REVIEW OF THE CURRENT STATE OF KNOWLEDGE REGARDING

MARINE LITTER IN WASTES DUMPED AT SEA

UNDER THE LONDON CONVENTION AND PROTOCOL

FINAL REPORT

LC&P
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INTERNATIONAL MARITIME ORGANIZATION

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Preface

In 2014, the Scientific Groups, having recalled the plan of action to cooperate with UNEP-GPA, which the governing bodies endorsed in 2009, agreed that a review of marine litter from waste streams was one of the remaining issues on the plan of action that needed to be addressed, with a target date of 2015. As a consequence, the Groups agreed that it would be beneficial to perform an initial review of marine litter in dredged material, sewage sludge and industrial discharges.

As one of the partners in the UNEP-led Global Partnership for Marine Litter (GPML), IMO is co-leading efforts on sea-based sources of marine litter together with FAO. Within the framework of this partnership, the Secretariat was able to allocate GPML funding to commission a study on marine litter in relation to the various waste streams under the London Convention and Protocol. In January 2015, a consultant was contracted to carry out this study.

A draft report, prepared by the consultant was reviewed by the Scientific Groups in May 2015. The main objective of the study is to provide an overview of the current state of knowledge regarding litter/plastics in wastes dumped at sea and their possible implication in relation to the London Convention and Protocol (LC/LP).

It should be noted that the purpose of the report is to serve as a starting point for discussions on the nature and extent of litter (in particular plastics) in the waste streams under the LC/LP. It does not claim to be a complete review of these aspects, but will hopefully stimulate further discussions, both in relation to the LC/LP and within the wider global community.

Acknowledgements

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Executive summary

1 There is firm evidence that the oceans are heavily contaminated with litter derived from anthropogenic activities Marine litter comprises many different materials in various sizes, including, e.g. metal, wood, glass and plastics. Plastics, and in particular microplastics, are major components of marine litter, ranging from heavy fishing gear to minute plastic particles originating from both industrial and domestic sources. It is widely accepted that measures to reduce and curtail inputs of litter to the sea are urgently required, at both national and international levels.

2 In this context, it is entirely appropriate that the procedures used to assess wastes prior to the issuance of permits for sea disposal, should include an assessment of their litter content. In order to determine the need for, and feasibility of, new procedures for assessing litter content of wastes regulated under the London Convention and Protocol (LC/LP), this review of related scientific literature is intended as an initial contribution to the discussion. It identifies the wastes most likely to contain litter and the most commonly occurring materials involved. It provides summaries of research into the properties and behaviour of litter in the marine environment and its interactions with marine biota, focusing in particular on sediments. Finally, it proposes a number of research topics needed to fill some of the more important gaps in information.

3 Of the different categories of waste that under certain conditions may be eligible for sea disposal, sewage sludge and dredged material are most likely to contain items and fragments of litter. A high proportion of the litter in these wastes is composed of plastics. Plastic materials consist of a wide range of polymer types, densities, colours and resilience. Although plastic litter items range from large and bulky to microscopic, by far the most numerous and widespread are microplastics consisting of tiny fragments, fibres, pellets and spherules. Such microplastics are now practically ubiquitous in the marine environment, clearly showing that they are readily transported by ocean currents.

4 Domestic sewage is a major source of microplastics which, because of their size (< 5 mm), can pass through the filtration process in wastewater treatment plants, especially if the filters are functioning incorrectly. A large proportion of microplastic fibres found in the marine environment may be derived from washing clothes, especially polyester and acrylic materials. Spherical microbeads, made from polyethylene or polypropylene, have now replaced natural exfoliating materials in skin cleaners (e.g. pumice, oatmeal, apricot or walnut husks); their dimensions are less than 100 microns.

5 Dredged sediments have also been found to contain microplastics and occasionally contain macrolitter and discarded fishing gear. Highest densities are found in areas of weak circulation and high sedimentation rates. On continental shelves, plastics (mainly bags and bottles) account for a very high percentage (more than 70%) of the items found. In coastal sediments around the world, microplastics appear to be ubiquitous at densities range from <10 to over 100,000 items per m2. Some of the highest densities occur in harbours. Discarded fishing nets (i.e. 'ghost nets'; largely polypropylene, polyethylene and nylon) are resistant to degradation and can trap large numbers of fish and crustaceans.

6 Much of the research into marine litter has focused on the occurrence, behaviour and effects of small plastic particles and fragments (microplastics). Floating litter may eventually sink to the seafloor, due either to an increase in weight because of absorbed water and/or the settlement of living organisms. Microplastics may also reach sediments through ingestion by filter-feeders, zooplankton and fishes; some of these reach the seafloor after their death, or become components of 'marine snow'. Due to complex interactions between fouling, erosion and surface-volume ratios of particles, it can be hypothesized that temporal changes in buoyancy of microplastics depends on particle size. Since microplastics are in the same size

range as sediment particles and some planktonic organisms, they are potentially available by ingestion to a wide range of marine fauna such as lower trophic suspensors, filter and deposit feeders, detritivores and planktivores. Particle capture and ingestion may be based on size selectivity.

7 Laboratory studies suggest that ingestion of microplastics could result in serious effects on marine invertebrates, both physical, such as internal abrasions and blockages, and chemical. Plastic litter readily accumulates persistent organic pollutants (POPs) which have a greater affinity for the hydrophobic surface of plastic than for seawater. The process could increase the exposure of marine organisms to POPs due to bioaccumulation and biomagnification through the food chain. The significance of co-ingestion of POPs with microplastics is unclear.

8 There are various techniques for segregating macrolitter from sludge and sediments involving the use of screens and filters. There are also techniques for segregating small plastic particles/fragments by means of flotation but to date these are mainly used on a small scale, e.g. for experimental purposes. The technical and operational feasibilities of separating microplastics from large amounts of dredged material are largely unknown. The engineering challenges involved are considerable and, at present, such separation is logistically and economically impractical.

9 To conclude, it is presently impossible to generalize regarding the litter content of either sewage sludge or dredged materials, in terms of litter types, properties or quantities. The main reasons for this are an overall shortage of data, differences in methodology and reporting, and the lack of systematic sampling in space and time. Nevertheless, it seems probable that various types of small and micro-sized plastics present the greatest hazards and warrant most concern. It is premature to speculate, however, on the specific materials that present the greatest risks for marine life or to focus on any particular line of experimental research that would enable actual effects to be evaluated.

10 Amongst the more important areas for further study are:

- methodologies for sorting and enumerating plastic fragments;
- the standardization of methods for assessing microplastic contamination;
- methods for reducing/removing microplastics in sewage and sediment;
- relationships between microplastic densities and biological effects; and
- the relevance of co ingestion of plastics, polymer additives and POPs.

1 Introduction: marine litter and microplastics

Marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed or abandoned in the marine and coastal environment (UNEP, 2009a). It includes the following categories: plastics, metals, sanitary waste, paper, cloth, wood, glass, rubber and pottery. While each category can pose problems in the marine environment, plastics, due to their lightweight and durable nature, have become the most prevalent, widespread element of marine litter (Derraik, 2002; Wright et al., 2013a).

The global annual production of plastics is around 280 million tons, the vast majority being for disposable items (Santos and Duarte, 2015). About 8% of oil produced in the world is used to manufacture plastics, half of which are polyolefins (such as polyethylene and polypropylene), mainly for single use packaging that is thrown away within a year (Browne et al., 2010). Through accidental release and indiscriminate discards, plastic waste has accumulated in the environment at an uncontrollable rate, where it is subjected to wind and river-driven transport, ultimately reaching the coast.

Marine litter can be broadly categorized according to its source, either land-based or sea-based. Land-based sources introduce litter mainly from domestic, agricultural and industrial activities that is washed out from land during storms and enters the marine environment through rivers, ephemeral streams and sewage inputs, as well as from wave action on the coast. Sea-based sources include fisheries, recreational boats, shipping, energy production, research, and legal and illegal dumping activities; they introduce a large number of different materials of various sizes (Straffella et al., 2014).

Marine litter has both environmental and economic impacts and presents risks to human health and safety. The types and sizes of marine litter determine the impact and fate of these materials in the ocean (e.g. submerged, floating, within a sensitive habitat).

Environmental impacts are wide ranging. Marine life can be physically harmed by marine litter through ingestion or entanglement (e.g. a turtle mistakes a plastic bag for food) or it can physically alter a sensitive ecosystem (e.g. smothering of a coral reef). Microplastics (plastic with dimensions less than 5 mm) are of environmental concern because their size makes them accessible to a wide range of organisms, at least as small as zooplankton, with potential for physical and toxicological harm. Microplastic particles comprise either manufactured plastics of microscopic size, such as scrubbers (plastic microbeads), and industrial pellets that serve as precursors for manufactured plastic products (primary sources), or fragments or fibres of plastics derived from the breakdown of larger plastic products (secondary sources) (GESAMP, 2015). Degradation processes for plastics are extremely slow; microplastics can persist for very long time periods in the marine environment (Hidalgo-Ruz et al., 2012).

Marine litter can harm three important components of the national economy: tourism, fishing and navigation. Damage to tourism may result from a reduction in the aesthetic value of coastal areas affected, coupled to the high costs of removing and disposing of litter.

Moreover, floating marine litter is a navigational hazard, entangling propellers and clogging water intakes on ships. Repairing ships damaged by marine litter is both time-consuming and expensive. Finally, fisheries could suffer significant economic impacts from marine litter. Commercial fisheries are impacted when fish and shellfish become by-catch in lost fishing nets (the so-called ghost nets). Fisheries also can be financially affected when fishing gear and vessels are entangled or damaged by marine litter.

For the above reasons, international organizations, such as the United Nations Environment Programme (UNEP), are developing and implementing a number of activities for the management of marine litter at a global level (UNEP, 2009a).

This review focuses mainly on the extent, sources, pathways and effects of plastics and microplastics in LC/LP waste streams, since scientific research in recent years has highlighted the negative effects of plastic contaminants on marine biota; other categories are taken into consideration only when their presence in waste streams could be considered a problem (e.g. smothering of benthic biota). This distinction is made because marine litter includes a large number of materials (e.g. metal, wood, ceramic, glass) that are of less concern to the environment and would not normally act as containers of toxic and harmful substances.

