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Scope, Fate, Risks and Impacts of Microplastic Pollution in Irish Freshwater Systems

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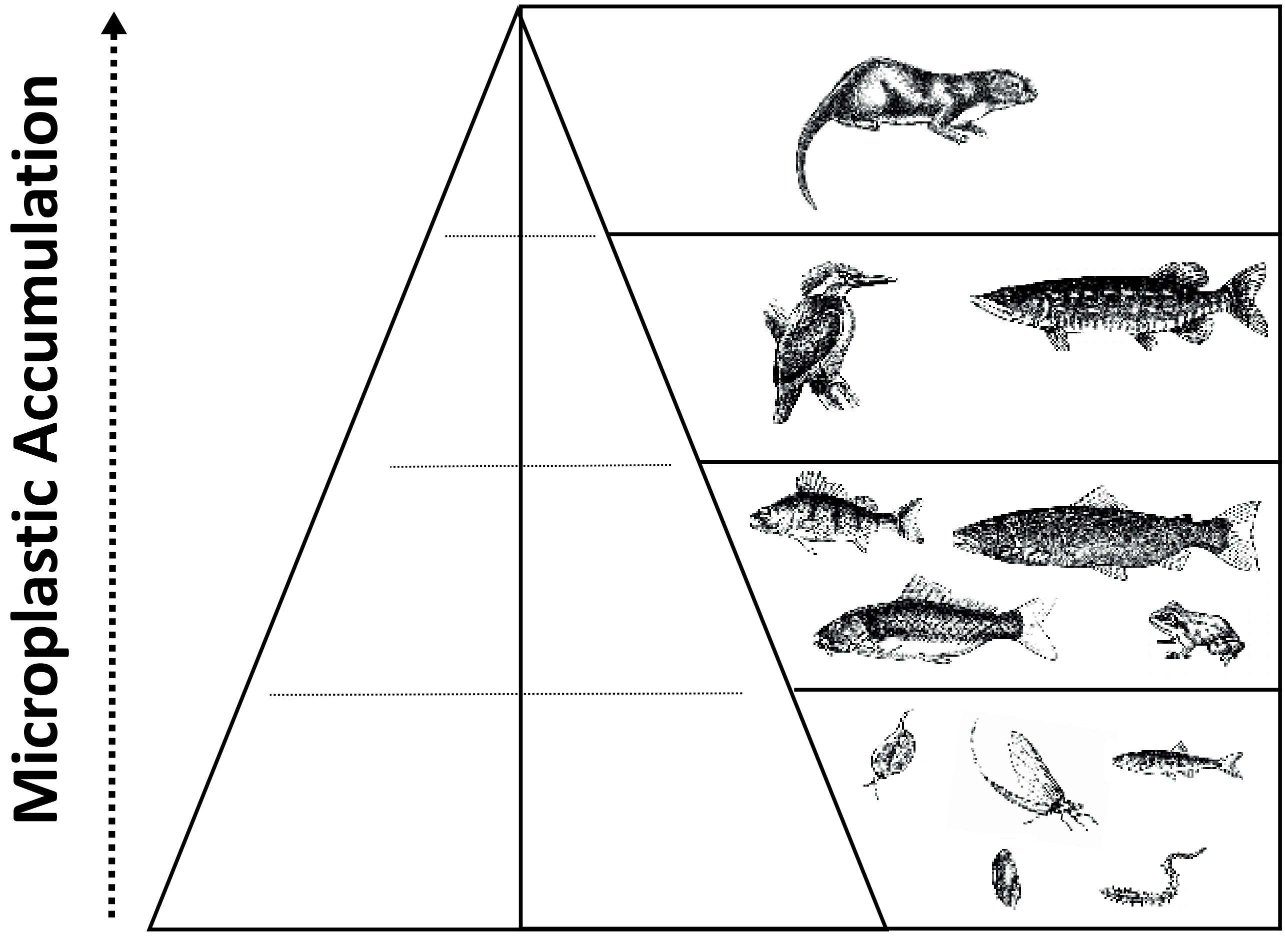

Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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- Office of Radiation Protection and Environmental Monitoring
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EPA RESEARCH PROGRAMME 2014–2020

Scope, Fate, Risks and Impacts of Microplastic Pollution in Irish Freshwater Systems

(2014-HW-DS-2)

EPA Final Report

Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

Cover Image

Infographic representing the accumulation of microplastics through the trophic levels. See Figure 4.4 on page 41 for more detailed information.

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Executive Summary

The worldwide production of plastics has increased considerably in the last 30 years (Plastics Europe, 2012). Microplastics are small (< 5 mm) fragments of plastic, which are of particular concern because of their bioavailability and their potential to accumulate organic contaminants in increasing quantities with decreasing size. When they enter aquatic systems, microplastics can be ingested by a range of organisms and accumulate through the food web, causing harm to humans and the environment. Plastic litter has become a priority for the G7 leaders who have acknowledged it as posing a "global challenge, directly affecting marine and coastal life and ecosystems and potentially human health" (G7 summit, 2015) and have passed an action plan on marine litter that includes a commitment to conduct further research.

This has prompted the development of large international consortia (e.g. JPI Oceans) that are striving to assess the potential eco-toxicological effects of plastic waste on the sea and to our food. The EU's Marine Strategy Framework Directive (MSFD) aims to achieve good environmental status (GES) by 2020. The elements that are relevant to microplastic litter (descriptor 10) stipulate that GES will be achieved when the "properties and quantities of marine litter do not cause harm to the coastal environment" and recommend monitoring to help achieve this outcome. As a major portion of marine pollution is derived from riverine inputs, where pollution concentrations are potentially higher because they are nearer the source, there has been a recent shift in focus to determine microplastic sources and to investigate how microplastics may impact freshwater environments. These priorities are pursued in this study as part of a work programme that aimed to identify the potential sources and the potential scale of microplastic pollution in Ireland, examine the potential environmental fates of microplastics and identify the potential impacts to both humans and priority species in Irish freshwaters. Compiling the results has allowed us to make some recommendations for policy development.

An initial scoping study identified several potential sources of microplastic pollution. Within Ireland's manufacturing industries, processes involving machining of polymers produce large amounts of microplastics. While all machining industries pose a potential for surface water contamination, the plastics recycling industry, which employs a washing process post machining of plastics, was found to release large amounts of microplastics to sewers. Urban waste water treatment plants (UWWTPs) were identified as receptors of the cumulative abundance of microplastics arising from industry, landfill and household waste. It was found that 98% of microplastics in the influent water (97,000 particles/m^3) become entrained in the sewage sludge. As over 96% of all UWWTPs in Ireland have a settlement stage, the destination for the majority of microplastics released to sewers is sewage sludge. The results of additional investigations of an EPA small-scale study (2015-CCRP-SS.6) on the effects of sludge treatment processes on the abundance and characterisation of microplastics in sewage sludge strongly suggest that the process of lime stabilisation, which is Ireland's primary treatment method for sewage sludge (N. Foley, EPA, 15 July 2015, personal communication), causes shearing of microplastic particles, resulting in an amplification of their potential as a pollutant (Mahon *et al.*, 2017). The environmental fate of microplastics in freshwater systems depends on complex interactions between the properties of the microplastics and other important physical and biological factors, including wind, flow velocities and the properties of the microplastics themselves.

In summary, lighter microplastic particles in UWWTP effluent that enter a relatively fast-flowing river without obstacles to reduce flow velocity may be transported directly downstream and eventually to marine environments. Where flow velocities are low, it is more probable that microplastics will sink and become entrained in benthic habitats. Heavier and larger particles are more inclined to sink in UWWTPs and will therefore remain in sewage sludge that is spread on agricultural land. The large number of small lakes in Ireland provide this type of low-flow environment and therefore could provide optimal conditions for the deposition of microplastics carried in rivers. In addition, microplastics that accumulate in front of dams and

weirs, where flow is reduced and silt build-up occurs, may subsequently be released, depending on precipitation events.

Impacts on humans through accidental ingestion during bathing in contaminated waters or consumption of contaminated fish will probably result in low levels of risk; however, ingestion of contaminated water may pose a much greater risk. Microplastics were discovered in well water samples and in mains water during a small-scale study that quantified microplastic pollution at potential sources in Ireland (2015-CCRP-SS.6). In addition, the use of mains water for the food-processing industries provides further potential pathways into the human food chain.

In addition to potential effects on humans, there are potential impacts on priority species living within, or associated with, freshwater habitats. Filter feeders, such as bivalves, have been shown to be adversely affected by microplastics. While there has not been a direct study on some of our protected filter-feeding species (e.g. the critically endangered pearl mussel, *Margaratifera margaratifera*), it is largely accepted that these would be adversely affected. Trophic transfer in freshwater systems could also mean that important insect life, such as the mayfly, along with a wide arrange of fish and birds, could be affected. As low numbers of microplastics were found in pike (*Esox lucius*) and perch (*Perca fluviatilis*) from Lough Corrib (O'Connell, 2015), it is also possible that predators of these species (e.g. otter, *Lutra lutra*) could be contaminated. However, such risks are considered to be low. While this study can only imply that the likelihood for potential impacts for our protected aquatic species is high, questions remain over whether or not these impacts would be similar to the impacts that have been recorded in marine species.

Exposure of freshwater systems to microplastic pollution will probably increase as world plastics production increases to meet the growing demand in Europe for plastics (Plastics Europe, 2012). The introduction of EU legislation [Waste Electrical and Electronic Equipment Directive (2012/19/EU); Packaging Directive (94/62/EC as amended); Waste Framework Directive (2008/98/EC) and End-of-Life Vehicles Directive (2000/53/EC)], while effectively diverting plastic waste from landfill into the recycling industry, may create a greater risk of microplastic pollution if the recycling processes are not managed effectively.

1 Introduction

1.1 Overview

Because of a growing global reliance on the plastics (synthetic polymer) industry (Plastics Europe, 2012), plastic-derived pollution has become a threat to global ecology (Teuten *et al*., 2009; Ivar do Sul and Costa, 2014) and a topic of international political concern (Sutherland *et al*., 2010; Eerkes-Medrano *et al*., 2015; G7 summit, 2015). Waterborne plastic pollution is of particular concern, because of its potential to adsorb organic contaminants from the surrounding environment (Teuten *et al*., 2009; Bakir *et al*., 2014). Adsorbed pollutants, along with plasticisers and additives inherent to the specific polymer, which can act as endocrine disruptors (Cole *et al*., 2011), may be released upon ingestion by biota or through environmental degradation, leading to risks to human health, priority species and habitats (Cooper and Corcoran, 2010; Andrady, 2011). Microplastics (fibres, fragments, pellets, film and beads < 5 mm in diameter) are formed through either the degradation of larger plastic pieces or the production of primary microplastics intended for the manufacturing, engineering or cosmetic industries (Fendall and Sewell, 2009; Lusher *et al*., 2014). Studies over more than a decade have found microplastics to be ubiquitous in the marine environment, even occurring in Arctic waters (Lusher *et al*., 2015a,b). With an estimated 80% of marine-based pollution coming from land-based sources (Andrady *et al*., 2011), attention has now turned to sources of microplastics, their pathways to marine environments and the potential for microplastics to be retained and impact freshwater ecosystems and human health (Eerkes-Medrano *et al*., 2015). This study aims to improve our understanding of the environmental fate of microplastics and the risks they pose in Irish freshwater systems, thereby informing policy development and implementation.

1.2 Objectives

The objectives of this project were to:

- develop a framework for assessing exposure of freshwater systems to microplastic pollution;
- identify potential impacts to human health, priority species and habitats;
- appraise risks posed by microplastic pollution in selected freshwater environments; and
- make recommendations for policy development on microplastic pollution in freshwater systems.

1.3 Literature Review

1.3.1 Sources of microplastics

The demand for plastics in Europe is, in descending order of demand, for polypropylene, polyethylene (low density), polyethylene (high density), polyvinyl chloride (PVC), polystyrene, polyurethane and polyethylene terephthalate (PET) (Plastics Europe, 2012) and, from studies to date, these comprise most of the plastics found in the marine environment. Sources include cosmetics (Fendell and Sewell, 2009), which amount to 500 tonnes per year in Germany (Essel *et al*., 2015), and industrial emissions (Lechner and Ramler, 2015). Industrial emissions can arise from the spillage of primary polymers in granular or pelleted form that are produced for the manufacture of plastic products; these amounted to 290 million tonnes worldwide in 2012 (Plastics Europe, 2012). Urban waste water treatment plants (UWWTPs) are receptors of microplastics that are derived from incoming effluent and have been found to emit microplastics through effluent water and sewage sludge (Browne *et al*., 2011; Magnusson and Norén, 2014). Other sources include the abrasion of synthetic rubber tyres; this is estimated to give rise to 60,000 to 110,000 tonnes of microplastics per year in Germany (Essel *et al*., 2015). Man-made fibres, including polyester, acrylic and nylon, that are used to make clothing and furnishings, such as curtains and carpets, are also an important source of microplastics. In a study investigating the shedding of microplastics during washing, it was found that fleeces and microfleece products shed the most and this increases with use over time, with 7360 fibres/m^2 clothing shed in one wash (Astrom, 2016). The levels of microplastics present in atmospheric fallout indicated that transport of microplastics through the air could be a significant pathway (Dris *et al*., 2016).

1.3.2 Weathering and fragmentation of microplastics

Microplastics will probably increase in abundance over the length of their pollution pathway in the environment. This increases not only their capacity to adsorb pollutants but also the range of biota to which they become bioavailable. Microplastic degradation rates are highly variable and are influenced by the inherent characteristics of the plastics, such as crystallinity, molecular weight, functional groups, plasticisers and additives (Artham and Doble, 2008) and on physical forces, such as heating/cooling and wetting/drying (Kamal and Huang, 1992). In addition, environmental conditions such as pH and ultraviolet (UV) light exposure (Shah *et al*., 2008), along with biotic interactions such as microbial assemblages (Yoshida *et al.*, 2016), can determine the rates of degradation.

1.3.3 Occurrence and fate of microplastics in freshwater environments

Microplastics have been recorded in freshwater studies worldwide; in Europe they have been recorded in Lake Geneva (Faure *et al*., 2012), Lake Garda (Imhof *et al*., 2013), the Danube (Lechner *et al*., 2014), the Rhine (Wagner *et al*., 2014; Klein *et al*., 2015), the Thames (Morritt *et al*., 2014) and the Tamar estuary (Sadri and Thompson, 2014). The environmental fate of microplastics in freshwater systems is largely unknown (Eerkes-Medrano *et al*., 2015), although a previous study of a Canadian lake showed the potential for preservation in lake sediment records (Corcoran *et al*., 2015).

The dispersal of microplastics in aquatic environments is dependent on the physical and chemical nature of the microplastics, the physical forces that drive their movements, the interactions between the particles and biota and the interactions between all of the above (Eriksen *et al*., 2013; Imhof *et al*., 2013; Free *et al*., 2014; Hoellein *et al*., 2014; Lechner *et al*., 2014).

Freshwater studies in large lakes (Imhof *et al*., 2013; Eriksen *et al*., 2013; Free *et al*., 2014) show that similar physical forces are responsible for the dispersal of microplastics as those in studies of marine environments. In Lake Garda, wind-affected surface currents were responsible for microplastic distribution (Imhof *et al*., 2013). In Lake Hovosgol, Mongolia, wave energy was found to be an important factor in distribution and a higher concentration of microplastics was found at the lake's drainage point (Free *et al*., 2014), and in Lake Erie, North America, converging currents were responsible for microplastic concentrations (Eriksen *et al*., 2013).

In riverine environments, the dispersal and transport of microplastics is comparable to sediment transport with flow velocity, water depth, bottom topography, river elevation and temporal variations, such as storms and floods, having an influence. The presence of water flow regulation structures such as dams may result in fluxes of sediment and particle transport (Chanson, 2004).

Although we can apply knowledge of physical processes that are known to affect the dispersal of microplastics in the marine environment to freshwater, this is limited because of the lower density of freshwater, which may have a significant effect on the vertical distribution of the polymer types (Ballent *et al*., 2012, 2013). The range of densities of common polymers is such that they can be distributed throughout the water column and be incorporated in the benthos (Morét-Ferguson *et al*., 2010). Transport of lighter microplastics [polypropylene, polyethylene, polystyrene, nylon, low-density polyethylene (LDPE) and high-density polyethylene (HDPE)] is subject to physical and biological forces acting on the water's surface. Wind drives surface movement of microplastics, which leads to the accumulation of microplastics on exposed shorelines, and increasing wave energy transports particles to subsurface layers (Kukulka *et al*., 2012; Imhof *et al*., 2013; Free *et al*., 2014). Denser microplastics, such as PVC, will probably sink to the bottom, where they may become entrained in the benthos or be bounced along the bottom by saltation in a similar way to sediment particles (Minshall *et al*., 2000); this potentially gives rise to further degradation of the microplastic particles. Resuspension of deposition microplastics can occur from turbulent flows of tides and waves (Ballent *et al*., 2012, 2013).

