean depths is well described (Cole et al., 2016; Kooi et al., 2017; Liu et al., 2020; Gopalakrishnan & Kashian, 2022) and microplastics have been retrieved from various depths of polar waters (Bergmann et al., 2017; La Daana et al., 2018; Cunningham et al., 2020; von Friesen et al., 2020). Jones-Williams et al. (2020) examined the rate at which pelagic amphipods encounter microplastics in sub-Antarctic waters and found that even at low microplastic concentrations, particles are encountered and potentially consumed by plankton. Knowing how much microplastic in the sub-Antarctic marine environment is neutrally buoyant and is therefore bioavailable to zooplankton would refine the level of risk from this

pollutant to zooplankton and the wider food web of the region.

5. Conclusions

Higher levels of microplastic pollution are observed in the coastal waters of the study region than in most other records of surface water from the Southern Ocean, but concentrations were still too low to statistically ascribe it to a local point source (research station wastewater outlet). South Georgia's broad range of anthropogenic activities makes it a barometer for the impact of such activities elsewhere in Antarctica and the Southern Ocean. How much microplastic pollution is being produced locally by said activities, and how much is being transported from afar remains uncertain but is worthy of further investigation to inform effective conservation of South Georgia's ecosystem health.

CRediT author statement

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Funding

This work was supported by the NERC Collaborative Antarctic Science Scheme and the British Antarctic Survey, and the Energy & Environment Institute of the University of Hull.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

With thanks to Jennifer Jackson, Philip Hollyman, Jerry Gillham, Alice Clement, Kirstie Jones-Williams, and Paul Geissler of British Antarctic Survey; the Government of South Georgia and the South Sandwich Islands; and Freija Mendrik and Daniel Parsons of the Energy & Environment Institute.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119379.

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