Because of the harm they may cause to marine biota (see chapter 4), it is important to identify the most relevant considerations applicable to procedures used to evaluate wastes containing plastic materials prior to disposal at sea. This applies, in particular, to the characterization of waste streams (including dredged sediments) in terms of plastics abundance, distribution and chemical composition. Possibilities for reducing plastics in wastes prior to disposal must also be considered. The purpose of this review is to initiate discussions to this effect.

2 Objectives of Review and Terms of Reference

In May 2014, the Scientific Groups of the London Convention and Protocol (LC/LP) noted the global attention to litter and plastics in the marine environment and highlighted the knowledge gaps with respect to the waste streams regulated under the Convention/Protocol. The Groups, therefore, agreed that it would be beneficial to perform an initial review of marine litter in relation to the various waste streams under the LC/LP, in particular dredged material, and possibly sewage sludge. The Secretariat agreed to investigate the possibility of carrying out such a study under the Global Partnership for Marine Litter[1] (LC/SG 37/16, paragraph 8.31).

Therefore, the principal objective of this review is to provide a comprehensive review of current knowledge regarding plastics in wastes dumped at sea and the implications, if any, for the LC/LP. Whereas the study focuses on dredged materials and sewage sludge, it is possible that many of the findings would also apply to plastics in other wastes, not regulated by the LC/LP, that enter the sea, e.g. industrial, land run-off, etc.

The study aims to answer, inter alia, the following questions:

1. What is the extent and nature of plastics (micro or otherwise) in dredged materials (identifying the scope of the problem, methodologies for estimating the nature and quantity of plastics in sediments, etc.)?
2. What are the sources and pathways of plastics that end up in dredged materials? In this context, what is the relevance of other waste streams (including land-based run-off, sewage disposal and industrial (wastewater) discharges)?
3. What is the nature of resuspension of plastics through dredging and what are the impacts on marine biodiversity during dredging and following disposal?
4. What are the current gaps in the available information?

Accordingly, this report constitutes a compilation and review of relevant information obtained through a search of selected reports and scientific journals.

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1 For more Global Partnership for Marine Litter (GPML), see http://www.marinelitternetwork.org/page/global-partnership-marine-litter

Since data on litter in the various waste streams of concern to the LC/LP are scarce, a general literature research was also conducted on the presence and consequences of plastics/litter in the marine environment, in particular sediments. The information obtained may prove useful in:

- identifying the most important implications of plastics in wastes dumped at sea;
- highlighting major information gaps; and
- formulating future management actions.

Chapter 3 identifies the waste streams dumped at sea that may contain plastics and microplastics, primarily dredged materials and sewage sludge. The discussion focuses on the reasons why plastics accumulate in these materials.

Chapter 4 describes the behaviour and fate of plastics in the marine environment, particularly in sediment. Plastics are classified according to their chemical composition, their shape, size and interactions with biota; the processes involved are also described.

Taking into account the findings of previous chapters, chapter 5 describes the more important information gaps that are currently apparent. Finally, chapter 6 synthesizes the principal findings from the review and proposes a future work programme for consideration by LC/LP Contracting Parties.

3 Litter content of wastes regulated by LC/LP

The types of waste streams for which sea disposal may be considered include:

a) dredged materials;
b) sewage sludge;
c) fish waste, or material resulting from industrial fish processing operations;
d) vessels and platforms or other man-made structures at sea;
e) inert or inorganic geological material;
f) organic matter of natural origin;
g) bulky items comprising primarily iron, steel, concrete or non-harmful materials; and
h) carbon dioxide streams from carbon dioxide capture processes for sequestration.

Currently, authorization procedures for such wastes do not specifically require analysis of the litter content, neither in the waste itself nor at the dump sites.

The chances of finding litter, especially plastics, in dredged materials and sewage sludge would appear to be high. Evidence of this is presented in the following sections.

The other waste streams would seem less likely to contain items typically described as litter but some of the larger and bulkier objects, even when dumped under controlled conditions, might be considered a form of marine litter.

3.1 Sewage Sludge: types and sources of plastics (mainly microplastics)

Sewage sludge is the residual matter remaining after treatment of domestic/municipal waste at a sewage plant. It is rich in organic matter but also contains chemical and biological elements. Sludge contains liquid domestic waste (black water), runoff water from the urban environment (white water) and also, in some cases, treated and non-treated industrial wastes.

For many small plastic items, in particular microplastics, sewage sludge is often their final destination. Microplastics, because of their size (< 5 mm), can pass through the filtration process in wastewater treatment plants, especially if the filters are functioning incorrectly. Microplastics with a density greater than that of water will end up in the sludge, while those suspended in the aqueous phase will have a more direct route to rivers and seas.

3.1.1 Microfibres

An important source of microplastics in sewage appears to be the washing of clothes. Forensic evaluation of microplastics in sediments showed that the proportions of polyester and acrylic fibres used in clothing resembled those found in sediments contaminated with sewage-discharges and in sewage effluent itself (Browne et al., 2011).

Experimental sampling of wastewater from domestic washing machines has demonstrated that a single garment can produce >1900 fibres per wash. This suggests that a large proportion of microplastic fibres found in the marine environment may be derived from clothes washing (Browne et al., 2011). Because people wear more clothes during the winter than in the summer and washing machine usage in households is 700% greater in the winter, authors suggest that more fibres could enter sewage treatment during the winter. Research is therefore needed to assess seasonal changes in the abundance of plastic fibres in sewage effluent and sludge.

Sandblasting media includes polymeric materials containing acrylic with a density of 1.19 g cm^{3} and amino thermoset plastics (1.47–1.52 g cm^{-3}), which would be negatively buoyant in water. These materials may also be found in sewage sludge (Santos and Duarte, 2015).

Since substantial quantities of sewage sludge and effluent are discarded into the sea, there is a considerable potential for microplastics to accumulate in aquatic habitats, especially in densely populated areas. In the United Kingdom, for example, certain subtidal marine sites contain large quantities of microplastics in their sediments because, for nearly 30 years, a quarter of United Kingdom sewage sludge was dumped at designated marine disposal-sites around the coasts; the practice was discontinued in 1998 (Brown et al., 2010).

A survey of marine sediments spanning six continents, marine sewage disposal sites and sewage effluent, found eighteen shores contaminated with microplastics (Browne et al., 2011). Abundance ranged from 2 to 31 fibres per 250 ml of sediment, consisting of polyester (78%) and acrylic (22%). To further examine the role of sewage as a source, microplastics were extracted from effluent discharged by sewage treatment plants and compared with sediments from disposal sites. Effluents contained, on average, one particle of microplastic per litre. As expected, polyester (67%) and acrylic (17%) fibres dominated along with polyamide (16%), showing that the proportions of fibres in sewage effluent resembles that in sediments from shores and disposal-sites. This suggests that these microplastic fibres were mainly derived from clothing rather than fragmentation or cleaning products.

Browne et al. (2010) also evaluated spatial patterns of plastic litter along the Tamar Estuary, United Kingdom. They observed more than four fibres per gram of sewage-contaminated sediment. Zubris and Richards (2005) have proposed synthetic fabric fibres as indicators of past spreading of wastewater sludge. Synthetic fibre detectability was examined in sludge and in soils from experimental columns and field sites where sludge had been deposited. Fibres (isolated by water extraction and examined using polarized light microscopy) were detectable in sludge products and in soil columns over 5 years after application, retaining characteristics observed in the applied sludge. Fibres were detectable in field site soils up to 15 years after application, again retaining the characteristics seen in sludge products. Fibres found along preferential flow paths and/or in horizons largely below the mixed layer suggest some potential for translocation.

In conclusion, polyester, acrylic, polypropylene, polyethylene, and polyamide fibres contaminate shores on a global-scale, particularly in densely populated areas and habitats that received sewage. To tackle this problem, designers of clothing and washing machines should consider the need to reduce the release of fibres into wastewater, and research is needed to develop methods for removing microplastics from sewage. One means of mitigation may be ultrafiltration.

3.1.2 Microspherules

Spherical microplastics could be derived from consumer products, such as facial cleansers and other personal products, since they contain spherical microbeads, labelled on the product as polyethylene (0.91–0.96 g cm^{-3}) or polypropylene (0.91 g cm^{-3}), which would float in water. Such additives have now replaced natural exfoliating materials in skin cleaners (e.g. pumice, oatmeal, apricot or walnut husks). Their dimensions are less than 100 microns and because of their small size, they are likely to escape capture by the preliminary treatment screens in wastewater treatment plants (typically coarse > 6 mm, and fine 1.5–6 mm screens) (Fendall and Sewell, 2009).

Microspherules are not captured by wastewater treatment plants and may therefore enter the oceans. Because of their low density, they do not sink immediately and this is probably the reason why they are not found in sewage sludge but only in wastewater. The aqueous phase of treated sewage is usually directly or indirectly released to sea and, by various means, some of its constituents will sink to the seabed. Subsequently, they be ingested by organisms such as filter-feeding polychaetes, echinoderms, bryozoans, bivalves and barnacles, deposit-feeding lugworms and sea cucumbers, and by detritivores such as amphipods (Thompson et al., 2004, Graham and Thompson, 2009) (see chapter 4).

Sewage sludge could contain microspherules if the wastewater plant handles effluents coming from plastic industries. Claessens et al. (2011) observed high microplastic concentrations, mainly polystyrene microspherules, in sediments collected in the Belgian harbour of Nieuwpoort (390.7 ± 32.6 particles kg^{-1} dry sediment), located inside a circular sluice complex where several rivers are connected to the harbour. The authors suggested that these high concentrations were not necessarily the result of harbour activities but may have originated from plastic industries that discharge to rivers. Since polystyrene spherules have a density greater than that of seawater (see Table 1), it is possible that they sink to the seafloor before they can be flushed out of the harbour.

3.2 Dredged Materials: types and sources of plastic litter

Dredging is an essential activity in order to ensure the navigability of harbours and rivers, for the development of docks, to mitigate the effects of flooding and to remove sediments for other human structures such as water intakes for industrial processes. Dredged material is often disposed of at sea.

Since dredged materials consist mainly of marine sediments, this chapter examines the different types of litter that may be found on the seabed. These include:

- macrolitter;
- lost and abandoned fishing gear (ghost nets); and
- microplastics.

Due to the practical problems of observing extensive sections of the sea floor, data on litter in sediments are scarce. The information given here has been obtained either through direct observations by divers or by Remotely Operative Vehicles (ROVs) and bathyscaphs. A useful indirect observation comes from analyses of marine litter collected with bottom trawls during demersal fish stock evaluations.