1.3.4 Potential impact of microplastics on human health

The potential for microplastics to be colonised by microbes could be an important factor when assessing

the risks to humans. The physical properties of plastic provide unique habitats for microbial communities (Keswani *et al*., 2016). Microbes belonging to the Campylobacteraceae family that are known to cause gastrointestinal infections in humans were found to colonise microplastics that were collected downstream from UWWTPs (McCormick *et al*., 2014). It is likely, therefore, that microplastics derived from UWWTPs pose a greater risk to humans than those from other sources. The potential for ingestion of microplastics in humans may arise through bathing or other recreational activities in contaminated waters or through consumption of water from contaminated abstraction water bodies. This potential is likely to increase closer to point sources, particularly in lakes where there is less dispersal. Furthermore, ingestion may occur through the consumption of contaminated foodstuffs. Foodstuffs may become contaminated through preparation with contaminated water or, in the case of edible aquatic organisms, the organism may be the primary consumer of the microplastics and the human the secondary consumer. Van Cauwenberghe and Janssen (2014) found that marine bivalves that were cultivated for human consumption contained microplastics and this was further substantiated by Li *et al*. (2015) in China. Upon ingestion, the rate of translocation of ingested microplastics into the lymphatic system has been demonstrated to be < 1% (Hussain *et al*., 2001). As cellular penetration is possible only in the nanometre size range, the chance of organ penetration is very low (Bouwmeester *et al*., 2015). However, it is likely that interactions between microplastics and fluids that are present in the gut may affect the immune system and cause inflammation (Powell *et al*., 2007), which could be magnified if the gut is colonised by harmful bacteria. There is also the potential for transfer of adsorbed toxins upon ingestion, although there is no evidence of this in humans.

1.3.5 Potential exposure of microplastics to species and habitats

A wide range of invertebrate taxa have been found to contain microplastics, including crustaceans (Murray and Cowie, 2011), bivalve molluscs (Van Cauwenberghe and Janssen, 2014), cephlopods, such as the Humboldt squid (*Dosidicus gigas*) (Ivar do Sul and Costa, 2014), zooplanktonic crustaceans, such as *Daphnia mangna* (Imhof *et al*., 2013) and the Norwegian lobster (*Nephrops norvegicus*) (Murray and Cowie, 2011). Furthermore, terrestrial species, such as the earthworm *Lumbricius terrestris*, were also found to ingest microplastics (Huerta Lwanga *et al*., 2016)

Microplastics have also been found in a large range of fish in marine habitats (Lusher *et al*., 2015a,b), estuarine habitats (Possatto *et al*., 2011; Dantas *et al*., 2012) and, probably because fewer studies have been conducted, to a lesser extent in freshwater environments, where they have been found in the gut of gudgeon *Gobio gobio* (Sanchez *et al*., 2014). Most studies suggest that direct ingestion of microplastics is the most likely route of exposure and this has been demonstrated by De Sá *et al*. (2015) for the case of the common gobi, *Pomatochistus microps*. However, transfer through the gills, as found by Watts *et al*., (2016) in the shore crab, *Carcinus maenus*, and through filtration in the bivalve *Mytilus edulis* (Van Cauwenberghe and Janssen, 2014) have also been observed. Although a range of benthic invertebrates were shown to take up microplastics under laboratory conditions, the microplastics were often rejected and expelled before digestion (Graham and Thompson, 2009). If volumes of microplastics reach a critical level, even with this expulsion process, reduced feeding can occur (Wegner *et al*., 2012). There has been some laboratory-based evidence for trophic transfer, with microplastics becoming incorporated at the base of the food chain, and microplastics have been found to affect photosynthesis in marine algae (Bhattacharya *et al*., 2010), resulting in reduced feeding of marine zooplankton (Cole *et al*., 2013). Microplastics have been found in a wide range of marine birds including fulmars (*Fulmaris glacialis*), shearwater (*Procellaridae*) and gull (*Laridae*) species (Kühn and van Franeker, 2012; Lindborg *et al*., 2012; Acampora *et al*., 2014). More recently, in a study in China, 94.1% of terrestrial or freshwater-dependent species, including the common buzzard (*Buteo buteo*), the large hawk-cuckoo (*Culculus sparverioides*) and the little grebe (*Tachybaptu sruficolis*), were found to contain microplastics in their digestive tracts (Zhao *et al*., 2016). Further up the food chain, microplastics have been found in the stomachs of harbour seals, *Phoca vitulina* (Bravo Rebolledo *et al*., 2013), which could have occurred through direct consumption or through the secondary consumption of contaminated fish and birds. Transfer through the food chain was also demonstrated by Farrell and Nelson (2013), who

provided evidence of microplastic transfer from the edible crab, *Mytilus edulis*, to the shore crab, *Carinus maenas*.

1.3.6 Potential impacts of microplastics on species and habitats

Impacts in biota have been observed in a range of taxa in laboratory conditions. These effects have been observed in marine algae (Bhattacharya *et al*., 2010), resulting in reduced feeding of marine zooplankton (Coles *et al*., 2013). Effects on invertebrates have included inflammation in the blue mussel, *Mytilus edulis*, following exposure to HDPE, where microplastics were found to cross over to the circulatory system (Von Moos *et al*., 2012). Confusion between microplastics and prey items by common gobi, *Pomatochistus microps* (De Sá *et al*., 2015) reduced their fitness and therefore affected the predatory performance of this species. Impacts may be determined partly by retention times in particular species. The retention of microplastics in fish is still relatively unknown; however, some evidence suggests that, following ingestion, they pass through the gut quickly and retention of particles increases with increasing size (Santos and Dos Jobling, 1992). As the Norwegian lobster (*Nephrops norvegicus*) retains filaments that they ingest through contaminated fish (Murray and Cowie, 2011), they may be more susceptible to negative effects. Regurgitation of microplastics, as found for the glaucous-winged gulls (*Larus glaucesences*) (Lindborg *et al*., 2012), and a greater abundance of microplastics in juvenile fulmars suggest that an increased risk to juveniles may occur during feeding (Kühn and van Franeker, 2012). To date, there have been no negative impacts described for ingestion of microplastics by birds; however, effects similar to those resulting from ingestion of macroplastics, such as nutritional deprivation and gut damage (Pierce *et al*., 2004), along with chemical toxicity (Tanaka *et al*., 2013), could occur on a smaller scale. As birds occupy high trophic levels, they potentially ingest plastic debris directly as well as from the consumption of contaminated species through secondary ingestion (Verlis *et al*., 2013). Zhao *et al*. (2016) suggested that birds that are opportunistic, feeding on a range of prey, such as birds, small mammals, amphibians and insects, may be at greater risk of ingesting microplastics. The presence of a digestive crop may extend the retention time of the microplastics, increasing the risk of cross-contamination. Effects are also extended to the terrestrial environment, where microplastics were found to reduce the growth rate of the earthworm, *Lumbricus terrestris* (Huerta Lwanga *et al*., 2016)

1.3.7 Legislative implications and policy development in relation to microplastics

Currently, there are no regulations concerning the levels of microplastics in freshwaters, despite the significant abundance of microplastics in several freshwater systems. There are several EU directives of potential indirect and direct relevance to microplastics pollution as an emerging contaminant. The Water Framework Directive (WFD; EU, 2000a), which requires monitoring of anthropogenic pressures and the protection of Natura sites designated under the Habitats Directive (HD; EU, 1992), and the Birds Directive (BD; EU, 2009) (Article 6, Annex IV), as well as the protection of waters used for the abstraction of drinking water (Article 7) could be relevant. The Marine Strategy Framework Directive (MSFD; EU, 2008a) requires prevention of litter inputs and reducing litter in the marine environment and is directly relevant. Freshwater environments indirectly benefit from this legislation, which aims primarily at safeguarding the marine environment. The EU Bathing Water Directive (EU, 2006) requires the production of a bathing water profile (BWP) for all designated EU waters containing details on possible pollution types that could have a negative impact on human health while bathing (Keswani *et al*., 2016). The European Drinking Water Directive (EU, 1998) requires protection against all sources of pollution.

The European Commission's green paper "A European strategy on plastic waste in the environment" (EC, 2013) expresses "particular concern" about microplastics within a review of waste legislation and highlights potential mitigation strategies at source.

In the event that microplastic pollution is deemed to be a risk to human health and priority species in freshwater environments, waste management regulation and enforcement may be necessary. Potential microplastic sources could be addressed under the following EU Directives: the Sewage Sludge Directive (EU, 1986), the Waste Framework Directive (EU, 2008b), the End-of-Life Vehicles Directive (EU, 2000b), the Waste Electrical and Electronic Equipment

(WEEE) Directive (EU, 2012); the Packaging Directive (EU, 1994, as amended), the Landfill Directive (EU, 1999) and the Industrial Emissions Directive (EU, 2010), for which regulation currently only applies to the manufacture of polymers. This reduces greatly the protection for freshwater systems from industries involved in the production of plastics goods for which the primary granules or pellets are required.

2 Task 1.1: Evaluation of Potential Scale and Scope of Microplastics in Ireland

2.1 Overview

Many studies have been conducted on the distribution of microplastics, particularly in the marine environment. Reports of high abundances in the marine environment have led to the development of plastics-collecting devices at sea and many beach clean-up initiatives. However, few studies have investigated and characterised the sources that could enable us to evaluate the feasibility of preventing or reducing microplastics entering aquatic environments. An evaluation of the potential scale of microplastic inputs was conducted to identify catchments with potentially high exposure. The objectives of Task 1.1 are described in Table 2.1.

2.2 Identification of Potential Sources of Microplastic Pollution in Ireland

A scoping study concluded that there were several potential sources of microplastics in Ireland, including industry, agriculture, landfill, UWWTPs, domestic waste water treatment plants (DWWTPs) (septic tanks), construction and demolition, littering/dumping, household waste, imported goods and agricultural plastics (Table 2.2). Sources of information used for further investigation into the characterisation of selected potential sources are described below in Table 2.2.

Table 2.1. Objectives and description of work for Task 1.1

Objectives	Description of work carried out
Identify the potential sources of microplastic pollution in Ireland	Potential sources were identified through a scoping study, literature searches and discussions with environmental managers
Characterise the potential sources of microplastic pollution in Ireland	Once identified, sources were characterised through available literature and assessment of industry processes, and verified through site visits to key industry sectors, including plastic producers, plastic converters, plastic machining industry and plastic re-processors
	In a separate EPA study,[a] "Quantification of Microplastic Pollution at Potential Point Sources in Ireland" (2015-CDCRP-SS.6), carried out at the same time as this desk-based study, microplastics were characterised in samples taken from landfill, industry, sewage sludge, one mains water supply and a well water supply from a karst region; the aim of this separate study was to substantiate the findings of the current study with enumeration and characterisation of the microplastics present at these sources
Estimate microplastic pollution load from these sources	Pollution loads were estimated on a relative, categorical scale and where samples had been collected and characterised as part of the quantification study (2015-CDCRP-SS.6), the results were also used to estimate loadings
Characterise the scale of these inputs	The scale was characterised in terms of number of entities, and their geographical distributions. Where industry visits were conducted, abundances were recorded
Identify catchments with a high potential exposure using land use maps and point source information	Data layers for a GIS representation for potential exposure

[a]N. Foley, EPA, 15 July 2015, personal communication.
GIS, geographic information system.

Table 2.2. Identified potential sources and source confirmation from international sources

Potential sources investigated	Sources of information
Manufacturing industry (C)	Industry visits and sample collection
	Viewing processes on websites
	Scientific literature searches
	Analysis of samples taken from industry
UWWTPs (C)	Site visit to UWWTPs (west of Ireland)
	Analysis of samples taken from inflow and outflow
	Scientific literature searches
Sludge/biosolids	Measurement of abundance from seven UWWTPs[a]
arising from UWWTPs (C)	Scientific literature searches
Construction and demolition (NC)	Data obtained from construction firm on quantities of plastics used in the construction industry
	Scientific literature searches
Household waste (C)	Scientific literature searches
Agricultural plastics (NC)	Scientific literature searches
	Communications with IFFPG
	Viewing of IFFPG report (IFFPG, 2014)
Landfill	Measurement of abundance from leachate samples from landfill sites[a]
	Practice research from within the scientific literature searches

[a]Data were collected under the EPA-funded project (2015-CCRP-SS.6) "Quantification of Microplastic Pollution at Potential Sources in Ireland" (N. Foley, EPA, 15 July 2015, personal communication).

C, confirmed source of microplastics; IFFPG, Irish Farm Film Producers Group; NC, not a confirmed source of microplastics prior to investigations.

2.3 Characterisation of Potential Sources of Microplastic Pollution in Ireland

2.3.1 Manufacturing industry as a potential source of microplastics in Ireland

Categories of industry involved in the manufacturing of polymers or goods produced from polymers were selected from Nomenclature statistique des activités économiques dans la Communauté européenne (NACE) descriptions. The resulting selection, including 1644 companies, provides an estimate of potential microplastic production in Ireland (Table 2.3). A small number of plastics-manufacturing companies were chosen to assess the potential for microplastic pollution across a range of processes within the industry. In a separate EPA study (2015-CCRP-SS.6), samples going to sewer were taken from these sites to quantify microplastic emissions (N. Foley, EPA, 15 July 2015, personal communication). A small number of plastics-manufacturing companies were chosen to assess the potential for microplastic pollution across a range of processes within the industry. In this study, samples going to sewer were taken from these sites to quantify microplastic emissions:

1. Plastics recycling company: a small to medium-sized enterprise (SME) operating under conditions stipulated by a waste permit. This company has a number of awards, has its own treatment facility and was thought to be representative of the "best-case" scenario regarding cleanliness of plastic processing procedures.
2. Medical devices company: a large multinational medical device company with many manufacturing plants worldwide. This company was chosen, as it is representative of many medical device companies based in Ireland.
3. Plastics-producing company: a large multinational company with many manufacturing plants worldwide operating under an Integrated Pollution Prevention and Control (IPPC) licence and reporting to the EPA. This represents regulated plastic producers, of which there are approximately 10 in Ireland.

Table 2.3. NACE categories of manufacturing industries which could potentially contribute to microplastic pollution in Ireland. Number of companies obtained from the Companies Registration Office (CRO) provided through Vision-Net, Ireland

NACE description (manufacturing unless otherwise stated)	Number of companies
Medical and surgical equipment and orthopaedic appliances	285
Other furniture	212
Recycling of non-metal waste and scrap	193
Other kitchen furniture	96
Other plastic products	87
Textiles	72
Sports goods	64
Electric domestic appliances	60
Electronic valves and tubes, and other electronic components	59
Other office and shop furniture	54
Plastic plates, sheets, tubes and profiles	54
Electricity distribution and control apparatus	51
Made-up textile articles, except apparel	51
Parts and accessories for motor vehicles and their engines	38
Carpets and rugs	32
Games and toys	32
Other textiles not elsewhere classified	29
Plastic packing goods	28
Builders' ware of plastic	25
Plastics in primary forms	21
Luggage, handbags and the like, saddlery and harness	16
Non-electric domestic appliances	15
Finishing of textiles	14
Insulated wire and cable	14
Chairs and seats	12
Man-made fibres	9
Recycling	9
Cordage, rope, twine and netting	6
Brooms and brushes	3
Production of abrasive products	3

4. Plastic packaging company (thermal forming). This was representative of an SME packaging company in Ireland, which used pre-formed sheets of polymers to thermally mould packaging items

Further investigations into industrial processes revealed that potential microplastic production varied greatly between the processes used (Table 2.4). Processes used in manufacturing of polymers or products made of polymers include: machining, polymerisation, moulding, thermal forming and extrusion.

Potential microplastic emissions to freshwater systems from machining of plastics

Machining processes such as milling, turning, sawing, shredding and scrubbing produce microplastic swarf (Figure 2.1). Milling may produce swarf with a mixed size range, some of which will qualify as microplastics, while sawing produces very fine swarf within the micrometre range. In Ireland, typical industrial sectors that adopt machining include the medical devices industry, precision engineering companies, the recycling industry and the construction industry. The

Table 2.4. Industrial processes with associated microplastic production, industries and examples of polymers used

Industrial processes		MP production potential	Associated industries	Example polymers
Polymerisation		High	Primary production of plastics	PMMA
Moulding		Low	Bottle making, medical devices, electronics	PET, HDPE
Extrusion		Low	Packaging, plastic films	LDPE
Thermal forming		Low	Packaging	Polyethylene, HDPE
Machining	Milling	High	Medical devices, precision engineering	HDPE
	Turning	High	Medical devices	HDPE
	Shredding	High	Recycling industry	PET, HDPE
	Sawing	High	Construction industry	PVC
	Scrubbing	High	Recycling industry	PET, HDPE

MP, microplastic production; PMMA, polymethyl methacrylate.

(a) (b)

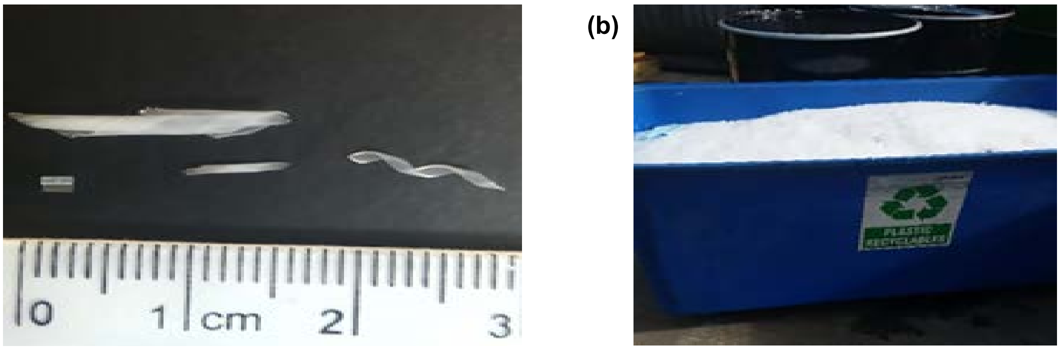

Figure 2.1. Photographs of (a) microplastic swarf from the milling of high density polyethylene and (b) storage of swarf before collection.

hazard potential for swarf can be estimated using a hazard ranking scale devised by Lithner *et al.*, 2011 (Table 2.5). This hazard ranking scale pertains to the residual unreacted monomers within polymers. These residual monomers can leach from plastic products and are much more susceptible to doing so as the particles decrease in size, increasing surface area available for leaching and adsorption of monomers and persistent organic pollutants (POPs). It is, therefore, possible to deduce that industrial production of the smallest particles with the highest hazard rating is the most hazardous to humans, biota and habitats. Figure 2.2 explains how this principle may have implications for different industrial sectors, showing that the construction industry could be the most hazardous in terms of microplastic production. Examples of products made up of hazardous polymers, which are normally machined, include PVC sewerage and water supply piping, and insulation boards for the construction industry.

Surface water run-off from industry can potentially transport contaminants into nearby streams and rivers, particularly in industrial estates, where there are large areas of impermeable surfaces, such as car parks, road-ways and yards resulting in significant volumes of surface water. Surface water/storm water emission points are usually created through a network of channels and gullies in industrial estates. Some industries install filters at these points to reduce accidental emissions that could enter rivers and streams through surface run-off. However, as there is no legal obligation to do this, it is often not the case. As many plastics are buoyant, accidental spillages and poor practices in waste management could easily result in contamination of freshwater systems through

Table 2.5. Hazard levels of polymer types[a]

Name	Abbreviation	Hazard category[a]	Hazard grade
Polyvinyl chloride	PVC	5	10,000
High impact polystyrene	HIPS	5	10,000
Polyurethane	PUR	5	10,000
Polyisocyanurate[b]	PIR	5	10,000
Polyacrylonitrile	PAN	5	10,000
Polystyrene	PS	4	1000
High-density polyethylene	HDPE	3	100
Low-density polyethylene	LDPE	3	100
Polyethylene terephthalate	PET/PETE	2	10
Polypropylene	PP	1	1

Data source: Lithner *et al.* (2011).

[a]The lowest hazard category is 1 and the highest is 5.

[b]Polyisocyanurate was not listed by Lithner *et al.*, but has a similar chemistry to that of polyurethane.

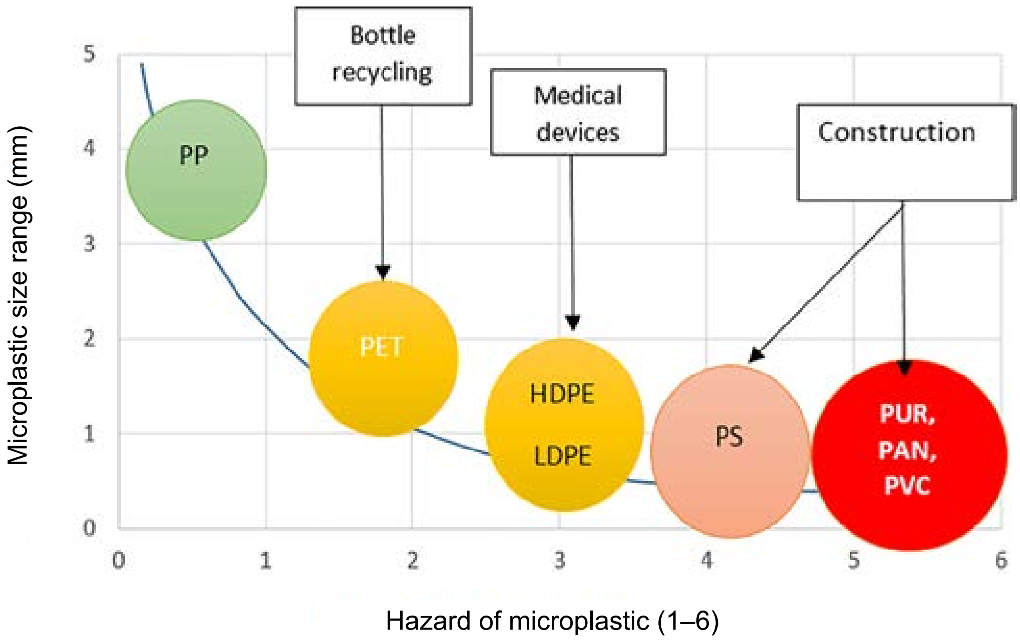

Figure 2.2. Microplastic hazard ratings as a function of particle size (in mm) and polymer hazard grades (Lithner *et al.*, 2011) (1 is the lowest and 6 is the highest hazard); see Table 2.5 for polymer abbreviations.

surface water. During site visits, poor practices relating to the transfer and containment of microplastics were observed; this resulted in spillages on the concrete surfaces outside the processing/manufacturing plants in the medical devices industry and particularly in the recycling industry [Table 2.6; Figure 2.1(b)]. In the recycling industry, the following observations were made:

- The processing line was relatively clean with little spillage onto the factory floor.
- There were significant amounts of microplastics and macroplastics on the yard close to storm water drains. Microplastics entering the storm water drains can end up in UWWTPs or can go directly into freshwater systems. The most likely cause of transfer is movement of plastic bales.
- There were no filters in the storm water drains to prevent the transfer of microplastics to surface water or to decrease the loading of microplastics at the UWWTPs.

Table 2.6. Industries visited, description of practices and potential microplastic contamination of freshwater through surface pathway and sewer

Industries visited	Potential contamination through the surface pathway	Potential contamination through sewer pathway
Plastic recycling (shredding)	There were significant amounts of microplastics and macroplastics on the yard close to storm water drains; the most likely cause of transfer is movement of plastic bales	Microplastic contamination to sewer confirmed
Medical devices (milling)	Yard generally clean, but transfer of swarf from machine to container was conducive to accidental spillages	No evidence of contamination
Plastic producer (polymerisation)	No evident of spillages	Microplastic contamination to sewer confirmed
Plastic packaging (thermal forming)	Possibility of some particles breaking away from baled plastic	No evidence of contamination

The medical device industry that was visited had limited spillages, but did have oil traps in the storm water drains; however, the effectiveness of these traps for microplastic pollution needs to be determined.

The only monitored parameter for emissions to sewer that encompasses microplastics is suspended solids. All IPPC-licensed facilities are permitted to emit a certain amount of suspended solids to sewer. These amounts differ for each facility depending on their activities and capacity. As microplastics are light, the level of allowable suspended solids could equate to high and potentially harmful levels of microplastics emitted to sewer on a daily basis. Microplastic emission to sewer was found in the plastics recycling plant visited.

In this recycling plant, plastic is shredded and then washed. This waste water is passed through an on-site waste water treatment system. The following was found:

- In the in-house waste water treatment plant, plastic fragments were visible on the water surface that had passed through the filtration system (150 µm).
- In the final waste water, following polyelectrolyte treatment, a 2 litre sample was taken and processed in the EPA study “Quantification of Microplastic Pollution at Potential Point Sources in Ireland” (2015-CCRP-SS.6). The results showed 661 microplastic particles per cubic metre (consisting of one-third fibres and two-thirds fragments).
- A Fourier transform infrared spectroscopy (FTIR) analysis of a sub-sample confirmed the particles to be made up of polymers (polypropylene and polyethylene).

The treatment system was ineffective in trapping microplastics/suspended solids. It was apparent that the filtration system employed was malfunctioning. This site visit and analysis verified the potential of the recycling industry as a source of microplastics.

Potential microplastic emissions to freshwater systems from polymer manufacturing industry

Polymerisation occurs in a reactor vessel, where a reaction mixture is transferred under nitrogen to a filter dryer system. The polymer is collected in the filter dryer and the mother liquor is transferred to external waste solvent tank (Figure 2.3). The polymer is then repeatedly washed with deionised water. The first wash of this is transferred to the waste tank and the last two washes (washes 2, 3) are discharged to the sewer. Polymers are then dried and passed on for further processing. The polymer is then milled to the correct particle size with a hammer mill and blended with other components to produce the desired powder. The powder is then packaged into pouches and sent off site for sterilisation. Upon return to the plant, it is packaged and shipped for global distribution.

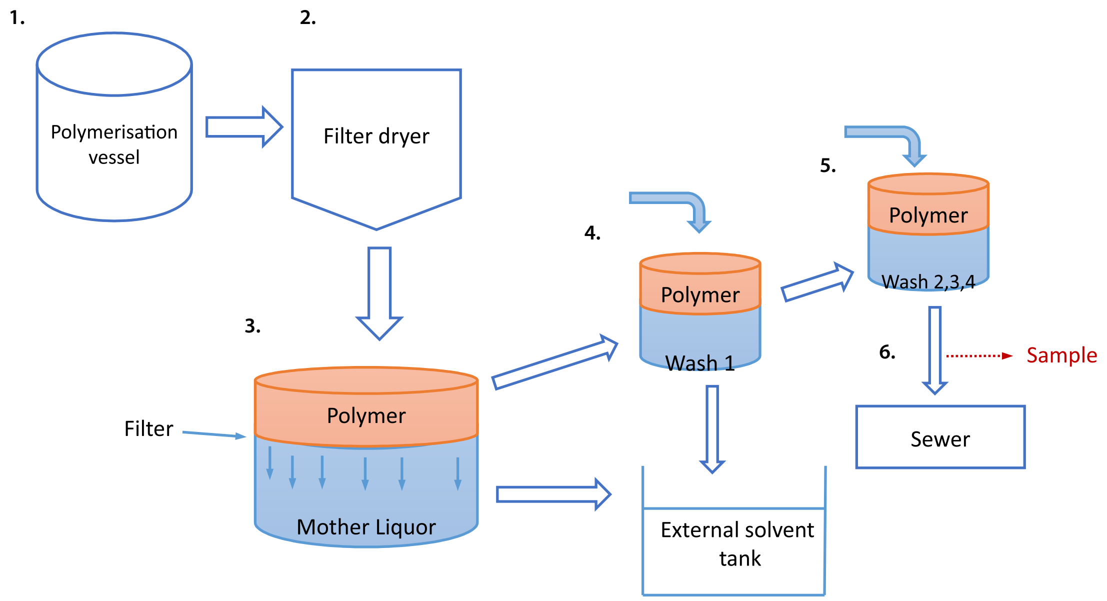

Figure 2.3. Diagram of processes in the primary production of polymers and the route of microplastics to sewer.

The site visit to the polymer-producing company revealed a microplastic particle abundance of 51,400/m³ in the water going to sewer (sampling location marked in Figure 2.3). This was verified through FTIR as being the same polymer that was in production. Two further site visits involved the viewing of thermoforming and moulding processes using powdered polymer. There was almost no potential for microplastic production in these manufacturing plants. As there was insufficient time to investigate each of the NACE descriptions listed, the medical devices industry and recycling industries were chosen for a thorough investigation, including site visits (Table 2.6).

Current regulation of potential microplastic-producing industries in Ireland

Within the framework of the EPA Integrated Pollution Control (IPC) Licensing schedule, the plastics-producing industry is covered under Class 5.12 of the first schedule (EPA, 2016). Class 5.12 covers operations during which the plastic/polymer is chemically synthesised, i.e. where a polymerisation reaction takes place. In IPPC-licensed facilities, the allowable suspended solid emissions measures in mg/L could permit large quantities of microplastics to be washed into the sewer each day. Allowable discharges of microplastics have also been flagged in an Austrian case study, which calculated a permitted release of up to 259 kg of microplastics within a 24 hour period (Lechner and Ramler, 2015).

Conclusions and recommendations

Industrial processes involving the machining of polymers are the main sources of microplastics. Of the machining industries, those that machine the plastics with the highest hazard rating can be deemed as having the highest potential risk if the plastics reach freshwater systems.

Microplastics have been found to enter the sewer from machining companies where the machining product is washed, e.g. the plastics recycling industry and in companies that produce primary polymers. On-site treatment facilities were found to be inadequate and failed to prevent discharge of microplastics. The potential for microplastics to enter surface waters was found in machining industries, particularly where plastic material or swarf is stored outside. Recommendations for reduction of microplastics in industry are listed below:

- Using moulding over machining where possible. Product size, thickness and polymer composition all influence the choice between moulding and machining. Moulding tools are designed for specific needs and are expensive; it is therefore often more economical to machine a component

that will not be mass-manufactured. On the other hand, there are several disadvantages to machining. Running, maintenance and raw material costs are high, and it produces a large volume of valuable scrap that must be disposed of.
- Re-incorporating the waste swarf into the production process. In the IPPC-licensed medical devices company visited, the swarf was not recovered back into the production line. Investment in plant to allow melting down and re-moulding of plastic billets would also increase revenue to the company. A cost–benefit and regulatory analysis could assess the feasibility of this.
- Containment of machined swarf. Machined swarf should be transferred from machine to containment area through a vacuum system. If swarf is stored on-site, it should be covered to prevent spillages.
- Installation and maintenance of filters. Where possible, filters should be installed to reduce the amounts of microplastics and nanoplastics entering the sewer. As found during this study, filters were not always effective and regular maintenance should be mandatory.
- A reduction in the allowable suspended solid emissions. A reduction in the allowable suspended solids will also reduce the amount of microplastics emitted to sewer.
- Implementation of a parameter within the environmental monitoring strategy which encompasses microplastic pollution. Sampling for microplastics is a simple process and could be implemented easily. Processing the sample for polymer identification requires FTIR. The feasibility of this must be assessed.

In addition, microplastic emissions in storm drains from industrial estates should be investigated using a sampling programme of storm water drains in these areas.

2.3.2 Urban waste water and domestic waste water treatment plants as potential sources of microplastics in Ireland

The combined intake of domestic waste water, industrial waste water, landfill leachate and storm water means that UWWTPs are receptors for the cumulative loading of microplastics. The partitioning of microplastic type and abundance within the UWWTPs is likely to vary between treatment processes/levels. Maceration of waste prior to treatment may increase the abundance of microplastics. The size of the preliminary screening will determine the size grade of the microplastics that pass into the treatment plant. The stages at which sludge settlement occurs will segregate lighter microplastic particles, which pass into the receptor body, while heavier ones become entrained in the sludge.