3.2.1 Macrolitter

The abundance and distribution of marine litter shows considerable spatial variability. The geographical distribution of litter on the sea floor is strongly influenced by hydrodynamics, geomorphology and human factors. Under the weight of fouling by a variety of organisms, otherwise buoyant macrolitter can sink to the bottom. Currents may then transport these items to areas where they can accumulate. Amongst the locations well-suited to the accumulation of litter on the seafloor are low-energy areas and gyres. Due to their persistence, the types and amounts of some materials littering the seafloor will reflect accumulation processes that have been operating for decades (JRC, 2011).

With few exceptions (Katsanevakis, 2008), the abundance of marine litter in shallow coastal areas (< 40 m depth) is generally much greater than on the continental shelf or the deep seafloor. This is especially true for bays and harbours, due to weaker currents. Litter accumulated on the sea floor is often an indicator of a local source, especially for the heavier materials such as glass, metals and rubbers. The presence of heavy litter in the deep sea is considered an index of shipping traffic, an important sea-based source (Ramirez-Llodra et al., 2013).

Sheltered harbours act as traps for litter transported from the open sea, introduced either directly or through rivers, wastewater or sewage. Moreover, harbours are usually located in heavily populated areas and harbour-based activities (e.g. fishing, loading and unloading of goods, pleasure craft, etc.) can produce considerable amounts of litter directly. This is crucial because most harbours are occasionally subject to dredging.

As mentioned previously, surveys of macrolitter on the seabed (in particular on continental shelves) have been conducted using bottom trawls. This is the most adequate method used to date, although quantities of litter may still be underestimated (i.e. it can be seen as a method for estimating relative litter densities rather than absolute densities). Research into litter deposits in the deeper seabed is restricted by sampling difficulties and costs. Large-scale evaluations of deep seabed litter distribution, and densities anywhere, are scarce. Of the areas investigated along European coasts to date, Mediterranean sites tend to show the greatest densities (Galgani et al., 1996).

In general, analyses of marine litter on continental shelves and in deep sea confirm that bottom litter tends to become trapped in areas of low circulation and high sediment accumulation. Deep submarine extensions of coastal rivers also influence the distribution of seabed litter. Investigations using submersibles at depths beyond the continental shelf have revealed substantial quantities of litter mainly in canyons adjacent to large cities (up to 112 items per kilometre and 70% plastics) (Galgani et al., 2000). Reports on quantities and distributions of litter on continental shelves indicate that plastics (mainly bags and bottles) account for a very high percentage (more than 70%) of the items found (Stefatos et al., 1999; Galgani et al., 2000; Lee et al., 2006; Pham et al., 2014, Strafella et al., 2014).

Concentrations of marine litter are usually expressed as the number of items per square kilometre (n. items/km^2) or weight per square kilometre (kg/km^2). Values vary greatly and, on continental shelves are in the range from tens and hundreds of items or kilograms per square kilometre. To summarize, locations that are particularly susceptible to litter accumulation (Figure 1) are as follows:

- coastal areas;
- areas close to terrestrial sources (e.g. sewage wastewater, river);
- depressions in the seabed; and
- low-energy environments (low currents, weak circulation).

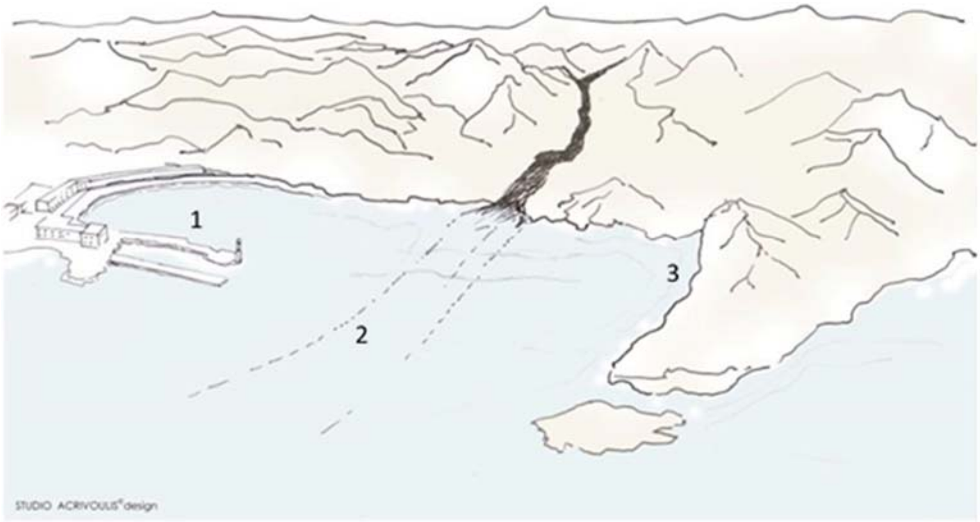


Figure 1: Locations susceptible to accumulations of litter on the seabed, reflecting hydrodynamics, geomorphology and human factors: 1. Harbours; 2. Morphological depressions (canyons, submarine extensions of coastal rivers); 3. Areas with weaker currents.

3.2.2 Microplastics

In coastal sediments around the world, microplastics appear to be ubiquitous, although there have been few dedicated studies of this issue (GESAMP, 2015). The concentration of microplastics is variously reported as the number of particles/items per:

- square meter (particles/items m^{-2});
- cubic meter (particles/items m^{-3});
- millilitres (particles/items ml^{-1}); and
- kg of dry sediment (Santos and Duarte, 2015).

The levels of microplastics in sediments vary widely between reports, ranging from low background concentrations of 8 particles kg^{-1} (Thompson et al., 2004), to very high, hot-spot concentrations of 621,000 particles kg^{-1} (Liebezeit and Dubaish, 2012). Kusui and Noda (2003) report abundances ranging from 0.21 to more than 77,000 items m^{-2} in sediments. Thus, the numbers of plastic particles in sediment can differ by many orders of magnitude.

As in the case of macrolitter, microplastics seem to concentrate in harbour sediments, according to the geometry of the harbour compartments. The flushing rate in harbours can be very low and the narrow entrances can produce tidal eddies. Microplastics trapped in such confined areas will eventually settle to the bottom where they are less susceptible to tidal flushing. Claessens et al. (2011) investigated the occurrence and distribution of microplastics in sediments from different Belgian locations (coastal harbours, beaches and sublittoral areas). Particles were found in large numbers in all samples, the highest being in harbours where total concentrations of up to 390 particles kg^{-1} dry sediment were observed; this is 15–50 times higher than the reported maximum concentrations in other, similar study areas. Plastic fibres formed the majority (59%) of microplastics sampled, with average concentrations of 81.0 ± 37.2, 65.6 ± 15.3 and 66.3 ±28.6 fibres kg^{-1} in dry sediments from beach, harbour and sea sampling stations respectively. The average concentration of microplastic particles in the harbour sediments (166.7 ± 92.1 particles kg^{-1} dry sediment) was significantly higher than those on the Belgian continental shelf (97.2 ± 18.6 particles kg^{-1} dry sediment) and in beach sediments (92.8 ± 37.2 particles kg^{-1} dry sediment).

The fibres identified in the above study consisted of polypropylene, nylon and polyvinyl alcohol; granular particles were identified as polypropylene, polyethylene or polystyrene (see Table 1). All the analysed plastic film fragments were identified as nylon. This is a relevant finding because most packaging material is made of polyethylene. Low-density polyethylene is defined by a density range of 0.910 – 0.940 g cm^{-3}, while the density of nylon (1.15 g cm^{-3}) is actually higher than the average density of seawater (1.025 – 1.03 g cm^{-3}). Also, Ng and Obbard (2006) reported differences in the prevalence of polyethylene fragments among different marine media, with higher concentrations found in subsurface waters compared to concentrations in sediments. They found nylon only in sediment samples. This suggests that polyethylene fragments are indeed more likely to remain in suspension while nylon fragments settle more rapidly.

To quantify the abundance of microplastics, Thompson et al. (2004) collected sediment from beaches, estuarine and subtidal sediments around Plymouth, United Kingdom. Less dense particles were separated by flotation. Those that differed in appearance to natural particulate material were removed and identified with Fourier Transform infrared (FT-IR) spectroscopy. One third were synthetic polymers; these polymers were present in most samples (23 out of 30), but were significantly more abundant in subtidal sediment (see Figure 2).

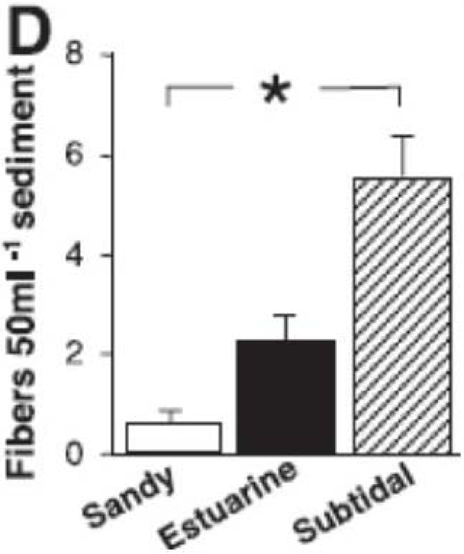


Figure 2: Microplastic densities in sediments from beaches, estuarine and subtidal areas around Plymouth, United Kingdom (source Thompson et al., 2004)

Nine polymers were conclusively identified in the Plymouth study: acrylic, alkyd, polyethylene, polypropylene, polyamide (nylon), polyester, polyethylene, polymethylacrylate, polypropylene, and polyvinyl-alcohol. These have a wide range of uses, including clothing, packaging and rope, suggesting that the fragments resulted from the breakdown of larger items.

It is not fully clear whether microplastic contamination of sediments is limited to the continental shelf or whether it extends to deep-sea sediments. Van Cauwenberghe et al. (2013) analysed 11 sediment samples from locations in the Atlantic Ocean and Mediterranean Sea, ranging in depth from 1,176 to 4,844 m. Only the top centimetre of the sediment cores was analysed for the presence of microplastics; particles were found at three of the four locations studied. A similar study (Fischer et al., 2015) was conducted in the northwest Pacific Kuril–Kamchatka Trench and its adjacent abyssal plain. Microplastics were ubiquitous in every sampling station from depths between 4869 and 5766 m. Densities differed between the stations, from 60 pieces per m^2 to more than 2,000 pieces per m^2. Around 75% of the microplastics were fibers.