At the Ireland West waste water treatment plant (WWTP), the influent water was found to contain 97,000 particles (> 250 µm/m^3). Samples of effluent, taken in May 2015, showed a reduction to 2000 particles/m^3 (Figure 2.4). This was halved again during the tertiary treatment, ending in a final release of 1000 particles/m^3 (Figure 2.5). These results were in agreement with a Swedish study, which found that there was partitioning of microplastics through the various treatment stages, with 99% of microplastics retained in the sludge following primary treatment (Magnusson and Norén, 2014). Although the abundance of microplastics was higher per population equivalent (PE) in Ireland West compared with the plant in Lysekil, Sweden, the percentage reduction in the sludge after primary treatment was almost identical: 99% and 98%, respectively (Table 2.7). Although the sludge from the Ireland West treatment plant was not analysed in this study, we will infer, based on the study of Magnusson and Norén (2014), that the microplastic particles have also been retained in the sludge post settlement (Figure 2.5). The fate of sewage sludge is, therefore, of upmost importance, as this is the medium with by far the highest concentration of microplastics that was investigated during this study. Since the introduction of the Urban Waste Water Treatment Directive 91/271/EEC (EU, 1991), Ireland has been working towards compliance with Article 4 of this Directive, which states that secondary treatment must be implemented where there is a PE > 2000, thereby diverting approximately 98% of microplastics in 95% of the national waste water load into the sludge stream (EPA, 2014a). The 2% of microplastics not retained in sludge should also be considered as a potentially significant input of microplastic pollution. In Ireland, only waste water discharge licences are required for discharge from agglomerations between 500 and 2000 PE, and plants with PE of < 500

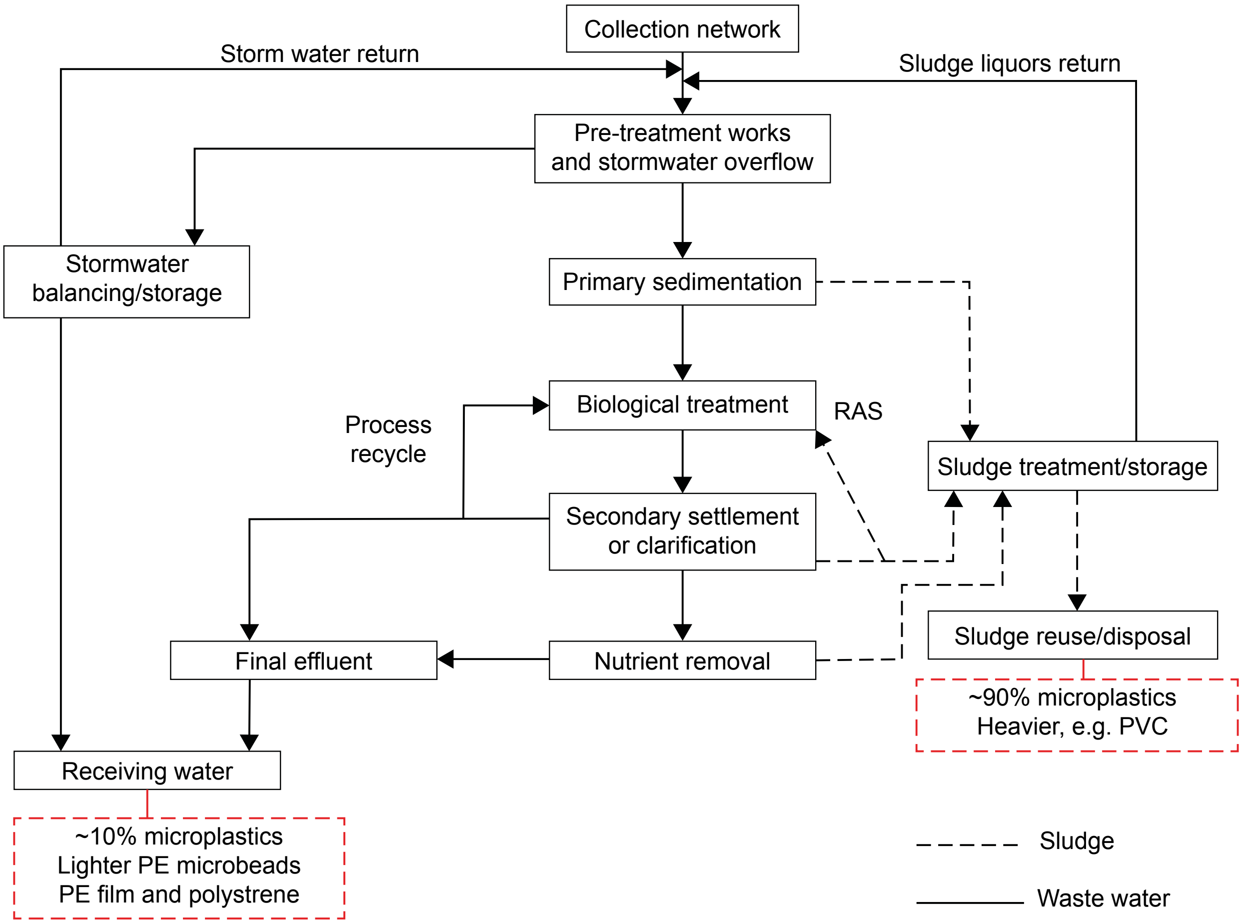

Figure 2.4. Waste water treatment plant overview and microplastic partitioning into sludge and receiving waters (modified from EPA, 1997). RAS, return activated sludge.

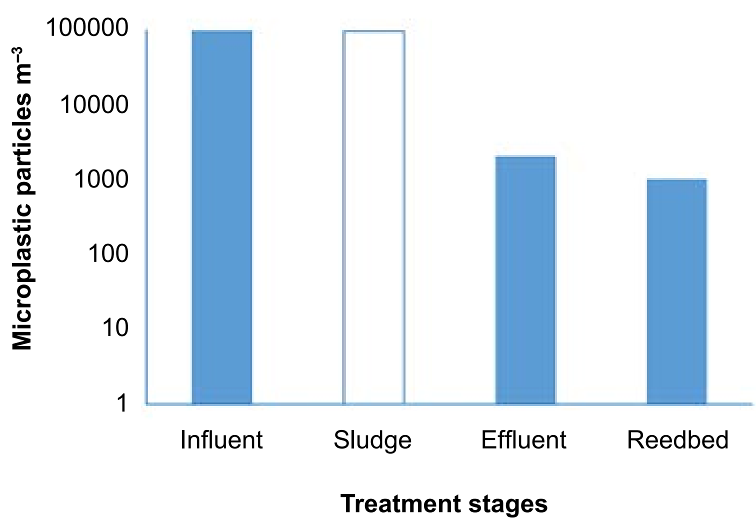

Figure 2.5. Microplastic particles found in influent, effluent and reed bed samples of the Ireland West treatment plant. The results are on log scale. Loading in sludge is estimated by deduction. These values are based on results from a one-off sample.

Table 2.7. Comparison of microplastic abundances in Irish and Swedish WWTPs

Waste water treatment plant	Population equivalent (PE)	Influent microplastic abundance (per m³)	Microplastics (per m³ for 1000 PE)	Reduction post-primary treatment
Lysekil, Sweden	12,000	15,000	1250	99%
Ireland West[a]	4000	97,000	24,250	98%

[a]**Preliminary results from a one-off sampling occasion.**

require a certificate of authorisation (COA) which allows direct discharge into receiving waters. At the end of 2013, there were 296 waste water treatment plants discharging into rivers and 15 discharging into lakes. Two of these treatment plants, one of which had preliminary treatment only and one with a PE of 16,977 that had no treatment (EPA, 2014b) will probably deliver 100% of the captured microplastics into the receiving freshwater water bodies. All the other plants will deliver approximately 10% of the captured microplastics into the receiving waters, which is a considerable amount when considered nationally.

Accidental discharges may lead to direct inputs of microplastics to freshwater systems. Approximately 150 incidents relating to uncontrolled releases from storm water overflows and emergency overflows were reported in 2013 (EPA, 2014b) and would contribute to these inputs.

In Ireland, there are an estimated 500,000 DWWTPs (CSO, 2011). There is potential for microplastics to leach through sub-surface pathways into freshwater systems but these mechanisms are unknown and require further investigation. The sludge derived from DWWTPs and removed to UWWTPs is discussed in subsection 2.3.4.

Conclusions and recommendations

Urban waste water has been one of the principal pressures on water quality in Ireland, and microplastics, which until recently were undetected, now contribute to that pressure. With the growing plastics industry and increasing demand for plastics in Ireland and in Europe (Plastics Europe, 2012), it is likely that emission of microplastics to freshwater systems will increase from UWWTPs. Furthermore, the feasibility of the UWWTPs as locations where effective mitigation could take place should to be fully investigated.

Recommendations:

- infrastructural mitigation:
  - maintenance of filters at preliminary treatment of 2 mm or under;
  - assessment of the feasibility of implementation of filtration systems for effluent waters which would remove microplastics;
- increase knowledge of effects of treatment processes:
  - assessment of the potential of preliminary screening to reduce the abundance of microplastics entering UWWTPs;
  - assessment of the potential of maceration to increase the abundance of microplastics entering UWWTPs;
  - assessment of the differences in the amounts of microplastics entrained in sewage sludge in activated sludge systems compared with primary settlement only. The function of the clarifying for skimming microplastics entrained in floating scum/grease layer;
- monitoring:
  - monitoring of microplastics in effluent waters;
  - monitoring of microplastics in tandem with other pollutants to assess for correlations;
- assessment of effects of effluent on biota:
  - ecological assessment of the impact of discharges on the biota of receiving waters.

2.3.3 Urban waste water treatment plant biosolids as a potential source of microplastics in Ireland

In the EU, sewage sludge is dealt with in a variety of ways among Member States, including use for energy production, use for construction materials and use as an agricultural fertiliser (Jiang *et al*., 2011; Gikas, 2014; Koutroubas *et al*., 2014). The application of sewage sludge to agricultural land is governed by the

EU Sewage Sludge Directive (86/278/EEC) on the protection of the environment and in particular of the soil when sewage sludge is used in agriculture, which requires that human health risks should be minimised through heat, chemical, or biological treatment.

In Ireland, a ban on disposal at sea (Directive 91/27/EEC) in 1999 increased the volume of sewage sludge for disposal/re-use in Ireland. In 2014, 53,543 tonnes (dry solids) were produced and treated, with 80% going to agricultural lands (EPA, 2014b). In addition, the volume of sludge removed annually from DWWTPs is estimated to be 473,381 m^3 (EPA, 2014b).

Application rates of sewage sludge in Ireland are regulated by the Sewage Sludge Directive (86/278/EEC), which defines permissible levels of nutrients and metals, in addition to permissible hydraulic loading. Guidelines for the treatment and use of waste water sludge in Ireland, detailed in *The Code of Good Practice for the Use of Biosolids in Agriculture* (DEHLG, 2008) were designed to reflect the requirements of legislation at European and Irish levels (DEHLG, 2008, Annex 1).

In Ireland, most sewage sludge undergoes treatment prior to spreading; most is treated by lime stabilisation, followed by thermal drying (TD), anaerobic digestion (AD) and composting. While these treatment methods may be effective in reducing levels of bacteria, few studies have investigated the effects of such treatment methods on microplastic characteristics (Zubris and Richards, 2005).

Microplastics in sewage sludge have been detected on land and at sewage sludge disposal sites at sea (Habib *et al*., 1998; Zubris and Richards, 2005; Browne *et al*., 2011). In the USA, one study looked at the effects of sludge treatments and found an increased number of microplastics at a smaller size range in the lime-stabilised samples (Zubris and Richards, 2005). Although this study was aimed at the potential of using synthetic fibre as an indicator of sludge spreading (and therefore did not include microplastic fragments), it gave some evidence that lime stabilisation created shorter and more numerous fibres. In addition, an assessment of techniques that isolate microplastics from biotic samples showed that alkaline hydrolysis caused melding of polyethylene film (Cole *et al*., 2013). This further substantiates evidence that the physical alterations caused by lime stabilisation to microplastics could potentially increase their impact because of decreased size and increased abundance.

Whether agricultural land is a sink or a source of microplastic pollution remains unclear, although microplastic fibres have been found on land 15 years post application (Zubris and Richards, 2005). These authors also found some suggestion of downwards translocation and a preference for microplastics to follow a flow path. While the mechanisms by which they are translocated remain unknown, the potential of contaminant leaching from microplastics on agricultural land should be investigated. It is important to characterise the microplastics prior to land spreading and to determine the effects of treatment mechanisms. Factors that are probably important in the translocation of microplastics from land-spread sewage sludge could include run-off coefficients, ground water vulnerability, soil type and rainfall.

The quantification study (2015-CCRP-SS.6) conducted by the Galway-Mayo Institute of Technology (GMIT) in tandem with the current project aimed to characterise microplastics in sewage sludge and determine the effects of treatment processes.

Treated sewage sludge (biosolids) samples were obtained from seven UWWTPs (Figure 2.6) with a range of PEs. Effects of AD, TD and lime stabilisation were characterised in terms of composition (using FTIR), size and surface textures (using scanning electron microscopy).

The findings revealed microplastic abundances ranging from an average of 4196 to 15,385 particles/kg (dry weight) among the seven sites. Significant differences in microplastic abundance between thermally dried and anaerobically digested samples taken from Site 1A ($P < 0.001$, $F = 135$) suggests that treatment process is an important explanatory variable for microplastic abundances in sewage sludge and that the processes of AD is related to lower microplastic abundance (Figure 2.6)

To investigate to effect of treatment on size partitioning of microplastics, each site was treated as an independent measurement and plotted using a box plot. A general linear mixed model (GLMM) revealed that, for small and medium particle sizes, the lime stabilisation treatment was significantly different from both TD and AS ($P < 0.001$ for size classes 1 and 3; $P < 0.05$ for size class 2, see Figure 2.7). This

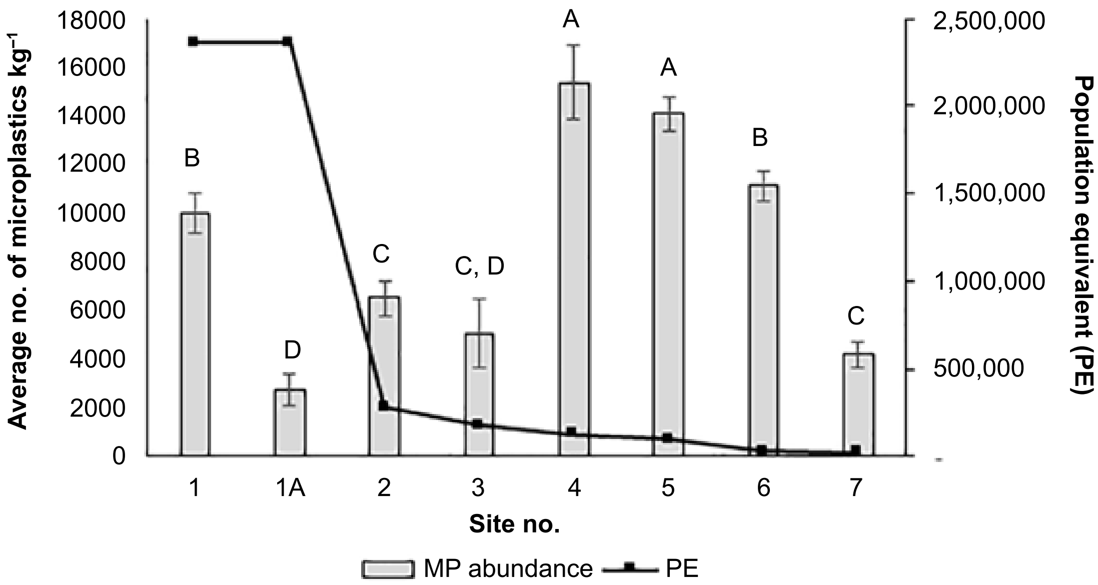

Figure 2.6. Average microplastic abundance and corresponding PEs for seven UWWTP sites. Sites sharing the same letter are not significantly different (Mann–Whitney U test, *P* > 0.005). MP, microplastics. Reproduced from Mahon *et al.*, 2017, with permission from the American Chemical Society.

confirmed the higher abundance of smaller particle sizes resulting from lime stabilisation.

Conclusion and recommendations

Based on the results described in this chapter, there are over a billion microplastic particles spread on agricultural land in Ireland each year and this is probably an underestimation.

Our results strongly suggest that treatment can have a positive or negative effect on abundance and microplastic particle size. For example, lime stabilisation appears to have a negative effect by making fibres more brittle, which causes fragmentation and makes them smaller and more numerous, as found by Zubris and Richards (2005). As the bioavailability and adsorption/adsorption rates of microplastics increases with decreasing size, the process of lime stabilisation may increase the potential risks to humans and biota that are associated with this pollutant. This could be particularly relevant in Ireland, where this is the most commonly used process employed for the treatment of sewage sludge.

However, from our results, there is some suggestion that the process of mesophilic AD could have a positive effect by reducing the abundance of microplastics in sewage sludge. The possibility of biodegradation of polymers by microorganisms has been confirmed (Gu, 2003) and mechanisms by which this could occur during the AD should be investigated further.

Although the presence of microplastics on the land poses a risk to ground water and surface water through leaching, the pathway and processes of microplastic leaching remain largely unknown.

In the absence of knowledge regarding the pollution pathway of microplastics in biosolids, it is impossible to assess the efficacy of guidelines under *The Code of Good Practice for the Use of Biosolids in Agriculture* in preventing exposure to freshwater systems. For example, at present, land spreading of sewage sludge is recommended 20 m from lakes and river channels and 10 m from small water courses and domestic wells. Further research is required to determine pathways of microplastics entrained in sewage sludge. When this knowledge has been gained, an assessment of the efficacy of *The Code of Good Practice for the Use of Biosolids in Agriculture* in preventing microplastics from entering freshwater systems should be carried out.

2.3.4 Urban waste water treatment plant agricultural plastics as a potential source of microplastics in Ireland

Under the Irish Farm Film Producers Group (IFFPG) scheme, farmyard collection services and bring-centres allow farmers to bring their plastic waste and

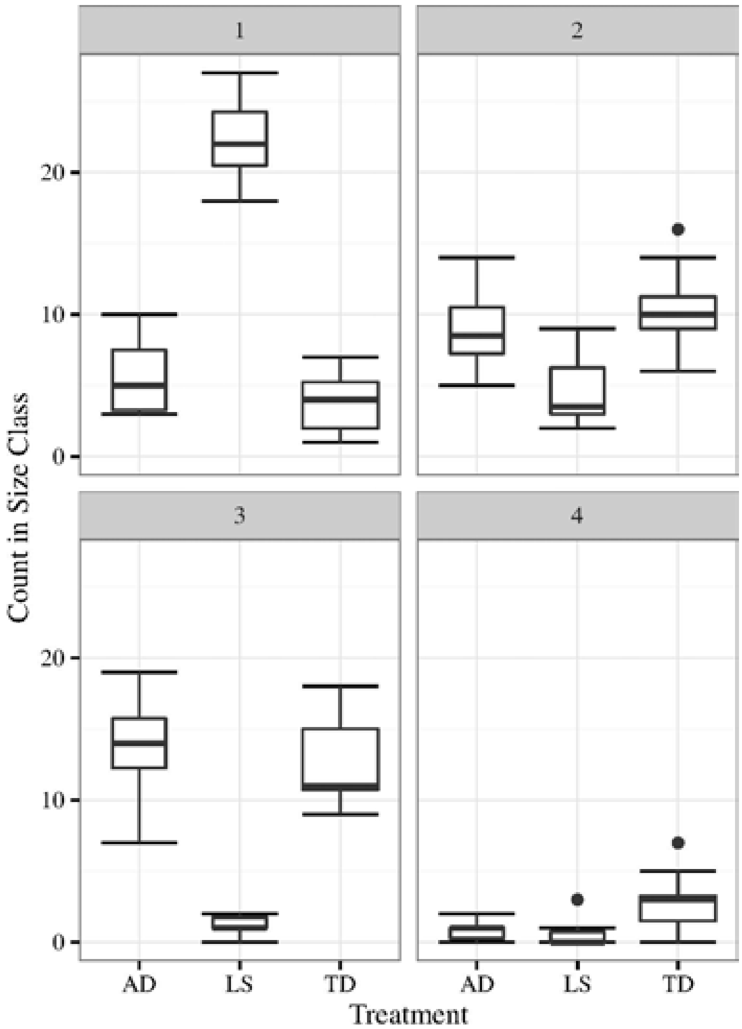

Figure 2.7. Counts of microplastics in different size classes (1–4) as a function of treatment type. AD, anaerobically digested; LS, lime stabilised; TD, thermally dried. Reproduced from Mahon *et al.*, 2017, with permission from the American Chemical Society.

recoup some of the cost of the plastic. The Waste Management (Farm Plastics) Regulations (2001) were designed to promote the collection and recovery of farm plastics waste (silage wrap, bags and sheeting) and an 80% recuperation rate is now estimated (IFFPG, 2014). As degradable films represent a relatively low proportion of the plastic used in agriculture, they are not considered in this study.

2.3.5 Landfill as a potential source of microplastics in Ireland

Both the abundance and type of plastics going to landfill are important factors in determining the potential for microplastic production. The EU Packaging Directive (94/62/EC, as amended) has increased the recovery and recycling of packaging waste in Ireland and this has resulted in the recovery of 87% of packaging waste in 2012 (EPA, 2014c). Waste electric and electronic equipment, of which fridges, freezers, washing machine etc. comprise the majority, have been diverted from landfill through the WEEE Directive (2012/19/EU). However, recycling and recovery of WEEE-derived plastics may be reduced if they contain POPs above a certain level, which are regulated by the EU Persistent Organic Pollutants Regulation (Regulation (EC) 850/2004). This also applies to plastics derived from end-of-life vehicles (ELVs). The exact disposal mechanism of plastics with high POPs is unclear but could be of prime importance, as they are potential sources of

microplastic pollution because of the chemical nature of plastic and their level of physical integrity.

Degradation of polymers occurs as a result of mechanical sheering, photo-degradation, thermo-oxidative-degradation or biological degradation, depending on:

1. the composition of accompanying waste going to landfill, as this may affect the degradation of the plastic waste;
2. the landfilling infrastructure (lining, capping);
3. landfill leachate management;
4. lifetime capacity of the landfill.

In modern landfilling practices, hazardous waste consisting mainly of industrial waste (solvents, sludges, oils and chemicals) goes to hazardous waste treatment facilities in Ireland or is exported (Waste Framework Directive 2008/98/EC, Annex II). This prevents degradation of plastic materials by substances that have oxidising, explosive, flammable and toxic properties and are probably major catalysts in the production of microplastics in landfill. However, indiscriminate loading of these substances and poor record maintenance (71% before the Landfill Directive came into effect) means that there is greater potential for microplastic production from deposited plastic materials at older landfill sites in Ireland (EPA, 2010).

Annex I of the Landfill Directive requires that "protection of soil, groundwater and surface water" is to be achieved by the combination of a geological barrier and a bottom liner. Before EPA licensing, there was evidence of leachate discharge to surface water. Modern landfill practices, such as capping and lining of landfills, greatly reduces the potential of landfill leachate as a direct means for microplastics to enter freshwater systems. However, although landfill lining can reduce the amount of leachate entering freely into nearby receiving waters, there is always a risk of leakage through tears in the liners (Schwarzbauer *et al*., 2002).

The capping procedure, which occurs daily, eliminates wind-blown plastics and reduces polymer breakdown through UV degradation. It also reduces biological breakdown and transfer by birds and vermin. However, it also creates an anaerobic environment that may result in the breakdown of polymers. The use of LDPE/PE and sprays and foams for capping should be investigated in terms of microplastic pollution.

All landfill sites produce waste water, otherwise referred to as leachate, that enters as rainwater and percolates through the solid landfill waste. Leachate derived from municipal landfill consists of organic and inorganic materials, which may be toxic in both liquid and solid form. In addition to the inherent properties of the plastic materials in landfill, conditions within the landfill, such as capping, lining and the lifespan of the landfill, will affect the composition of landfill leachate (Slack *et al*., 2005).

The degradation of plastics into microplastics, the leaching of plastic additives and the contaminants adsorbed do not only depend on environmental conditions. Microplastics have not been measured in landfill leachate, but levels of plasticisers such as phthalates and bisphenol A have been analysed (Schwarzbauer *et al*., 2002; Teuten *et al*., 2009). It is impossible to determine whether these compounds are derived from macroplastics or microplastics, but the creation of microplastics through the physical damage of larger plastic items will increase the amount of leaching of plasticisers and adsorption of other POPs and metals.

As part of an EPA-funded project to quantify microplastic pollution at various sources (2015-CCRP-SS.6), leachate samples from landfill sites were obtained and microplastic abundances determined. The efficacy of microplastic reduction by on-site treatment facilities was determined from two sites (Table 2.8). A more detailed comparison was carried out for landfill at Site 9, where a number of leachate samples were taken at cells where landfilling lifetimes and practices differed (Table 2.9).

The results of the leachate analyses showed an average abundance range of 2500 ± 500 particles/m^3 at Site 9_2, which has been operation since 2008, to 49,600 ± 18,385 particles/m^3 at Site 8, which has been operation since 2005 (Table 2.9).

The effect of the on-site treatment on the Site 8 facility showed limited efficiency in reducing microplastic particles with an average of 45,000 ± 4242 post treatment (Table 2.8). A similar comparison of before and after on-site treatment in landfill Site 6 revealed efficiency of over 90 % in the removal of microplastic particles.

Table 2.8. Effect of on-site leachate treatment on the abundance of microplastics

Landfill number	Average number of microplastic particles per m³		
	Treatment type	Before treatment	After treatment
Site 6	Constructed wetland	2800 ± 2333	None detected
Site 8	Reverse osmosis	49,600 ± 18,385	45,000 ± 4242

Table 2.9. Landfill sites visited and microplastic abundances in leachate samples

Landfill site	Landfilling started	Landfilling ended	2013 leachate AER per m³ per year	Average number of particles per m³
Site 1	2003	2011	9652	4500 ± 500
Site 2	1997	2010	33,796	11,500 ± 500
Site 3	2005	2008	34,541	3000 ± 2000
Site 4	1997	2010	67,830	5000 ± 2000
Site 5	1998	2011	25,626	500
Site 6	1968	2013	3000	2800 ± 2333
Site 7	2001	2014	47,744	15,000 ± 1000
Site 8	2005	Operating	51,903	49,600 ± 18,385
Site 9_1	2003	2008	–	4000 ± 1000
Site 9_2	2008	Operating	–	2500 ± 500
Site 9_3	1991	2004	–	2500 ± 1500
Site 9_4	1991	2004	–	2500 ± 1500
Site 9_5	2000	2003	–	2500 ± 500
Site 9_6	1991	2000	–	5500 ± 2500
Site 9_7	1991	2004	–	5500 ± 2500
Site 9_8	1991	2004	–	4500 ± 500
Site 9_9	1975	1991	–	11,500 ± 500

AER, annual equivalent rate.

Conclusions and recommendations

Results from the analysis in Ireland confirmed that microplastics are present in landfill leachate. There may be some potential for removal by on-site treatment but these systems should be more rigorously evaluated in terms of their efficiency.

There was a reduction of more than 80% in the number of landfills in Ireland between 1995 and 2008 and their numbers continue to decrease (EPA, 2010). However, approximately 200 landfill sites have closed since 1995 and many other historical sites, which would not have had liners or capping technology, represent a significant potential source of microplastic pollution to the freshwater environment. Currently, there are significant volumes of leachate being collected; this amounted to over > 1 million/m³ in 2013 (EPA, 2015). Although some of this leachate is treated on-site, the majority is diverted to UWWTPs, thereby increasing the load on these facilities as receptors of microplastic pollution. During periods of high precipitation, periods of high leachate production will coincide with periods of maximum hydraulic loading at UWWTPs (Brennan *et al*., 2016). The limitation of UWWTPs in dealing with the added volume may lead to an increased risk of diversion of microplastics into freshwater, particularly during times of higher hydraulic loading, such as during rain events.

With diversion of packaging waste, WEEE and ELVs away from landfill, the amount of plastic entering landfill has been reduced; however, in 2012 there was still approximately 43,278 tonnes of this form of waste going to landfill. It is imperative that plastics are not mixed with POPs and, if they are deemed to contain POPs, they should be dealt with in a manner that will not result in fragmentation in the environment, which would result in the POPs being more readily leached. Further investigations into all of the above sources

should be carried out, including the potential for leakage of PVC into the drinking water mains supply.

2.4 Estimation of Microplastic Pollution Load

Microplastic pollution loading from all potential sources was estimated and, in some cases, confirmed from site visits, available literature and interactions with stakeholders during the project workshop; the results are depicted in Figure 2.8. As UWWTPs are receptors of many other sources (see Figure 2.8; Table 2.10), it is estimated and has been confirmed that they are large point sources of microplastics. Microplastics were discovered in both mains water and well water, but the pathways through which they arrived there remain unknown (Table 2.11). However, UWWTP biosolids arising from plants with secondary treatment processes contain 90% of the microplastic waste within the UWWTP and therefore have the highest loading. The pathway from UWWTP biosolids/sludge to freshwater systems remains unknown. Some microplastic pollution receptors, such as landfill and UWWTPs, have the potential to produce additional microplastics as a result of fragmentation.

2.5 Characterisation of the Scale of Sources

The geographic characterisation proposed considers the locations of potential microplastic sources, their scale and their pollution loading (Table 2.12). While most sources are concentrated within urban areas, some (e.g. the spreading of UWWTP biosolids) may also contribute considerably to microplastic pollution in rural areas. Here, UWWTP distributional data was gathered for the following sources: UWWTPs, DWWTPs, UWWTP biosolids, landfill and industries that are known to contribute to microplastic production. Sources of information are listed in Table 2.2. These sources were ranked and scored. The total scores were then calculated within a 5 km grid using the geographic information system (GIS) to show the overall exposure rating within each water catchment area. As DWWTP occurrence was dense, this was dealt with separately so that the results were not skewed. The resulting maps show high exposure in the south-east of the country and at other sporadic points throughout the country (Figure 2.9). On a water catchment level, the Slaney and the Suir had very high exposure ratings, with the Shannon lower, the Barrow

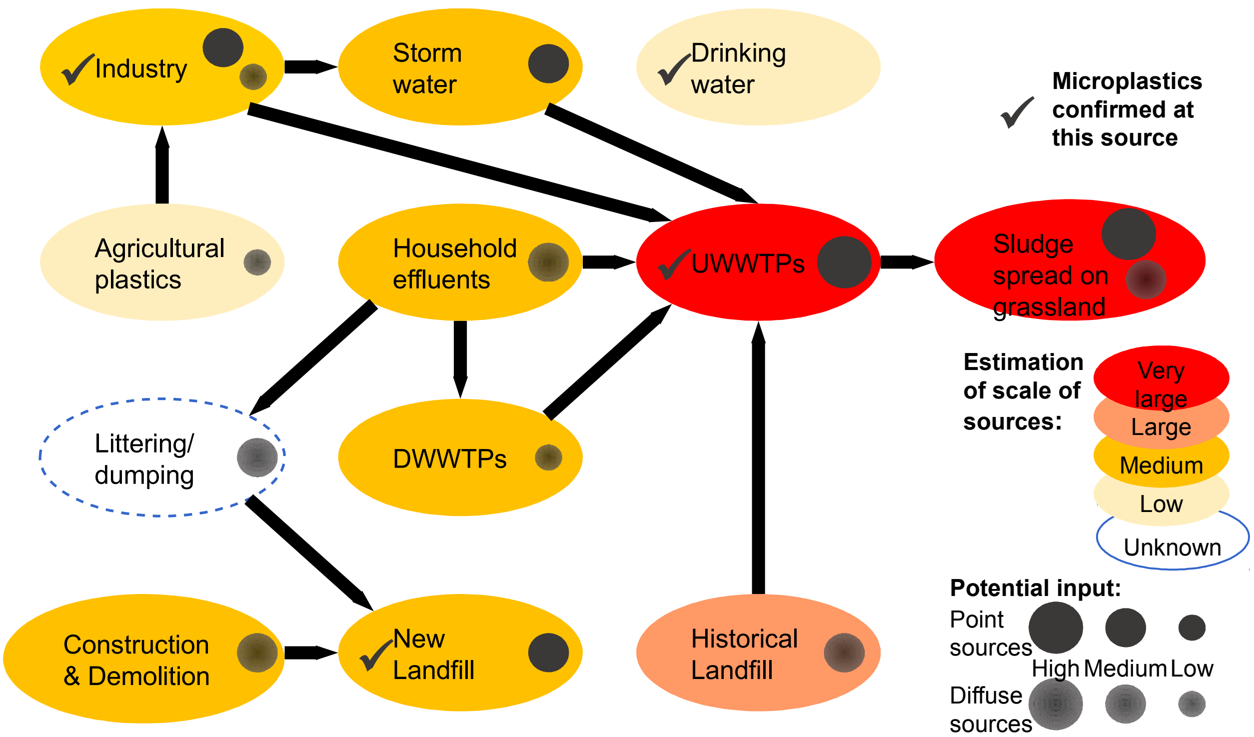

Figure 2.8. Potential microplastic sources in Ireland, estimation of size of sources and scale of potential point and diffuse inputs to freshwater systems. Sources where sampling has confirmed the presence of microplastics are indicated.

Table 2.10. Listings of detailed sources that input to the sources in Figure 2.8

Source	Description
Imported goods	Textiles/clothing, electronics, recycling material
Home industry	Medical devices industry, precision engineering companies, industries for construction, PVC pipe making, PVC/other window manufacturers, insulation manufacturers, textile industries, recycling industries, manufacture of furniture
Agriculture	Silage wrap, fertiliser bags, silo covers, biodegradable films
Household effluents	Clothing fibres, washing machine, cosmetics/toothpaste (microbeads)
Construction/demolition	Insulation, roofing, flooring
Littering/dumping	Food wrapping, cigarette packaging, cigarette butts, other
Household	Nappies, packaging, WEEE waste, clothing, plastic bags
Other sources	Equestrian centres, astroturf sports grounds, road coatings, cemeteries, vehicle tyres

Table 2.11. Summary enumeration of microplastic particles derived from various source and environmental sampling points derived from the EPA study (2015-CCRP-SS.6)

Source class	Sampling point	Number of particles/ range[a]	Comparable result from literature	Source
WWTPs	Influent	97,000/m^3	15,000 ± 225/m^3 (Sweden)	Magnusson and Norén (2014)
	Post-secondary treatment	10,000/m^3	8.25 ± 0.85/m^3 (Sweden); 85/m^3 (Scotland)	Magnusson and Norén (2014); Murphy *et al*. (2016)
	Post reed bed	5,000/m^3	NCA	
	WWTP sludge	2742–15,385/kg dry weight	16,700 ± 1,960/kg dry weight	Magnusson and Norén (2014)
Landfill (waste water)	Boreholes	2500–26,000/m^3	NCA	–
Industry (waste water)	Polymer production (sewer)	51,400/m^3	NCA	–
	Recycling (sewer)	661,000/m^3	200 g/day (Borealis, Austria)	Lechner *et al*. (2015)
Other	Well water	6500/m^3	NCA	–
	Mains water	100–1600/m^3	NCA	–

[a]Range refers to samples that were analysed from multiple sites.
NCA, not currently available.