Browne et al. (2010) examined the influence of wind and depositional regime on spatial patterns of microplastics within the Tamar Estuary, United Kingdom. Particles were categorized according to density and they consisted mainly of polyvinylchloride, polyester and polyamide. Generally, there were greater quantities of plastic at downwind sites and there were clear patterns of distribution for denser items. Less dense microplastic litter (polyethylene and polypropylene) was distributed evenly throughout the estuary but was low in abundance with no more than 1 particle per 50 ml of sediment.

3.2.3 Lost and abandoned fishing gear (ghost nets)

Lost/abandoned fishing gear is an evident and increasing nuisance worldwide. It is assumed that hundreds of thousands of tonnes of non-degradable fishing nets are abandoned or lost in the world oceans every year. Due to the resistance to degradation of synthetic materials (nylon, polyethylene and polypropylene) used in fishing gear, once discarded or lost these materials remain in the marine environment with negative economic and environmental impacts. Worldwide, this phenomenon is having an impact on the sustainability of already stressed fisheries. ‘Ghost fishing’ kills thousands of fish that might otherwise have found their way to the market. An estimated US$250 million in marketable lobster is lost each year from ghost fishing (UNEP, 2005).

Fishing gear could be lost at sea for several reasons (bad weather conditions, accidental cutting of buoys by vessels, etc.) or abandoned when it becomes irreparable (leaving it in the sea, although illegal, is a convenient means of disposal). Another damaging, particularly evident in fishing harbours, is where fishermen habitually dump old fishing gear in a place where they don‘t fish. In shallow coastal areas, fishing activities significantly contribute to littering of the seafloor (Katsanevakis and Katsarou, 2004)

When dumped or otherwise lost at sea, "ghost nets" sink because they consist mainly of nylon 6, which is denser than sea water. Fishing gear remains functional for a long period of time in the sea, is beyond human control and continues to cause mortality of marine organisms. For this reason, lost/abandoned fishing gear could be considered the most dangerous form of marine litter for the marine ecosystem.

The code of conduct for responsible fisheries developed by the Food and Agricultural Organization (FAO) of the United Nations considered ghost fishing an important issue, causing additional mortality in already overexploited marine ecosystems (UNEP/FAO, 2009). Ghost nets are sometimes described as perpetual "killing machines" that never stop fishing. Some studies have attempted to measure the efficiency of ghost nets; this depends on many factors such as the type and depth of seabed where the net remains, the velocity of biofouling development, visibility or transparency of water, etc. (Kaiser et al., 1996; Erzini et al., 1997, Saldanha et al., 2003).

Actual catch rates of lost/abandoned fishing gear vary so greatly that a global estimate would be meaningless (Brown et al., 2005). Sancho et al. (2003) estimated that lost tangle nets caught around 5%of the total commercial catch. Several studies on static fishing gear have shown it can catch about 10% of the target population. Fish and crustaceans, such as lobsters and crabs, are frequently caught in lost or discarded fishing gear. Major damage seems to be caused by lost cage traps, resting on the sea bottom, which continue to attract fish and crustaceans searching for food or shelter (i.e. the so-called ‘self-baiting’ phenomenon).

Abandoned fishing gear in the form of nets and ropes can also cause significant risks to vessel operations. For example, entanglement of vessel propellers and rudders results in costly repairs, significant loss of operational time and risks to boat and crew safety (Johnson, 2000).

Other fishing gear, such as trammel nets with three vertical layers of netting, used to entangle fish or crustaceans, may also kill a great number of marine fauna. They are used especially near the coasts, in rocky habitats characterized by high biodiversity.

4 Plastics in the sea: Behaviour and impact on marine life

This chapter examines the behaviour, fate and effects of plastics in the marine environment with particular attention to the sediment, as this is the medium most affected by dumping activities. Much of the discussion deals with microplastics, due to their ubiquity and potential effects on marine life.

Microplastics occur in the sea as either primary or secondary particles. Primary microplastics are those manufactured for specific purposes, such as microbeads used in cosmetic products (Fendall and Sewell, 2009) that can be found in wastewater. Secondary microplastics are produced through degradation of larger-sized products. As noted previously, microplastic fibres, such as polyester and polyamide present in domestic wastewater are not retained during sewage treatment and can thus enter the marine environment directly or through the dumping of sewage sludge (Browne et al., 2011).

Once in the ocean, floating plastics are transported by currents resulting in highly variable surface concentrations, which makes detection of long-term trends difficult. For instance, oceanographic models and field observations find very high concentrations (up to 10^6 pieces km^{-2}) of floating microplastics in subtropical ocean gyres, far from land-based sources. In general, microplastics move differently than macroplastics in the sea; the distribution of macroplastics can often be explained by the prevailing currents and wind, while the mechanisms that drive the distribution of microplastics are less well-known and are possibly influenced by particle aggregation or animal activities (Hidalgo-Ruz et al., 2012).

According to its weight and shape, marine litter can be divided into two categories: floating litter and sinking litter. There are great differences in the distances that litter can be transported from its source, depending on the buoyancy and longevity of the different items and materials. For instance, while some plastics may float on the surface, travelling great distances before sinking, glass and metal will sink rapidly close to where they were initially released (Strafella et al., 2014). Floating objects eventually settle near shore or sink to the seafloor due to water absorption and/or fouling by organisms (Lee et al., 2006).

With the exception of localized spills, the relationship between microplastic concentration and its sources is poorly understood because of complex transport mechanisms and unknown fragmentation rates (Law and Thompson, 2014).

4.1 Pathways of plastics to marine sediments

The sea floor is a sink for much of the plastic litter that enters the sea (Goldberg, 1997), but the mechanisms by which these materials reach the sediment are still poorly understood (Gregory, 2009). For larger plastic litter, heavy fouling is a possible mechanism (Figure 3).

Microplastics, on the other hand, could reach the sea floor as marine snow (Van Cauwenberghe et al., 2015), a biologically enhanced aggregation of small particles (microaggregates) that normally contain phytoplankton, organic litter and clay particles; these are held together through the action of extracellular polymeric material exuded by living or dead cells. Sinking rates of marine snow are estimated to range from 1 to 368 m day^{-1} (Alldredge and Silver, 1988). Through the incorporation of microplastics in these microaggregates, even low density plastic particles (such as polyethylene and polypropylene) that normally float on the sea surface can be transported to the sea floor. As such, it is hard to predict the type of plastic (i.e. low-density vs. high-density plastic) that will not sink (Figure 3).

Microplastics of low specific density are positively buoyant and thus likely to spend a long time in the upper water column, where they can potentially be transported over long distances. They can be found in remote places, e.g. on sandy beaches, distant from their sources. However, particles of low specific density have also been found in subtidal sediments, mainly through overgrowing of epibionts (Brown et al., 2011; Thompson et al., 2004; Claessens et al., 2011). In contrast, erosion may lead to decreases in specific density, thereby enhancing buoyancy. Biofouling and erosion thus both cause changes in specific density, affecting exchange processes between different environmental compartments (Moret-Ferguson et al., 2010). Due to complex interactions between fouling, erosion and surface-volume ratios of particles, it can be hypothesized that temporal changes in buoyancy of microplastics depends on particle size. More research is needed to understand the interaction between epibionts and microplastics and their effects on particle buoyancy (Harrison et al., 2011) (Figure 3).

Microplastics of high specific density are negatively buoyant and thus sink more rapidly to the seafloor; consequently they can be expected to accumulate in subtidal sediments near their sources (Barnes et al., 2009) (Figure 3). On the other hand, to manage the environmental problems of plastic, it would be crucial to understand and target the major sources and pathways of microplastics into habitats; also to better define best mitigation measures to be carried out.

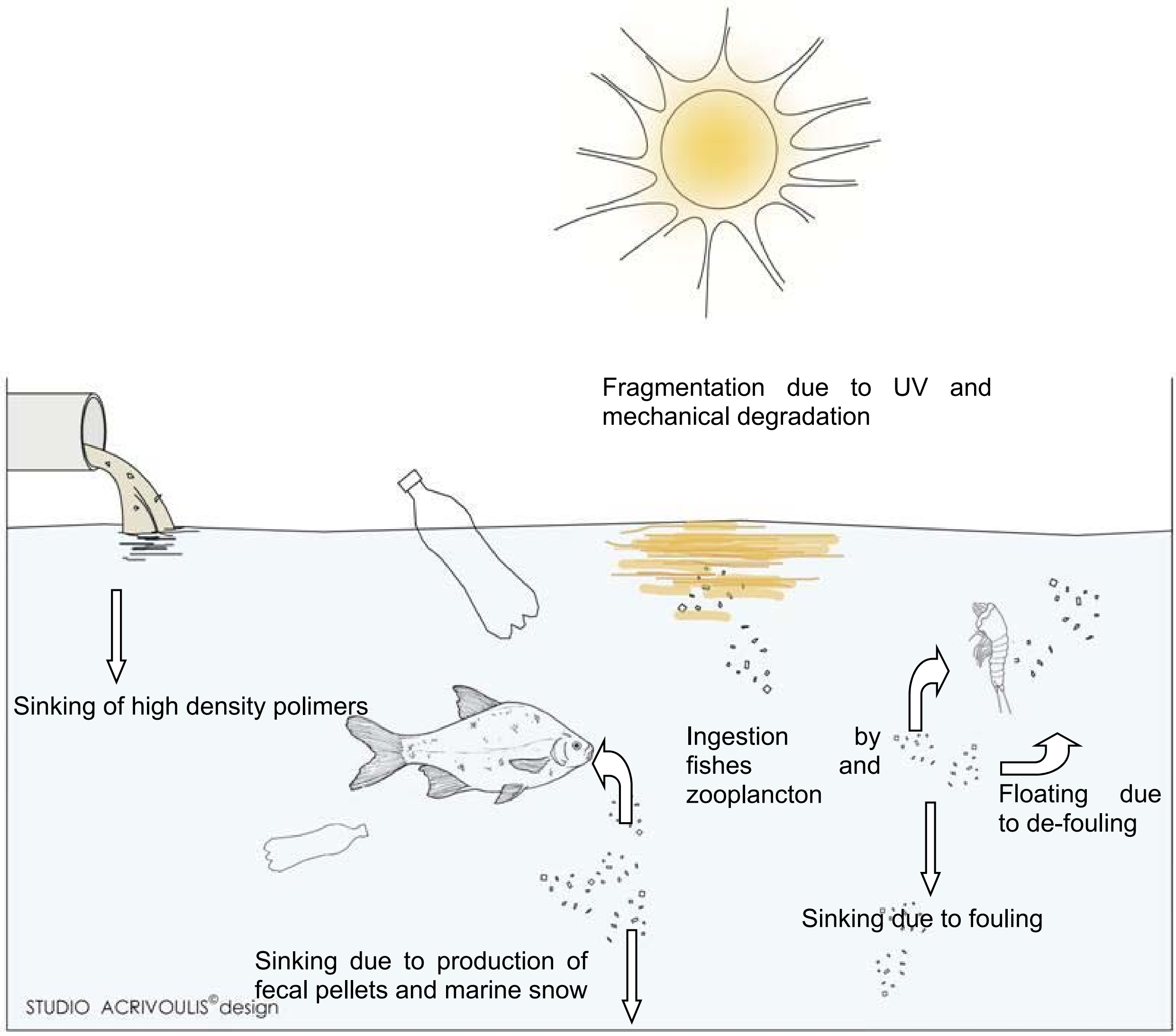


Figure 3: Potential pathways for the transport of microplastics on seabed (*modified from Wright et al., 2013a*)