Table 2.12. Geographical scale of sources with a comparative scale of loadings

Sources	Geographic scale	Loading scale
UWWTP biosolids	Concentrated in the south-east of the country	Very large
UWWTPs	Wide scale with higher proportion in urban areas	Very large
DWWTPS	Wide scale	Medium
Landfill old	Wide scale with higher proportion in urban areas	Large
Industry	Wide scale with higher proportion in urban areas	Medium
Landfill new	Wide scale with higher proportion in urban areas	Medium
Construction	Wide scale with higher proportion in urban areas	Medium
Household	Wide scale with higher proportion in urban areas	Medium
Agricultural plastics	Wide scale	Low

and the Nore having high exposure ratings (Figure 2.10). Although UWWTPs are the main driver of exposure, spreading of sludge in the south-east of the country is mainly responsible for these results (Figure 2.11). The exposure distribution for DWWTPs within these selected catchments indicated some very high exposure areas, for example around Limerick city and Kilkenny (Figure 2.12). Sewage spreading is likely to be high in these regions because of the large areas of flat agricultural land.

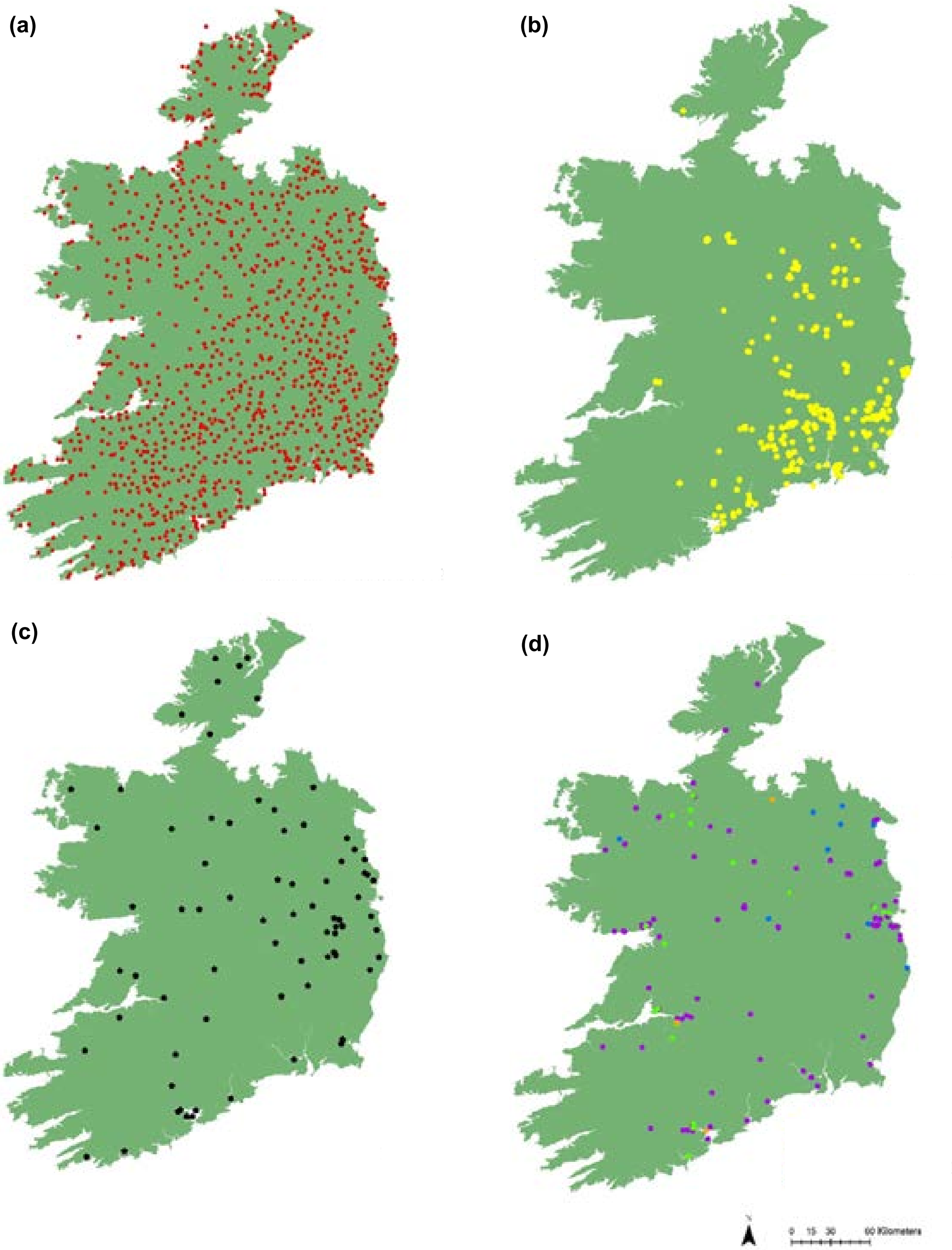

Figure 2.9. Distribution of potential microplastic source sites for (a) UWWTPs (red circles), (b) UWWTP biosolids (yellow circles), (c) licensed landfill (black symbols) and (d) selected industries [recycling companies (blue circles), polymer producers (orange circles), precision engineering companies (light green circles) and medical device companies (purple circles)].

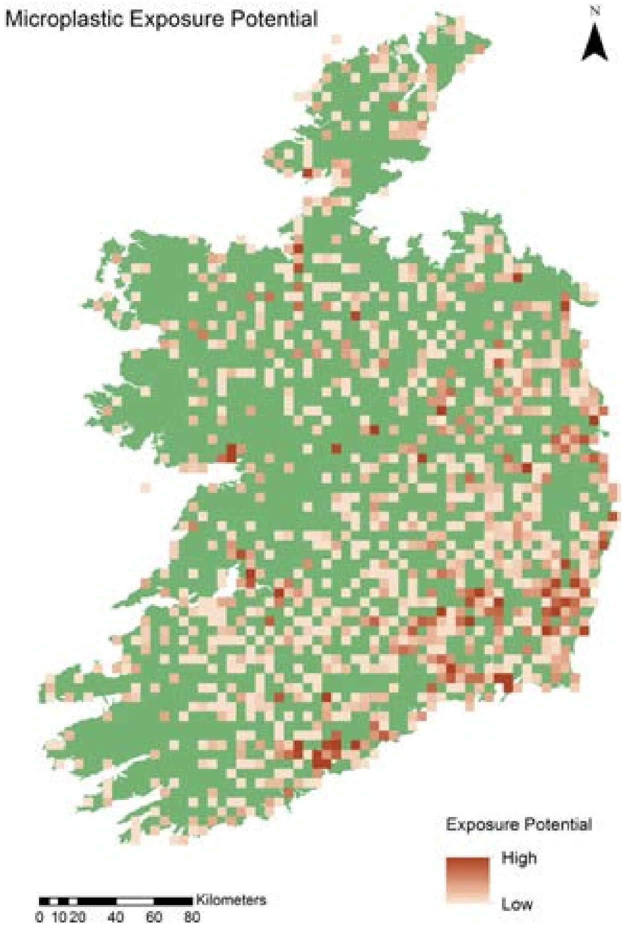

Figure 2.10. Identification of catchments with a high microplastic exposure potential using land use maps and point source information.

2.6 Discussion

The potential sources of microplastics are diverse; however, the main contributors and their scales were estimated and, in some cases, verified in a quantification study (2015-CCRP-SS.6). It was found that industry and landfill are potential point and diffuse sources of microplastics. The introduction of various EU Directives (WEEE Directive, 2012/19/EU; Packaging Directive, 94/62/EC as amended; Waste Framework Directive, 2008/98/EC; End-of-Life Vehicles Directive, 2000/53/EC) has effectively diverted plastic waste from landfill into the recycling industry and this may create a greater risk of microplastic pollution if the recycling processes are not managed effectively, as reported in this study. UWWTPs are receptors for the cumulative loading of microplastics derived from these sources. The partitioning of microplastics within UWWTPs, resulting in the majority of microplastics being spread on agricultural land in Ireland, is crucial for the management of this pollutant. As indications show that treatment of sewage sludge affects the abundance of microplastics, careful selection and modification of these processes may be the key to reducing microplastics in freshwater systems. In Ireland, water catchment areas in the east of the country were estimated to have the highest exposure rates based on high sewage sludge/biosolids spreading in the south-east of Ireland. Currently, there is little known about the transport of microplastics from agricultural land; this is a gap in the knowledge for this pathway. It will be necessary to ascertain the transfer routes to freshwater systems to assess impacts and risks properly.

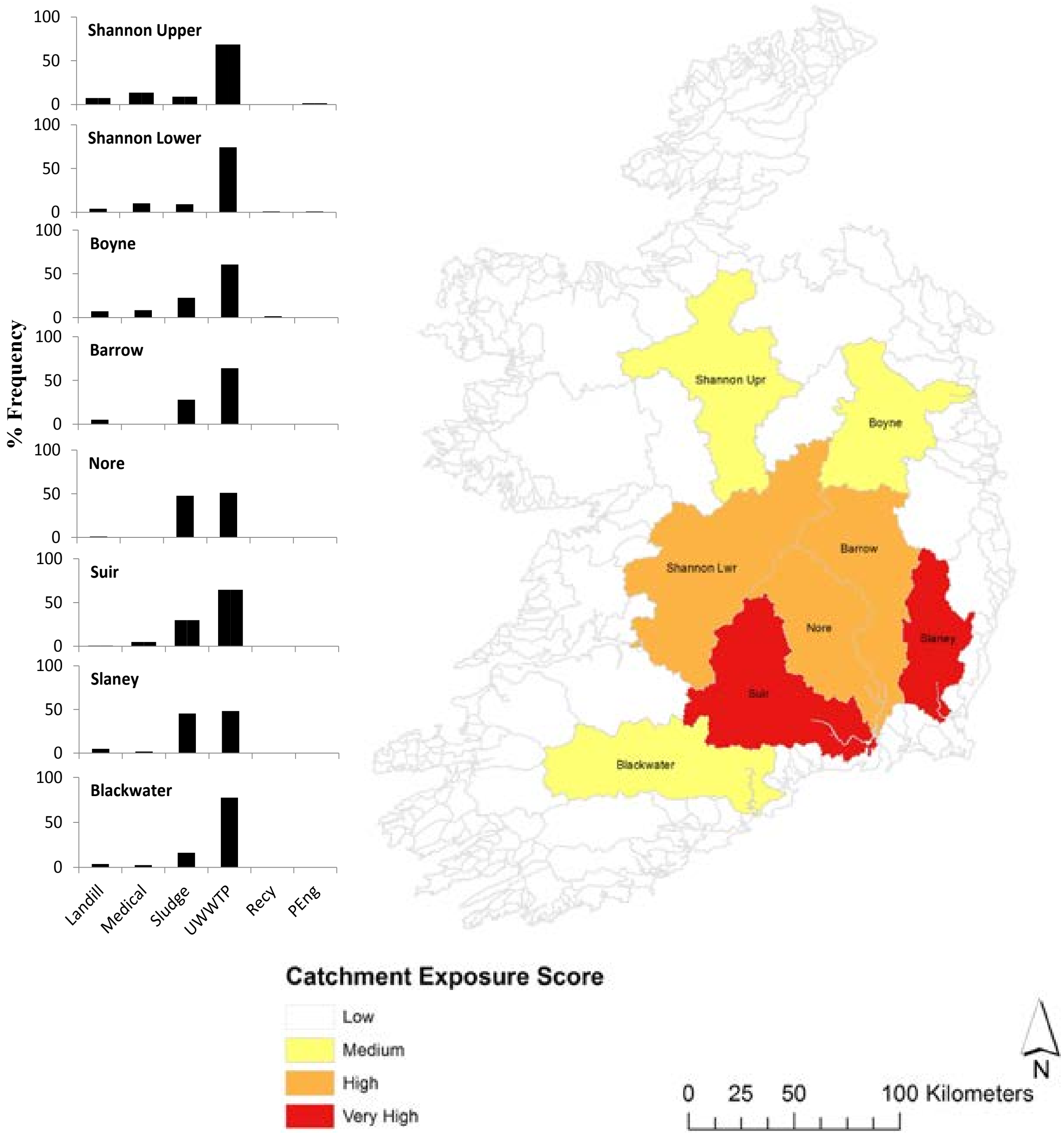

Figure 2.11. Catchment exposure scores and frequencies of landfill, medical devices industries, UWWTPs, sludge spreading, recycling industries (Recy) and precision engineering (PEng).

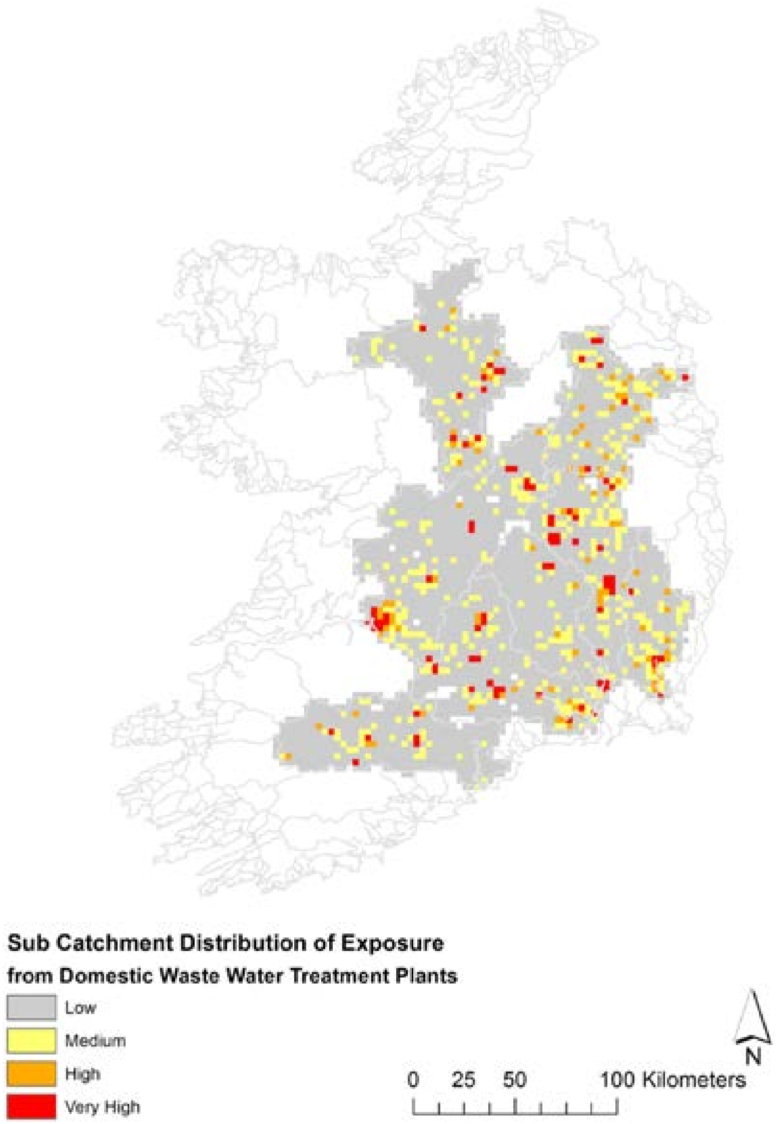

Figure 2.12. Average abundances and corresponding PEs of microplastics.

3 The Environmental Fate of Microplastics in Irish Freshwater Systems

3.1 Overview

The now widely documented presence of microplastics as a pollutant in our rivers and lakes illustrates how important it is to understand the environmental fate of microplastics, i.e. whether they are carried on the surface or in the water column, or incorporated in the benthos or in the biota. Once a pollutant, such as microplastics, enters a water body, there are a number of potential routes it can take and, subsequently, a number of influencing factors that can determine its destination, including, but not limited to the following (see Figure 3.1):

- microplastic properties: density, shape, size;
- physical properties of river/lake bed: gradient, width, depth, length and bottom topography;
- hydrometric properties: flow velocity, residence times, water density, stratification;
- meteorological conditions: wind; and
- biological interactions: biofouling of microplastic particles, ingestion by fauna.