4.2 Comparison of various types/fractions of plastics

Plastic litter (in particular microplastics) comprises a very heterogeneous assemblage of objects that vary in size, shape, colour, specific density, chemical composition and other characteristics; these are all factors contributing to their distribution in the environment and availability to organisms. In general, microplastics can be separated using one of two methods:

- morphological and physical characterization; and
- chemical characterization and quantification.

Microplastics have a dimension < 5 mm (some studies report a dimension < 1 mm) and possess physico-chemical properties (e.g. size, density, colour and chemical composition) that are key contributors to their availability to organisms (Van Cauwenberghe et al., 2015; Santos and Duarte, 2015).

The identification of microparticles is often based on the characteristics of well-known polymers, such as specific density, shape, and colour. While such methods are economical, they are not always reliable (Santos and Duarte, 2015).

The specific density of plastic particles varies considerably in the range 0.8 – 2.3 g cm^{-3} (see Table 1), since it depends on the type of polymer and the manufacturing process. These values do not take into account the effect of additives that might be incorporated into the production process or the effects of biofouling and weathering (Hidalgo-Ruiz et al., 2012).

Table 1: Some different polymer types, their specific densities and possible uses (*modified from Hidalgo et al., 2012*)

Polymer type	Density (g cm^{-3})	Some examples of use
Polyethylene (HDPE and LDPE)	0.917−0.965	Cleaners, cosmetic, airblast cleaning (scrubbers), packaging
Polypropylene (PP)	0.917−0.965	Carpets, ropes, scrubbers
Polystyrene (PS)	1.04-1.1	Scrubbers, plastic cutlery and dinnerware
Expanded polystyrene	< 0.05	Thermal insulation, packaging, fish boxes
Polyamide (nylon)	1.02−1.05	Clothes, carpets, ropes, airbags, fishing nets, balloons, packaging, liquids and medical supplies
Polyester	1.24−2.3	Packaging and textile applications
Acrylic	1.09−1.20	Textile application, component of paints
Polyoximethylene	1.41−1.61	Resistant devices like gear wheels, ski bindings, fasteners, lock systems
Polyvinyl alcohol	1.19−1.31	Fishing lines, papermaking, textiles, and a variety of coatings
Polyvinylchloride (PVC)	1.16−1.58	Construction of pipes, doors, windows, non-food packaging, cards, electrical cable insulation
Polymethylacrylate	1.17−1.20	Substitute glass in some applications (Plexiglas)
Polyethylene terephthalate (PET)	1.37−1.45	Beverage, food and other liquid containers
Alkyd	1.24−2.10	Paints, moulds for casting, “binder” component in “oil-based” coatings
Polyurethane	1.2	Rigid foam insulation panels, resistant wheels and tires

Plastics that float in fresh (density@4°C 1.00 g cm^{-3}) and seawater (density@4°C 1.025 g cm^{-3}) are polystyrene in foamed form, high and low density polyethylene, and polypropylene. Plastics that sink are polyester, acrylic, polyoximethylene, polyvinyl alcohol, polyvinylchloride (PVC), polymethylacrylate, polyethylene terephthalate (PET), alkyd and polyurethane. In seawater, plastics with high specific density (negative buoyancy) will quickly sink and are thus absent from neuston samples (interface water/air) (Figure 4).

The density of plastic particles will determine their availability in the water column; hence, the type of plastic ingested may vary between organisms. Planktivores, filter feeders and suspension feeders inhabiting the upper water column are likely to encounter positively buoyant, low-density plastics such as PE (specific gravity 0.91 - 0.94), at or near the surface. Increasing buoyancy through de-fouling by foraging organisms is a potential mechanism for particles to return to the air-sea interface. Such a cycle could make microplastics available to organisms occupying different depths at different times. Alternatively, fouled microplastics could continue to sink, as would high density plastics such as PVC (specific gravity 1.38) (see Figure 4). Sinking particles will become available to benthic suspension and deposit feeders, as well as detritivores, eventually reaching the seabed (Wright et al., 2013a).

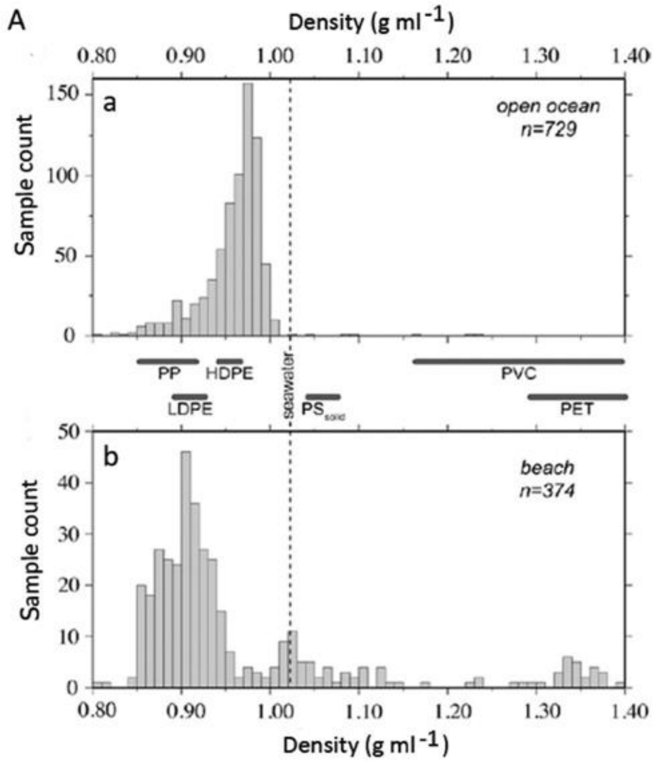


Figure 4: Frequency of microplastics of different specific densities found (a) at the sea surface and (b) in beach sediments. Broken vertical line indicates the specific density of seawater and bold horizontal lines show the specific densities of particular polymers (*from Hidalgo et al., 2012*)

Microplastics vary in shape from irregular to spherical to long, thin fibres. The shape depends on the fragmentation process as well as residence time in the environment. Sharp edges might indicate either recent introduction into the sea or the recent break-up of larger pieces, while smooth edges are often associated with older fragments that have been continuously polished by other particles or sediment. Most fragments found in subtidal and estuarine sediments were fibres (Browne et al., 2010).Circularity varied inversely with particle size. Larger particles had more elongate shapes and/or irregular surfaces, while progressively smaller particles were consistently more circular. It is likely that particles continue to fragment and degrade to become even smaller particles over time.

Degradation and erosion of the particle surface are caused by biological breakdown, photodegradation, chemical weathering or physical forces (wave action, wind, sand-blasting). This can cause visible cracks on the plastic surface, producing many different particle shapes. The surface texture of microplastics can determine the concentrations of sorbed chemicals (see section 4 below).

Particle colour is also an important factor in classifying and assessing microplastic contamination. Particles with eye-catching colours have a high probability of being isolated for subsequent examination, while those with dull colours are easily overlooked, thus potentially introducing bias. Indeed, microparticles of unknown origin could be erroneously characterized as microplastics, a problem that increases considerably with decreasing particle size. For this reason, the use of spectroscopy (FT-IR spectroscopy, near-infrared spectroscopy, and Raman spectroscopy) is strongly recommended for identifying small plastic fragments as it can determine the chemical composition with high reliability.

Table 2: Categories used to describe microplastics (*from Hidalgo-Ruiz et al., 2012*)

Categories	
Sources	consumer product fragments (e.g., fishing net) and raw industrial pellets
Type	plastic fragments, pellets, filaments, plastic films, foamed plastic, granules, and styrofoam
Shape	*for pellets*: cylindrical, disks, flat, ovoid, spheruloids *for fragments*: rounded, subrounded, subangular, angular *general*: irregular, elongated, degraded, rough, and broken edges
Erosion	fresh, unweathered, incipient alteration, and level of crazing (conchoidal fractures), weathered, grooves, irregular surface, jagged fragments, linear fractures, subparallel ridges, and very degraded
Color	transparent, crystalline, white, clear-white-cream, red, orange, blue, opaque, black, grey, brown, green, pink, tan, yellow, and pigmentation

4.3 Interaction with biota on the seabed

Interactions between biota and microplastics depend on several factors such as microplastic abundance, size, colour and density (GESAMP, 2015).

The increasing abundance of microplastics in the marine environment will increase the chances of an organism encountering a microplastic particle.

Since microplastics are in the same size range as sediment particles and some planktonic organisms, they are potentially available by ingestion to a wide range of marine organisms such as lower trophic suspensors, filter and deposit feeders, detritivores and planktivores (Thompson et al., 2004; Graham and Thompson, 2009; Browne et al., 2008, Boerger, 2010; Wrigth et al., 2013; Santo and Duarte, 2015). Many of these organisms show limited selectivity between particles and capture anything of appropriate size. Higher trophic planktivores could passively ingest microplastics during normal feeding behaviour or mistake particles for natural prey (Wrigth et al., 2013; Van Cauwenberghe et al., 2015).

The ingestion of plastics and microplastics by pelagic organisms may determine the transport of plastics to sediments. Some of these reach the seafloor after their death, or become components of marine snow (see Figure 4). This is particularly the case for zooplankton and some pelagic fish that show diurnal vertical migration. Lusher et al. (2012) found microplastics in 36.5% of fish belonging to 10 species sampled from the English Channel, irrespective of habitat (pelagic vs. demersal). An average of 1.9 ± 0.1 particles were recovered from those which contained plastic, the main polymers being polyamide and polyester, materials that are commonly used in the fishing industry. Such findings are comparable to those from the North Pacific Central Gyre reported by Boerger et al. (2010). Small plastic fragments were found in approximately one third of all fish caught. Individuals from the most common species caught (*Myctophum aurolanternatum*, Myctophidae) contained an average of six plastic pieces and the most frequently ingested size class across all species was 1 - 2.79 mm. The majority of fish caught in this study belonged to the Myctophidae, a low-trophic, mesopelagic family which adopts diurnal feeding behaviour, preying upon plankton near the surface at night. Myctophidae may mistake small plastic fragments for their natural food source. Alternatively, they may consume plankton that has previously ingested microplastics or ingest them passively. The Myctophidae are, in turn, preyed upon by tuna, squid, odontoceti whales, seabirds and fur seals. Thus, there are several pathways for microplastics within the food chain and to sediments.

The colour of microplastics may contribute to the likelihood of ingestion, due to prey item resemblance. Some commercially important fish and their larvae are visual predators, preying on small zooplankton, and may feed on microplastics that most resemble their prey, i.e. white, tan and yellow plastic. This may also be the case for pelagic invertebrates which are visual raptorial predators (Wright et al., 2013a).

4.3.1 Ingestion of microplastics by marine organisms

The potential for microplastics to cause harm in marine organisms depends, in the first instance, on the degree to which species ingest and/or interact with them. Selectivity in the ingestion of natural particles is evident in a range of species and it seems likely that this would extend to microplastics. It is important to note that ingestion of microplastics by marine organisms is not necessarily harmful.

Particle capture and ingestion may to be based on size selectivity. Filter-feeders and suspension-feeders seem to ingest plastic microspheres due to their similarity to algae (Figure 5). In a laboratory study investigating particle capture and suspension feeding methods, sea urchin, sea star, sand dollar, brittle star and sea cucumber larvae captured and ingested 10 - 20 µm PS di-vinylbenzene (dvb) microspheres (Wright et al., 2013a).

The non-selective benthic scavenger and predatory crustacean *Nephrops norvegicus* has been shown to ingest small plastic fragments (Figure 5). Gut content analysis found that 83 % of animals collected from the Clyde Sea contained plastic, the majority of which took the form of tangled nylon-strand balls. This coincides with the dominance of plastic fibres contaminating sediments reported above (Murray and Cowie, 2011). Similar observations have been made in studies of brown shrimp (*Crangon crangon*) collected in coastal waters of the southern North Sea (Devriese et al., 2015). Brown shrimp are opportunistic feeders living on the seabed in shallow waters and estuaries. They are an important food item for a range of predators, such as gadoids, pleuronectids and gurnards as well as for birds and crustaceans. Synthetic fibers (monofilaments) ranging from 200 up to 1000 µm size were detected in 63% of the assessed shrimp. The majority (97%) of the microplastic contamination was categorized as synthetic fiber; only in a few cases were granules and films observed. Microfibers were not found in peeled shrimps, suggesting that particles are present in the digestive tract and not in the abdominal muscle tissue used for human consumption.

Graham and Thompson (2009) showed that four species of deposit-feeding and suspension-feeding sea cucumbers (Echinodermata, Holothuroidea) not only ingest small (0.25 mm < maximum dimension < 15 mm) nylon and polyvinyl chloride (PVC) fragments along with sediment, but also significantly more plastic fragments than predicted given the ratio of plastic to sand grains in the sediment. Holothurians are scavengers feeding on litter in the benthic zone and ingest large volumes of sediment; the associated organic litter and microorganisms are retained. The marine polychaete *Arenicola marina* also demonstrates size-based selectivity, whereby smaller particles stick to the mucus-lined proboscis papillae and are retained, whilst larger particles are rejected (Van Cauwenberghe et al., 2015).

Benthic suspension feeders such as bivalve molluscs can ingest sinking microplastic particles. For example, the common mussel *Mytilus edulis* has been shown to capture and ingest microplastic particles ranging from 2 to 16 µm in size. Browne et al. (2008) have shown these particles can translocate to the tissue and persist there for at least 48 days. However, bivalves are able to sort particles prior to ingestion; unfavourable particles are rejected as pseudofaeces. Pre-ingestive sorting of microplastics has so far not been described (Wright et al., 2013a).

Van Cauwenberghe *et al*. (2015) studied the uptake of microplastics by the blue mussel *Mytilus edulis* (filter feeder) and the lugworm *Arenicola marina* (deposit feeder) at six locations along the French–Belgian–Dutch coastline. Microplastics were present in all specimens collected in the field: on average 0.2 ± 0.3microplastics g^{-1} (*M. edulis*) and 1.2 ± 2.8 particles g^{-1} (*A. marina*). The particles consisted of low density polyethylene, high-density polyethylene and polystyrene.

Farrel and Nelson (2013) investigated the trophic transfer of microplastics from mussels to crabs and their translocation to haemolymph and tissues. Mussels (*Mytilus edulis*) were exposed to 0.5 µm fluorescent polystyrene microspheres, then fed to crabs (*Carcinus maenas*). Tissue samples were taken at intervals up to 21 days. The number of microspheres in the haemolymph of the crabs was highest at 24 h (15.033 ml^{-1} ± SE 3146), and was almost gone after 21 days (267 ml^{-1} ± SE 120). The maximum amount of microspheres in the haemolymph was 0.04% of the amount to which the mussels were exposed. Microspheres were also found in the stomach, hepatopancreas, ovary and gills of the crabs, in decreasing numbers over the trial period. It is important to note that accumulation and trophic transfer of plastic particles is different to traditional contaminants, which can pass into cells.

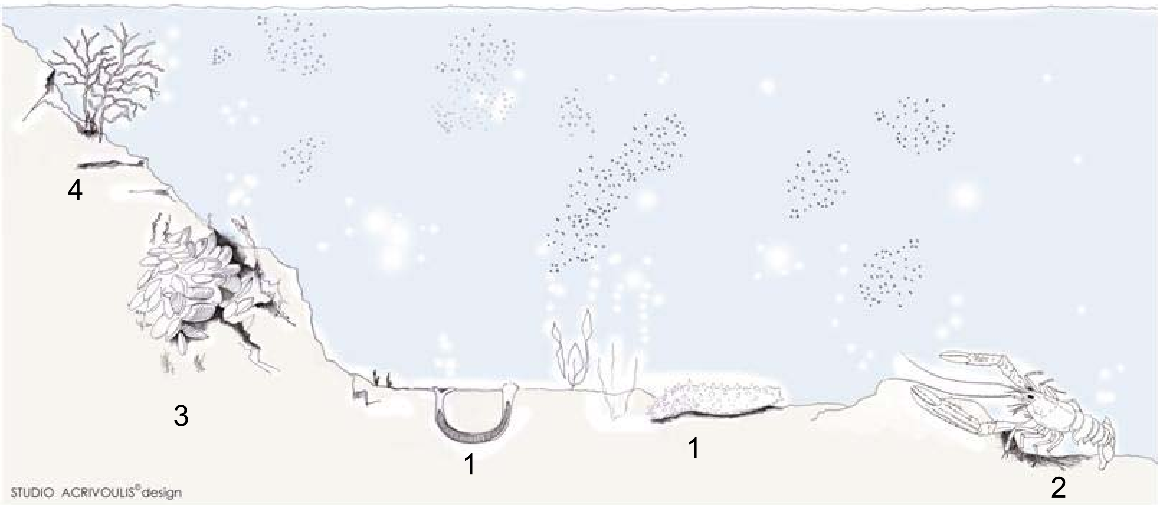


Figure 5: Potential biological interactions of microplastics with benthic organisms

1. Scavengers (detritivorus and deposit feeders) could ingest microplastics in sediment; Non-selective benthic predators could ingest microplastics on the seabed or suspended in lower part of water column;
2. Filter-feeders seem to ingest plastic microspheres due to their similarity with algae. They may be susceptible to sinking microplastic particles;
3. Suspension-feeders, like filter-feeders, seem to ingest plastic microspheres due to their similarity with algae. They may be susceptible to sinking microplastic particles

4.4 Impacts on marine organisms and ecosystems

4.4.1 Impacts of macrolitter on benthic biota

Macro litter and ghost nets can have the following impacts on marine biota:

- entanglement of biota, e.g. by ghost nets (see section 3.2.3);
- ingestion of plastic by biota, e.g. marine reptiles (sea turtles), birds and mammals (whales and pinnipedes) leading to suffocation, starvation or malnutrition;
- smothering of seafloor;
- alteration of benthic species assemblages.

Plastic macrolitter can alter hard sea bottom habitats and may suffocate benthic organisms as has been observed on certain coral reefs (Gall and Thompson, 2015), sometimes causing partial or total mortality of coral reef assemblages (Chiappone et al., 2005). On Majoro atoll, Richards and Beger (2011) observed a significant negative relationship between the level of marine litter cover and coral cover, demonstrating that litter can cause suffocation, shading, tissue abrasion and mortality of corals.

Hard items settling on soft bottoms can be colonized by faunal assemblages typically found in rocky environments. Habitat change can influence the relative abundance of organisms, promoting a population explosion among some species and decrease of others (Green et al., 2015).

Both conventional and biodegradable plastic carrier bags can alter marine assemblages and the ecosystem benefits they provide (Green et al., 2015). After 9 weeks, the presence of either type of bag created anoxic conditions within the sediment along with reduced primary productivity and organic matter and significantly lower abundances of infaunal invertebrates.

4.4.2 Impacts of microplastics

Laboratory studies suggest that ingestion of microplastics could result in serious effects on marine invertebrates, both physical, such as internal abrasions and blockages, and chemical. Blockages of the digestive system suppress feeding due to satiation. Toxicity could also arise through leaching of contaminants such as plasticizers, flame retardants and antimicrobial agents that are incorporated into plastics during manufacture (Wright et al., 2013a; Law and Thompson, 2014; Santos and Duarte, 2015; GESAMP, 2015).