The typical geography and dynamics of freshwater bodies, such as rivers, will show correlations between the transport mechanisms of microplastics and of sediments, because both are influenced by the stage of river or area of a lake they enter. As with sediment particles, high-speed river flow in the early upper reaches is dominated by erosion and this flow will transport both microplastic particles that are buoyant and those that are susceptible to resuspension. This is because of the strength with which the water moves through these areas to the mouth of a lake or to the more mature stages of the river, the mid and lower courses, where most of the deposition of sediments typically occurs (Figure 3.2).

3.2 Potential Transport Routes of Microplastics in Irish Freshwater Systems

In Ireland, the relatively small rivers and large lakes mean that the physical forces acting on the surface of rivers and larger lakes probably result in distinct surface microplastic transport routes between these systems. On larger lakes, such as Lough Ree, Lough Derg and Lough Corrib, wave energy, wind and circulation of currents is likely to contribute to the transport of microplastics.

Dams on the Shannon and on the Lee may provide microplastic fluxes and possibly sinks in the area of silt build-up. At Parteen Weir, Leixlip Dam and Poulaphuca Dam, sediment build-up of over 3 m had accumulated below the intake gate and along the dam wall. As water intake was becoming restricted,

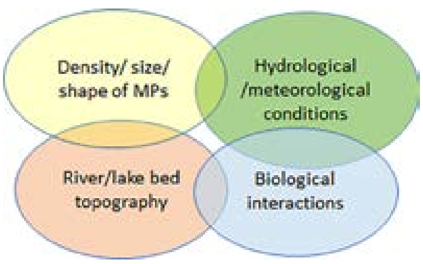

Figure 3.1. (above) A conceptual diagram depicting the interactions between the principal factors driving microplastic dispersal.

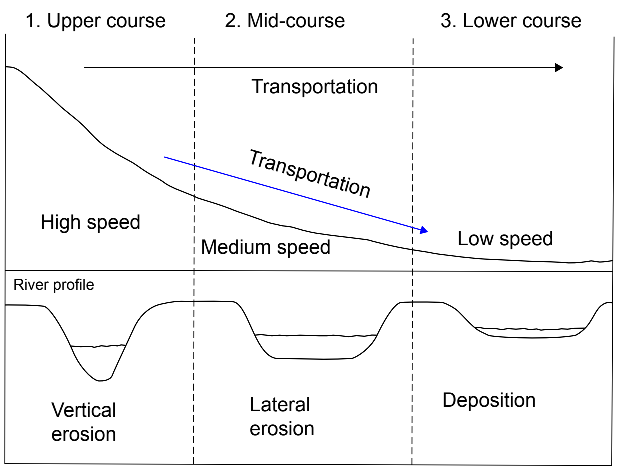

Figure 3.2. (right) A schematic diagram of a river profile, depicting gradients and deposition processes.

removal of this silt was necessary between 2009 and 2012 (ESB, personal communication). Given the potential sources of microplastics in Ireland (Chapter 1), Figure 3.3 depicts the estimated likelihood of microplastic pollution being retained in freshwater systems or transported to marine environments. For example, the discharge of buoyant microplastics from UWWTP effluent that enters a fast or medium flowing river without lakes or dam structures could result in the rapid passage of microplastics to the marine environment, whereas microplastics in heavier sludge entering the lower river course may be deposited in the flood plains (Figure 3.3). Deposition is likely to occur:

- at the entrance of fast-running rivers into lakes;
- in lakes that have sewage sludge input;
- in small lakes with long residence times;
- on the exposure shore on larger lakes that have UWWTP input;
- on flood plains when the water recedes;
- in front on dam walls, where a high amount of siltation occurs; and
- in front of weirs, where flow is reduced.

Deposited particles can either remain in the sediment, becoming entrained in the benthos, or can be resuspended through physical processes (turbulence) or through biological interactions (fish ingestion).

3.3 The Environmental Fate of Microplastics in the Slaney River Catchment Area

The Slaney river basin district was identified as having potentially high microplastic exposure (Figure 3.4). This is as a consequence of the high density of UWWTP biosolid application sites and the presence of landfill activities and UWWTPs (Figure 3.4). It is likely that the lighter particles derived from UWWTPs in the upper reaches of the catchment will be transported downstream as a result of high flow velocities (Figure 3.2). Reduction in flow velocity as the lower order rivers enter the Slaney may lead to the deposition

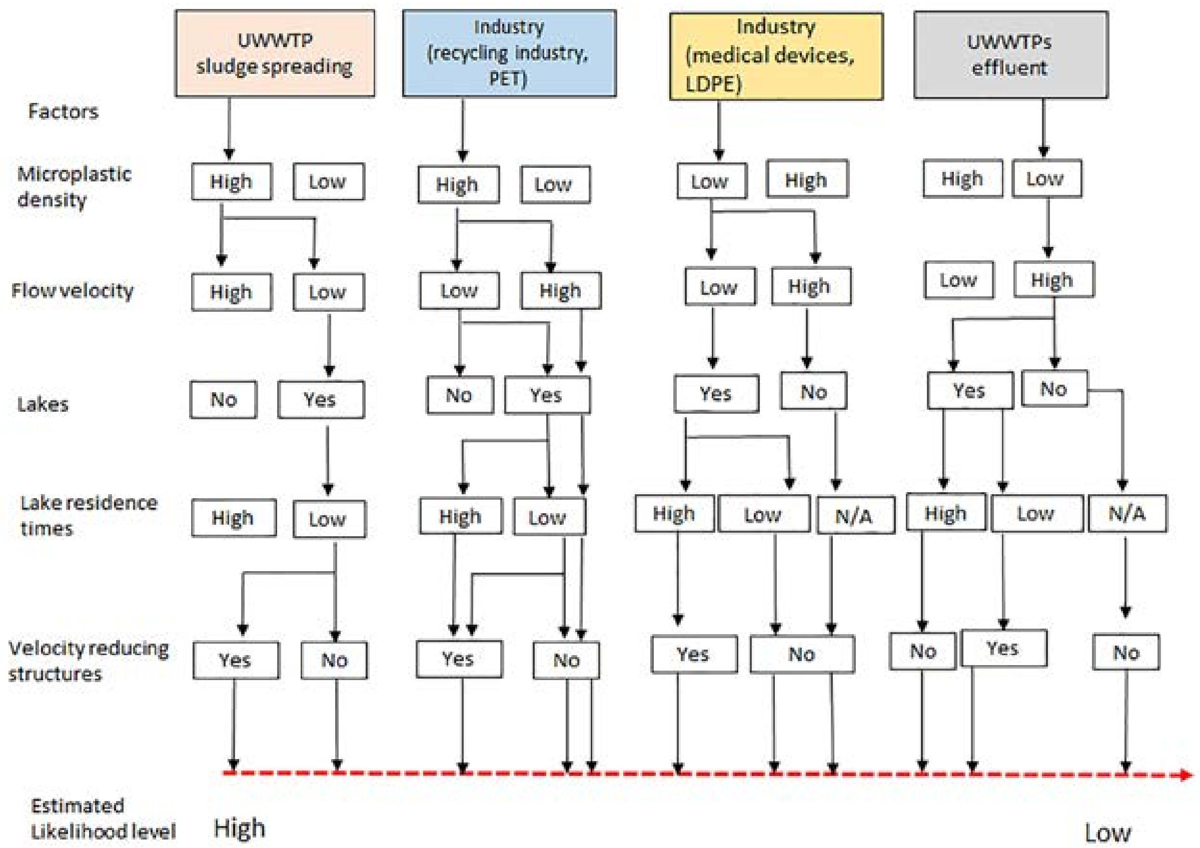

Figure 3.3. Level of likelihood of microplastics being retained in freshwater benthic environments based on microplastic density and physical forces, including flow velocity, the presence of lakes, residence times and the presence of velocity-reducing structures.

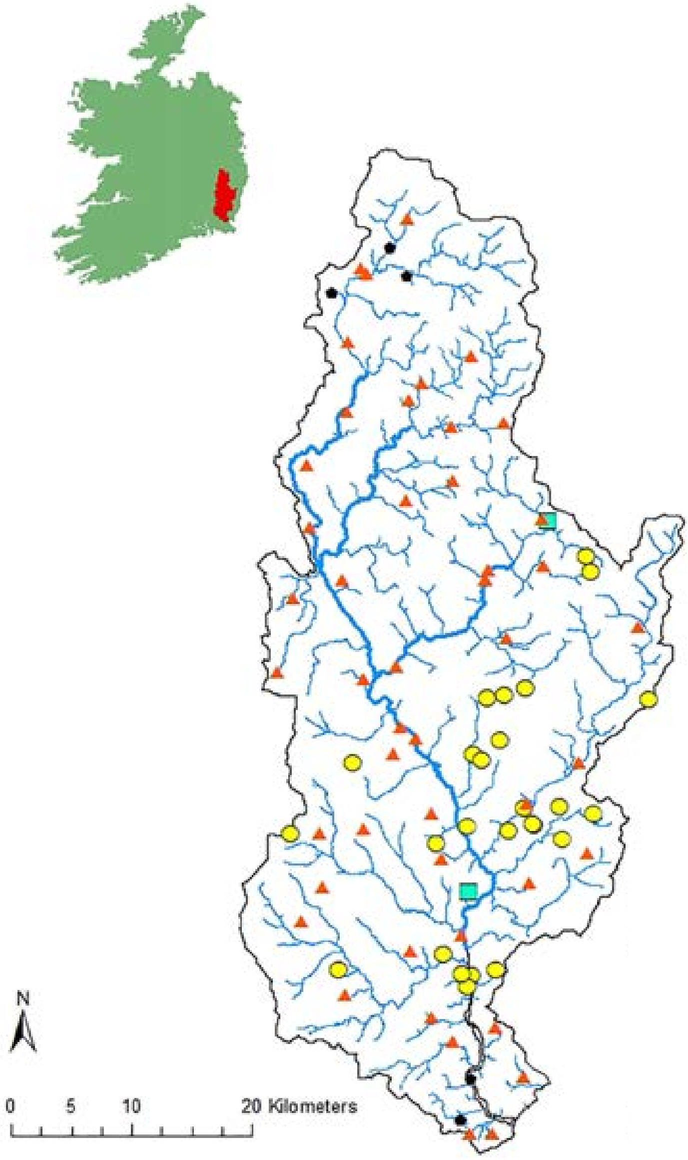

Figure 3.4. Map of Slaney catchment with potential microplastic source input. Sources: landfill (black symbols); medical industry (green squares); UWWTP sludge application (yellow circles); UWWTPs (orange triangles).

of microplastics at those points. The increased frequency of UWWTP biosolid applications containing denser particles in the mid- to lower-catchment areas increases the potential for microplastics to be deposited into the benthic layer (Figure 3.5).

3.4 Conclusion

Factors determining the environmental fate of microplastics in freshwater systems are complex and more knowledge is required to fully understand the mechanisms involved.

This study has allowed us to make some crude estimations of the environmental fate of microplastics based on what we know about source characteristics and the transport mechanisms in freshwater. Because of the denser nature of microplastics that are derived from recycling industries and UWWTP biosolids applications, these will more likely reside in freshwater systems than be transported to marine environments. However, multiple physical and biological forces can influence the transport mechanisms.

A closer look at the Slaney river catchment basin shows the potential for the deposition of microplastic

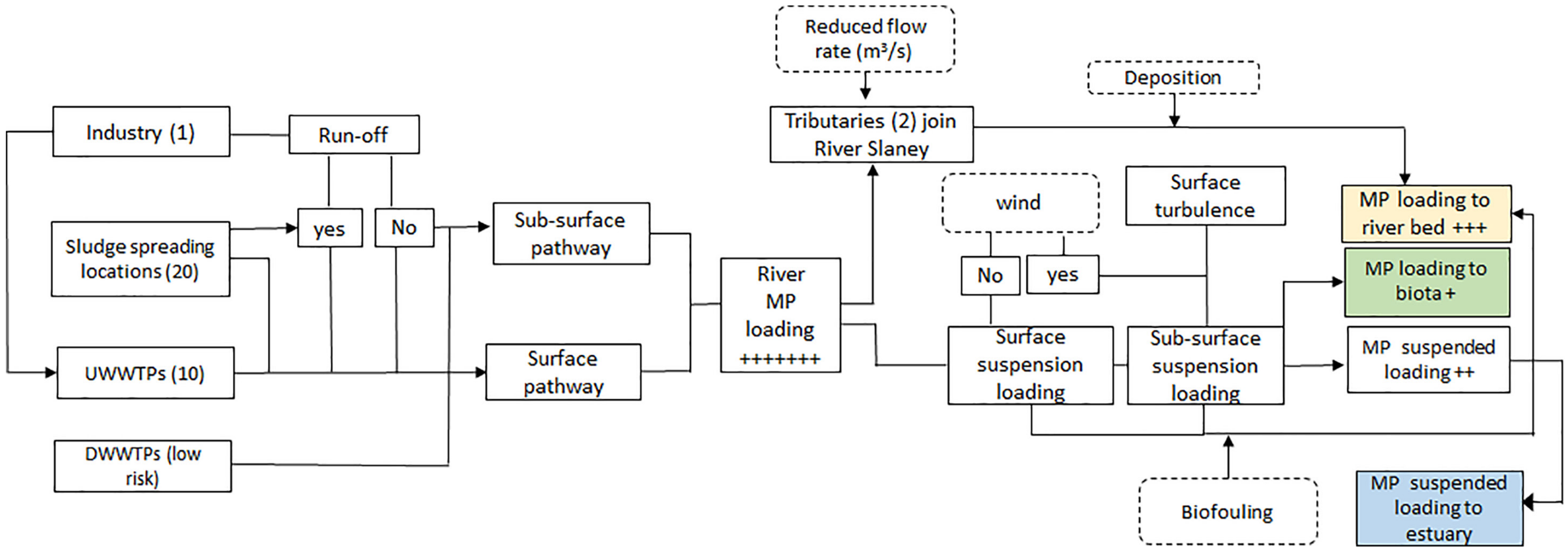

Figure 3.5. Conceptual model of microplastic transport and fate within the Slaney river catchment area.

pollution in the lower reaches of the River Slaney; this can be primarily attributed to land application of UWWTP biosolids. It is therefore vital that we that we gain further knowledge regarding the pollution pathway of land-spread biosolids into freshwater environments.

4 Potential Impacts for Human Health, Priority Species and Habitats

4.1 Overview

Microplastics have the potential to enter a variety of freshwater habitats through surface and ground waters (see Chapter 2). Given the potential to impact human health, biota and habitats, it is important to investigate the pathways through which microplastics could be ingested. A wide range of protected freshwater taxa are currently exposed to microplastics, from water beetles, damselflies and dragonflies, to fish, birds and mammals. Evidence exists for impacts to species in laboratory-based trials and the presence of microplastics has been documented in a wide variety of marine organisms, and to a lesser extent freshwater organisms, at various trophic levels. This study investigates the potential pathways that can result in exposure to humans, priority species and habitats.

4.2 Potential Exposure Through Ingestion by Humans

The ways in which humans can ingest microplastics include the consumption of species that have been exposed to microplastics, direct or indirect consumption of water containing microplastics and accidental ingestion through recreational activities, for example bathing (Figure 4.1).

4.2.1 Microplastics in edible freshwater species

In Ireland, salmon, trout, pike and perch are the species of freshwater fish that are eaten. Although it is apparent that microplastics are present in a wide range of freshwater fish, there is no evidence that microplastics are present in organs other than the digestive system. While the potential of microplastic ingestion through the consumption of contaminated species in Ireland remains a possibility, the scale is thought to be very low without further evidence.

4.2.2 Recreational activities and microplastics

Microplastics do not permeate the skin; therefore, this is not a likely pathway of exposure for humans. However, recreation-associated activities could result in the ingestion of microplastics that are present in surface waters. Bathing and falling into waters during activities increases the potential for ingestion of microplastics. This is attributed to the known positive buoyancy of some microplastics and their occurrence in the surface or subsurface layers.

Estimates of microplastic particle densities of 44/m^2 in surface water in a remote lake and up to 463/m^2 near an industrial area in the Laurentian Great Lakes in Canada have provided a realistic range of microplastic particle densities present in the surface of lake waters (Eriksen *et al*. 2013; Free *et al.*, 2014).

4.2.3 Microplastics in drinking water

Microplastics can be ingested directly or indirectly through drinking water or through the consumption of food prepared using drinking water. On a European level, Ireland's abstraction of freshwater for drinking supply per inhabitant is high (Figure 4.2). Drinking water quality and water used for the food processing industry in the EU is regulated by the Drinking Water Directive 98/83/EC (1998), which ensures that water is treated to meet the requirements of this Directive. Public water supplies provide water for 83.3% of the population in Ireland and are regulated by the EPA in accordance with Drinking Water Regulations (S.I. 122 of 2014), whereby microbial, chemical and indicator parameters (e.g. for *Escherichia coli*, lead, turbidity and pesticides) are tested to ensure that drinking water is clean and safe for human consumption (EPA, 2015). Water supplies exempt from this legislation include private wells; although their owners are advised to test their water and employ treatment if necessary, they are not obliged to do so (Table 4.1). Private wells supply over 10% of Ireland's population.