Plastic litter readily accumulates persistent organic pollutants (POPs) such as dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs) from seawater, increasing their concentrations by orders of magnitude. POPs have a greater affinity for the hydrophobic surface of plastic than to seawater. Microplastics can become heavily contaminated due to their large surface area to volume ratio (more so in fibres than in microspherules). This process is reversible, with microplastics releasing contaminants upon ingestion (Derraik 2002; Teuten et al., 2007; Wright et al., 2013a). The degree of transfer depends on the polymer, contaminant and conditions in the organism, particularly pH and temperature. The process could increase the exposure of marine organisms to POPs due to bioaccumulation and biomagnification through the food chain. The significance of co-ingestion of POPs with microplastics remains an important topic for further study (Wright et al., 2013a; Law and Thompson, 2014; Santos and Duarte, 2015).

Although ingestion of microplastics by mammals, fish, birds and invertebrates is now well documented (Law and Thompson, 2014), it is unclear whether they transport chemicals to biota in amounts high enough to cause substantial damage.

Lanternfish (*Myctophidae*) sampled at locations with elevated plastics densities have significantly higher concentrations of polybrominated diphenyl ethers (PBDEs) in their tissues suggesting that higher brominated congeners of PBDEs, added to plastic additives as flame retardants, may be suitable indicators of plastics contamination in the marine environment (Rochman et al., 2013).

Microplastics may indirectly be ingested by baleen whales through consumption of planktonic prey. Recently, it has been suggested that mono-(2-ethylhexyl) phthalate (MEHP) contamination of the blubber of the Mediterranean fin whale *Balenoptera physalus* is an indication that microplastic ingestion occurs, either through the water or the plankton (Fossi et al., 2012).

Ingestion of small quantities of microplastics can disrupt physiological processes in marine worms, compromising their ability to store energy (Browne et al., 2013).

Due to a lack of enzymatic pathways available to break down plastics in marine organisms, microplastics are unlikely to be digested or absorbed and might therefore be considered bio-inert. However, they may pass through cell membranes and become incorporated into body tissues following ingestion. Phagocytosis is the primary mechanism for translocation of microplastics. Presently, more research is required to determine the particle size limits for translocation to occur. In addition, the behaviour and fate of micro-particles of different polymer types and shapes, needs to be established (Browne et al., 2008).

5 Current gaps in knowledge

It is presently impossible to generalize regarding the litter content of either sewage sludge or dredged materials, in terms of litter types, properties or quantities. The main reasons for this are an overall shortage of data, differences in methodology and reporting, and the lack of systematic sampling in space and time. Nevertheless, it seems probable that various types of small and micro-sized plastics present the greatest hazards and warrant most concern. It is premature to speculate, however, on the specific materials that present the greatest risks for marine life or to focus on any particular line of experimental research that would enable actual effects to be evaluated.

Clearly then, until more data can be gathered and evaluated it would not be appropriate to draw firm conclusions about the environmental effects of plastics, or other types of litter, introduced to the sea in sewage sludge and dredged material, or the relative impacts of these and other litter sources. To advance understanding of this issue, far more extensive investigations will be required.

5.1 Sampling and analytical protocols

To date, no studies have considered trends in marine litter abundance over time. The main difficulties are the lack of standardization of sampling methods and techniques for distinguishing between different plastic polymers. These deficiencies are most evident in relation to microplastics. More specifically, the problems relate to:

- differences in the size range (lower and upper limits) extracted/examined ;
- the sensitivity of the applied extraction technique;
- the wide variety of reporting units (Van Cauwenberghe et al., 2015).

These issues are highly relevant to the assessment procedures under LC/LP in which the characterization of both waste streams and dumping sites is an important element. In order to assess and compare the plastic litter component of wastes and sediments, there is a need for reliable, harmonized methodologies for measuring the abundance and distribution of microplastics and for determining their composition.

Thus, research is needed to consider sediment sampling design in terms of the number and the size of replicates, the spatial area and the frequency of coverage, the methodology used for sampling (i.e. type of core for sediment samples) and laboratory methods used for identification of microplastics. These studies should take into consideration the relationships between sampling effort and variability (Santos and Duarte, 2015).

Several publications have described methodologies for separating plastic particles from sediments. Several of these are summarized below.

Separation of microplastics from sediment samples can be done by density flotation, filtration and sieving. Since sand or sediments have densities around 2.65 gcm^{-3}, the difference in density can be used to separate the lighter microplastics from the heavier sand or sediments. A salt-saturated solution (usually NaCl or NaI) is added to sand or sediments and mixed by shaking or using a vortex. After mixing, the sediment will settle to the bottom, while the microplastics will remain in suspension or float to the surface of the solution. The supernatant is then extracted for further processing of the microplastics particles. However, the use of saturated solution of NaCl (1.2 g cm^{-3}) or tap water may lead to underestimation of the microplastics content in sediments because the solution density is too low to enable the flotation of all polymers, principally those containing additives. Instead, a NaI-saturated solution density (1.6 g cm^{-3}) is enough to separate the polymers containing additives, so this solution is preferable (Hidalgo-Ruz et al., 2012; Santos and Duarte, 2015; Cauwenberghe et al., 2015).
Imhof et al. (2012) developed a method for the separation of plastic particles in aquatic sediments. They improved the density-separation approach by constructing the Munich Plastic Sediment Separator. A $ZnCl_2$ solution (1.6–1.7 kg/l) was used as separation fluid and the device provided recovery rates of 100% and 95.5% for microplastics particles of 1–5 mm and < 1 mm, respectively.

Visual sorting is one of the most commonly used methods for the identification of microplastics (using type, shape, degradation stage, and colour as criteria). Chemical and physical characteristics (e.g. specific density) have also been used. Identification of the polymeric composition of microparticles is often performed using Fourier transform infrared (FT-IR) spectroscopy since the IR spectra of an unknown microplastics sample can be compared with the IR spectra of known polymers available from IR spectra libraries. Micro-FT-IR spectroscopy enables the simultaneous visualization, mapping of samples and collection of spectra. This technique requires expensive equipment (FT-IR linked to a microscope) and a trained operator and is time consuming; however, it remains the most widely used, reliable and reproducible method for characterizing microplastics in the environment (Hidalgo-Ruz et al., 2012; Santos and Duarte, 2015).

Although FT-IR has proved to be a useful technique for identifying the polymeric composition of microparticles, there is still a lack of analytical methods capable of characterizing and quantifying the chemical composition of microplastics in real environmental samples. Further interlaboratory comparison exercises are needed in order to ensure the comparability of data collection, separation, and chemical characterization and quantification.

5.2 Relationships between environmental concentrations and effects

As mentioned in section 4.4, it is essential to understand the fate and the effects of plastic compounds (e.g. phthalates, bisphenol A, and polybrominated diphenyl ethers) in marine organisms in order to establish the significance of plastic litter in the marine environment (Santos and Duarte, 2015). Work is needed to determine if chemicals contained in plastics or transported with them can transfer from the environment and accumulate in food-webs through ingestion (Brown et al., 2011). Moreover, the relevance of co-ingestion to the trophodynamic behaviour of plastics, polymer additives and POPs remains an important topic for further study (Wright et al., 2013a; Law and Thompson, 2014; Santos and Duarte, 2015).

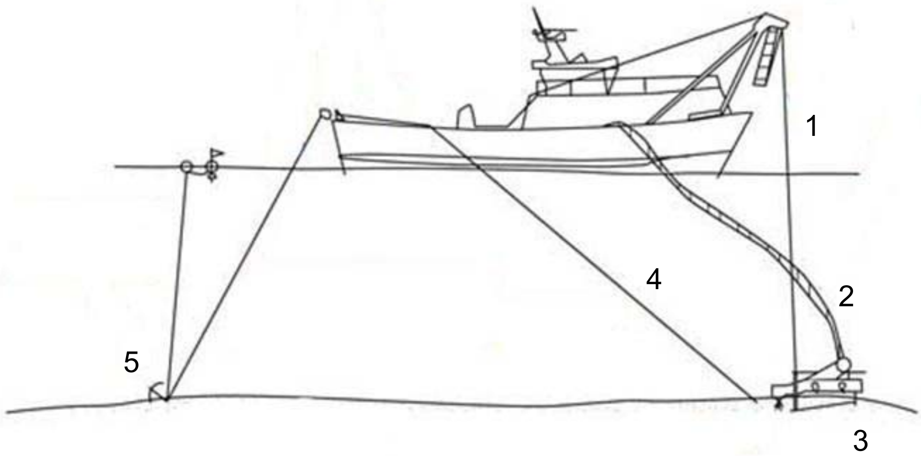
Ingestion and entanglement of microplastics can be lethal for many marine species but little is known about the effects at population and community levels. The relationship between quantities of ingested microplastics and lethal or sub-lethal effects, under different environmental conditions, warrants investigation (JRC, 2011). The findings might then be used to establish threshold levels for use in evaluating wastes to be dumped at sea.

5.3 Methodologies to reduce plastics in dredged materials or sewage sludge

Part of the process for evaluating dredged materials and sewage sludge to be dumped at sea, is to assess possibilities for reducing or eliminating plastic litter prior to disposal.

Elimination of macro litter can take place before the waste is transported to the disposal site. Regarding sewage sludge, a filtration process is generally used before the formation of sludge (at least in systems that function efficiently). This filtration does not eliminate microplastics for which it might be necessary to utilize ultrafiltration, an expensive technique that also needs further development.

Some benefit may be derived by collecting macro litter before a dredging operation takes place using divers or bottom-scraping devices such as trawl nets or dredges used to collect clams (Figure 6). These hydraulic dredges penetrate several centimetres into the sediment and could collect objects or litter greater than a particular grid diameter (usually 2.5 cm, lower limit of macro-litter) into a metal cage. Dredge movement is facilitated by a water jet. This method might also be useful to remove macro litter like tyres, big metal objects, steel cables, etc. The utility of such techniques warrants further evaluation in areas with known high deposits of macro-litter.



1. *Cable to lower and raise the metal cage;*
2. *tube for the water jet;*
3. *metal cage;*
4. *towline;*
5. *anchor.*

Figure 6: Hydraulic dredge used to collect clams on seabed

Separation/filtration of macro litter during actual dredging operations is much more difficult, especially where a mechanical dredge is used as it tends to reduce the dimensions of collected material.

Some experimental work on litter and trash removal has been carried out by the U.S. Army Corps of Engineers (USACE) with the aim of reducing the amount of contaminated dredged material that needs to be stored in Confined Disposal Facilities (CDFs), thus enabling alternative, beneficial uses (Meyers and Adrian, 2000; Spaine et al., 2001).

Separation of litter and trash from dredged material presents technical and economic problems because the separation process must take place at low cost. Transportation costs to dispose of litter and trash removed during dredged material processing increase with distance from the disposal site.

Separation could be accomplished through a series of screens, such as:

- grizzly screen;
- rotating screen scrubber;
- vibrating screen.

Most treatment processes include coarse separation using Grizzly screens as an initial treatment step. Grizzlies are the simplest and coarsest devices for removing litter. Grizzly screens are generally made up of inclined parallel iron or steel bars spaced from 2 cm to30 cm. The material to be screened is loaded either directly by bucket or front-end loader (Figure 7), or may be fed by conveyer. Objects larger than the spacing of the bars are separated into a separate stream that may be treated or disposed of independently. In some cases, collected litter is often separated from sediment using a barge-mounted grizzly and deposited on a separate barge for final disposal.

Figure 7: Grizzly screen used to collect and separate litter from sediment (*from Spaine et al., 2001*)

In conjunction with a Grizzly screen, a rotating screen scrubber (Figure 8) could be used to remove small litter. The most common configuration consists of a rotating, slightly inclined cylinder of sturdy wire mesh. Scrubbers may be used as a second stage after a grizzly or as a first stage, depending on site and/or material characteristics.

Vibrating screens act by putting the screen into either a reciprocating, gyrating, or vibrating motion. Particle size separation depends on the cloth chosen for the screen. The screen is subject to extreme wear and requires frequent replacement, especially those with smaller apertures.

Figure 8: Example of vibrating screen (*from Spaine et al., 2001*)

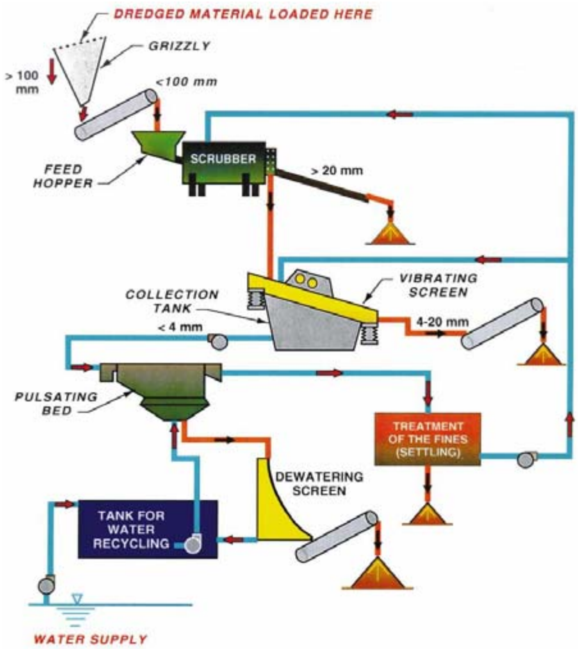


Figure 9: Minnesota Pilot Plant for separating litter and trash from dredged material (*from Meyers and Adrian, 2000*)

Finally, separation of silt and clay fractions from the sand could be realized through a hydrocyclone or a pulsating bed separator.

Figures 9 and 10 show two possible dredged material processing schemes and equipment layout, for separating litter and trash from dredged material.

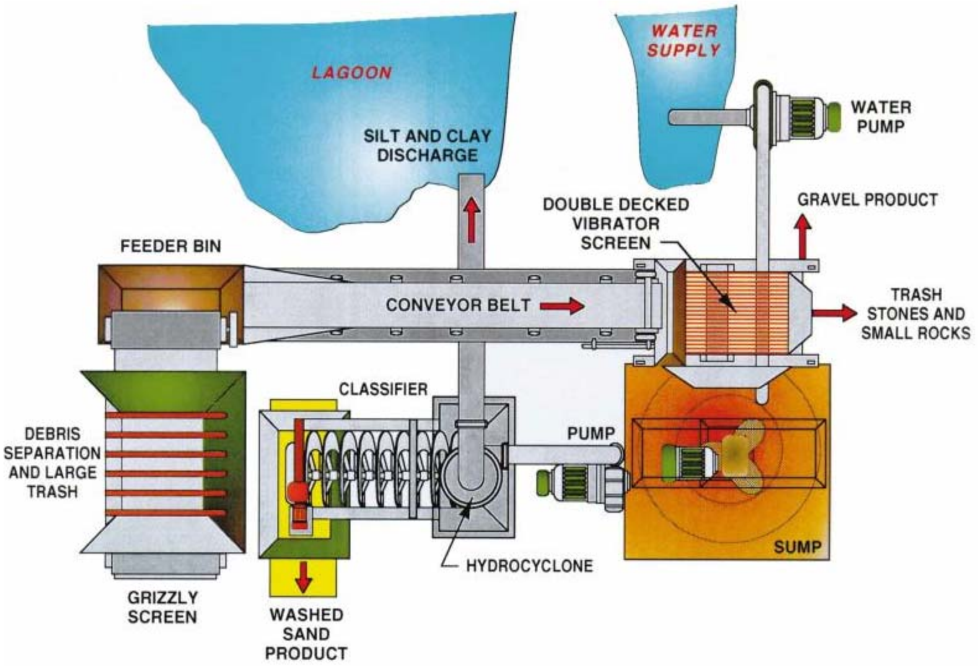


Figure 10: Dutch Pilot Plant for separating litter and trash from dredged material (*from Spaine et al., 2001*)

In a recent example, sediment in a Los Angeles estuary was contaminated with a large amount of plastic litter following a major storm event. To render the sediment suitable for beach replenishment, the plastic was removed by use of a 1-inch mesh screening device attached to an 8-inch clamshell. To remove the plastic efficiently, a pipe was inserted under the excavator and into a bin with holes. Water was used to move the sediment through the bin and into a larger container, allowing macroplastic litter to be retained in the first bin (Figure 11). A booster pump than picked up the sediment and dredged material and pumped it down to the beach (Safra Altman, USACE Engineer Research and Development Center (ERDC) Environmental Laboratory, pers. com.).

Figure 11: Separation of macrolitter from dredged material using a 1-inch mesh screening device attached to an 8-inch clamshell (*Safra Altman from USACE ERDC Environmental Laboratory, personal communication*)

The technical and operational feasibilities of separating microplastics from large amounts of dredged material are largely unknown. The engineering challenges involved are considerable and, at present, such separation is logistically and economically impractical.

6 Conclusions and future work

A bibliographic search has provided information relevant to the questions to be addressed in this review (Chapter 2, Objectives). It is clear that dredged materials and sewage sludge are the waste streams regulated by LC/LP that with high probability would contain marine litter.

The findings most relevant to each of the four questions are given below. It will be apparent that the extent of knowledge on individual topics varies widely and that certain aspects of the questions remain unanswered.

1 What is the extent and nature of plastics (micro or otherwise) in dredged materials (scope, knowledge gaps, methodologies for estimating the nature and quantity of microplastics in sediments)?

Dredged materials are primarily sediments, usually from harbours, approach channels and rivers, for the development of docks, to mitigate the effects of flooding and to develop or maintain other human structures such as water intake for industrial processes. These areas generally appear to have a high abundance of macro litter, ghost nets and microplastics. Harbours are probably the area where accumulation is concentrated because: 1) they act as a trap of marine litter thrown directly or from rivers, wastewater, sewage or transported by open sea; 2) they are near the coast; 3) they are located near populated areas; and 4) currents are generally low. Marine litter found on the seafloor is represented mainly by denser polymers. However, floating litter may eventually sink to the seafloor, due either to an increase in weight because of absorbed water and/or the settlement of living organisms. Microplastics may also reach sediments through ingestion by filter-feeders, zooplankton and fishes.

2 What are the sources and pathways for plastics to end up in dredged materials? What is the relation with other waste streams (including land-based run-off, sewage disposal and industrial (wastewater) discharges)?

It is very difficult to identify the sources of marine litter present in dredged material. With reference to harbour sediments, the types and amounts of solid waste often depend on the particular practices that take place within the harbour, for example fishing, commercial or tourism harbours. Harbour sediments are also influenced by discharges of urban and/or industrial wastewater (treated or not) and the location relative to estuaries or mouths of rivers.

Sewage sludge represents the final destination of most plastics, in particular microplastics, contained in wastewater. Microplastics with a density greater than that of water will end up in the sludge, while the others remain in the water and can reach rivers and seas directly. An important source of microplastics in sewage appears to be fibres from washing clothes, in particular polyester and acrylic fibres.

Only plastics present in sewage sludge have a clear link with particular sources: liquid domestic waste (black waters), runoff water from the urban environment (white waters); and also, in some cases, a part of treated and non-treated industrial waste. Dredged materials, on the other hand, could contain litter from a diverse range (maritime or terrestrial) of sources. This is particularly true for plastics that are less dense than water, that spend a long time at the sea surface (or in the water column), and may thus be transported over long distances.

3 What is the nature of re-suspension of plastics through dredging and what are the impacts on marine biodiversity during dredging and after disposal?

Re-suspension of plastics through dredging is of questionable relevance, essentially for two reasons: polymers denser than sea water will sink directly to the seabed; floating polymers are presented in dredged materials because they have undergone a weathering process (e.g. developing of fouling, inclusion in marine snow, etc.) that bind them to heavier materials allowing them to re-sink. However, more research is needed to evaluate the dispersion of re-suspended particles from the dumpsite pending resettlement.

4 What are the current gaps in the available information?

The main existing gaps are summarized in Chapter 5. Based on these apparent deficiencies, the principal objectives of future studies should include:

1. to improve the understanding of how widespread plastic contamination is, where it accumulates, and the source of this material;

2. to develop and agree on standardized procedures for extracting, identifying and quantifying plastics in sludge and sediments;

3. to improve knowledge regarding the relationship between the concentration of microplastics in dumped wastes and their effects. This knowledge might enable the establishment of threshold levels for use in regulating waste streams to be dumped at sea; and

4. to stimulate the development of practices and methodologies that could be used to reduce plastics in dredged materials, especially harbour sediments, and sewage sludge prior to their disposal at sea.

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