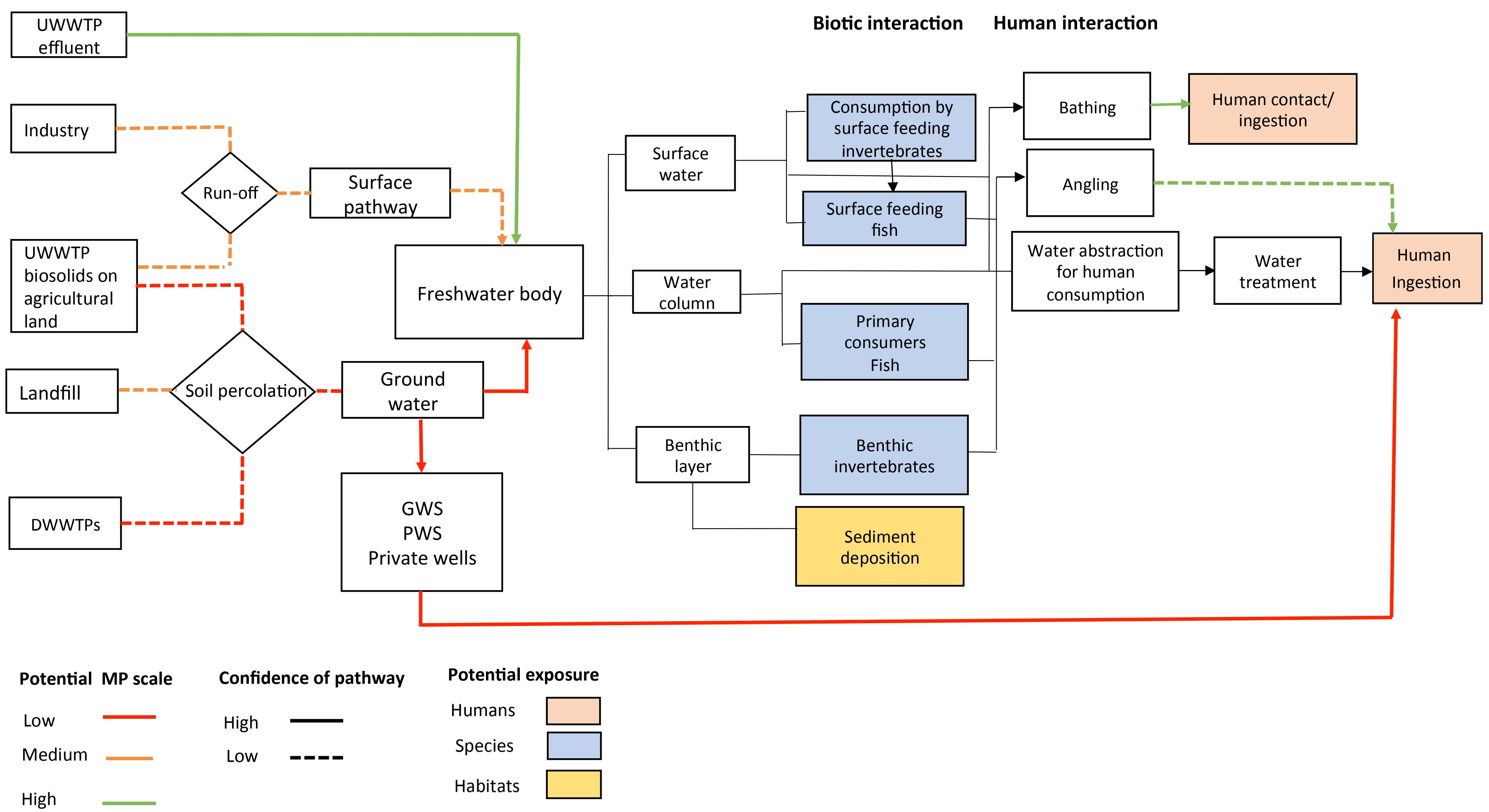

Figure 4.1. Schematic representation of potential microplastic pathways to humans and biota, indicating scale (abundance: low, medium, high) and confidence of pathway (high, low). GWS, ground water supply; MP, microplastics; PWS, public water supply.

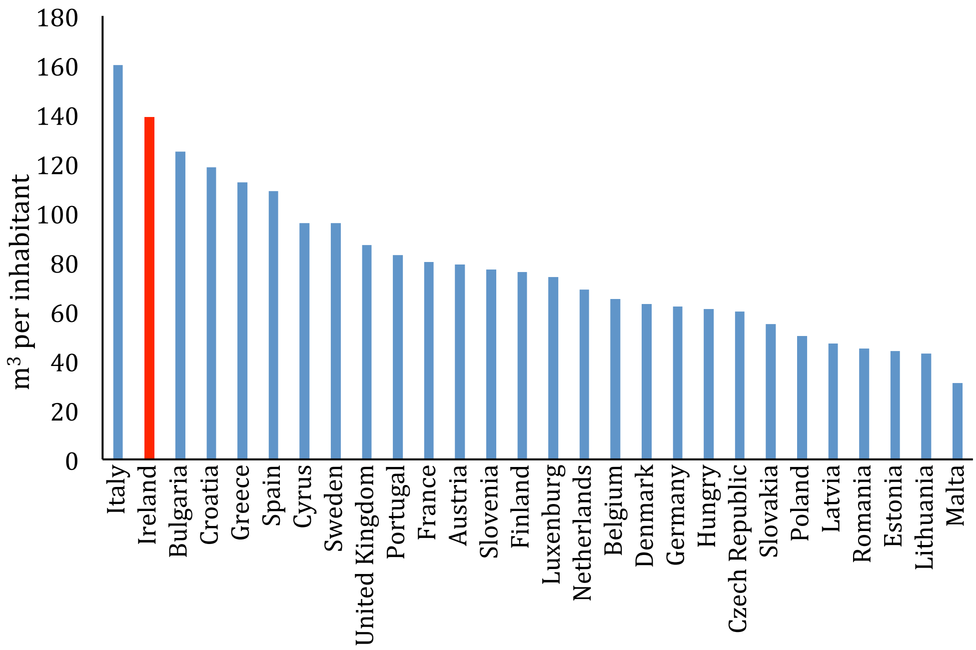

Figure 4.2. Volume (m³ per inhabitant) of freshwater abstraction by public water supply across EU Member States for 2007–2012.

Table 4.1. Supplies of freshwater, sources and the percentage of the population served

Supply type	Supplier/supplying	Supervisory authority	Water supply source	Population served (%)
Public water supply	Irish Water	EPA	Ground or surface water or mixed source	81.9
Public group water schemes (supplied by PWSs)	Local group	Local authorities	Ground or surface water or mixed	1.8
Private group water schemes	Local group	Local authorities	Ground or surface water	4.2
Small private supplies (part of a commercial or public activity) (0.8% of population	Commercial/public activity	Local authorities	Ground or surface water	0.9
Exempted supplies[a]	Individual supplier	Exempt	Mainly ground water supply, private wells or boreholes	11.1

[a]Exempted supply means a supply of water that constitutes an individual supply of less than 10 m³/day on average or serves fewer than 50 persons and is not supplied as part of a commercial or public activity, or is used exclusively for purposes in respect of which the relevant supervisory authority is satisfied that the quality of the water has no influence, either directly or indirectly, on the health of the consumers concerned (EPA, 2014b).

PWS, public water supply.

Results from a study quantifying microplastics (2015-CCRP-SS.6) recorded microplastic concentrations of up to 6500/m³ in untreated private well water samples and 1600/m³ in public water supplies. These concentrations could potentially result in the ingestion of approximately 12 microplastic particles per day for well water and three particles per day for public water supplies in Ireland, based on 2 litres of water ingested per person. Furthermore, boiling of water prior to consumption could potentially increase the risk of cumulative impacts, as boiling may induce leaching of contaminated materials and plasticisers from microplastics.

Current treatment process in removing microplastics

Treatment of public water supplies can include screening, flocculation, sedimentation/floatation, filtration, disinfection, pH correction and fluoridation, but many only have disinfection as a treatment. The extent to which these full treatment steps trap microplastics is unknown; however, various possibilities are discussed here and shown in Figure 4.3. The range of sand material (150–350 μm in size) used during the filtration process removes particles down to 10 μm diameter (Ratnayaka *et al.*, 2009). This filtration is likely to be effective for fragments, but may be less effective for the majority of fibres, which have a diameter of less than 10 μm. This is significant, as fibres are currently the most commonly found shape of microplastic found in the environment (Lusher *et al.*, 2014). Disinfection by the addition of chlorine dioxide or ozone, or using UV systems, may have effects on the microplastics that have passed through the treatment system. The strong oxidising capacity of chlorine dioxide may induce degradation, resulting in the release of organic contaminants or monomers.

Results from the microplastics quantification study (2015-CCRP-SS.6), in which microplastic fibres were found in the public water supply (1600/m^3), used samples that came from a lake used for water abstraction. The treatment process for this water involved fine screening (5 mm), coagulation,

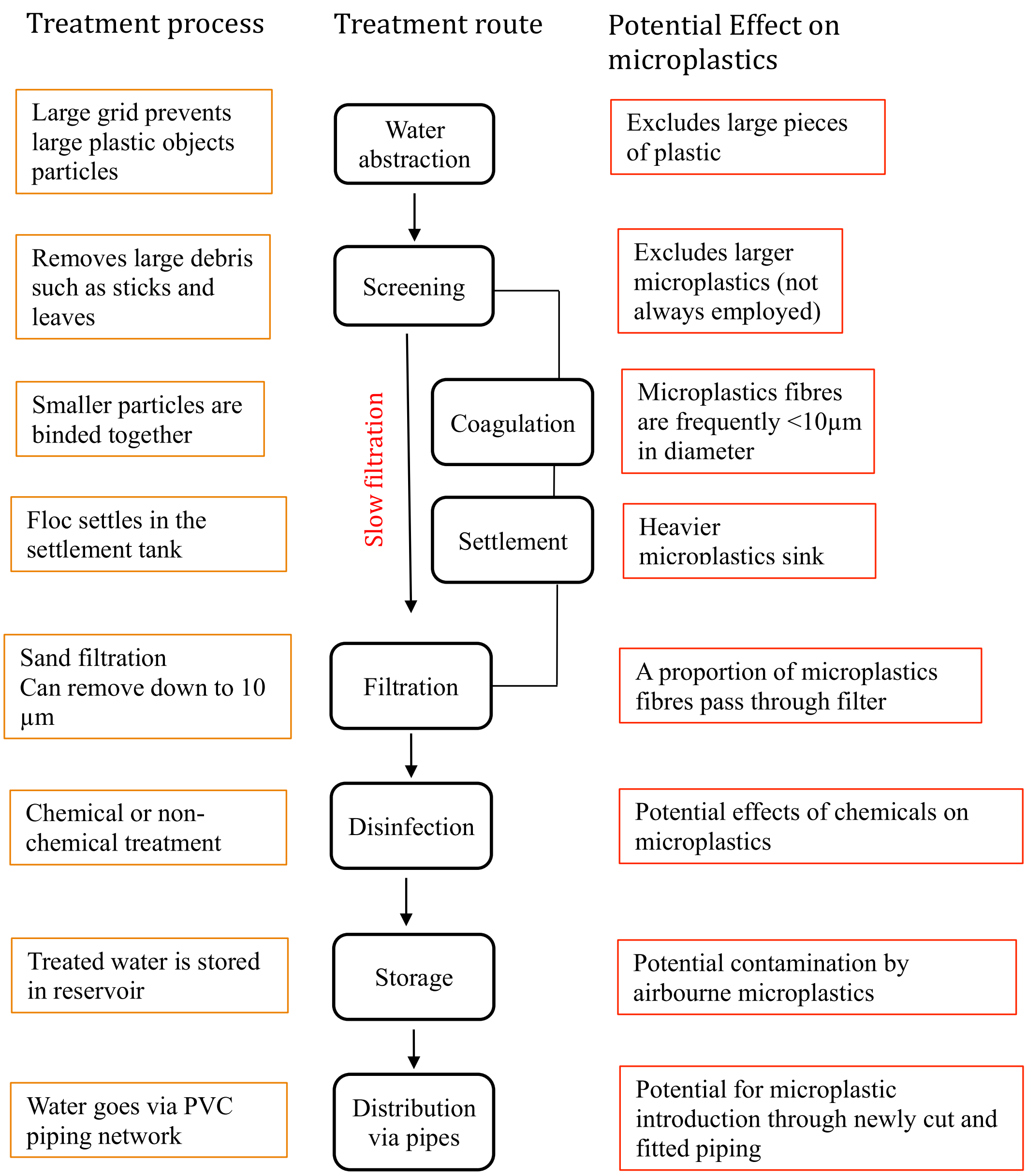

Figure 4.3. Water treatment regimes in Ireland and their potential efficacy in removing microplastics.

settlement, pH correction, rapid-gravity filtration, UV treatment, disinfection and fluoridation. The ability of fibres to pass through a treatment system that employs possibly the most rigorous treatment process that is available in all 900 public water supply plants in Ireland, may indicate that systems that employ fewer treatment stages may not be as efficient in capturing microplastics as this particular plant. A more robust study is required to investigate the efficacy of a range of public water supply treatment systems in removing microplastics.

4.3 Potential Impacts to Priority Habitats and Species

4.3.1 *Impacts to habitats*

Microplastics derived from various sources have the potential to enter surface and ground waters, and the interaction of biological and physical forces will determine where they can or pass though and where they will accumulate (see Chapter 2). Effects on habitats may be most pronounced as a result of deposition and incorporation of microplastics into the benthos (Figure 4.1). Leeching of organic pollutants and plasticisers here could produce toxic effects on primary producers.

As microplastic exposure is expected to be higher in the areas where there are higher rates of sewage biosolid spreading and more UWWTPs, lowland species have a greater potential exposure than those in upland habitats. However, upland lakes, where tourism is significant, may also be affected, as found in a study of a remote Mongolian lake (Free *et al*., 2014).

The probability of these effects occurring in aquatic protected habitats increases with increased residence times and with decreased flow, which both facilitate deposition. Table 4.2 shows protected habitats that may be susceptible to microplastic pollution, the pathway involved and the likelihood of deposition.

4.3.2 *Impacts on species*

Microplastics have been found throughout the food web, spanning several phyla. In addition, impacts from microplastic pollution have been recorded, under laboratory conditions, to a range of biota. Microplastics may be directly consumed from the benthos, water column and surface, as well as indirectly consumed through the consumption of prey or food items that are themselves contaminated with microplastics.

A list of protected species thought to be susceptible to microplastic pollution is presented in Tables 4.3 and 4.4.

Table 4.2. Habitats protected under the Habitats Directive

Protected habitats potentially impacted by microplastic pollution	Designations	Potential pathway	Likelihood of MP deposition
Turloughs	SAC, Biogenetic reserve Natural World Heritage Site	Ground water, Surface water	High
Alkaline fens	SAC	Ground water	High
Alluvial meadows of river valleys	SAC	Surface water	Medium
Dystrophic lakes	SAC, Ramsar site	Surface water	Medium
Naturally eutrophic lakes	SAC, Ramsar site	Surface water	Medium
Vegetated water courses of plain to montane levels	SAC	Surface water	Low
Vegetated rivers with muddy banks	SAC	Surface water	Low
Oligotrophic waters containing very few minerals of sandy plains	SAC, Ramsar site	Surface water	Medium
Mesotrophic standing waters with vegetation	SAC, Ramsar site	Surface water Ground water	High
Hard oligo-mesotrophic waters with benthic vegetation	SAC, Ramsar site	Surface water	Medium

SAC, special areas of conservation.

Table 4.3. Molluscs, fish and amphibians with protection/conservation status (CR, critically endangered; EN, endangered; VU, vulnerable; LC, least concern), legal status under the Habitats Directive (listed as Annex II, IV and V species) and the strength of the microplastic pollution pathway. Strength is based on habitat type, feeding strategy and occurrence in areas judged to have exposure potential

Taxa	Species	Legal status under the HD	Conservation status	Habitat type	Feeding strategy	Occurrence in medium to high MP exposure catchments (Y/N)	Potential strength of pathway (high, medium, low)
Molluscs	Freshwater pearl mussel (*Margaratifera margaratifera*)	II, V, WA[a]	CR	Well-oxygenated rivers	Benthic substrate, water column	Y	High
	Nore freshwater pearl mussel (*Margaratifera durrovensis*)	II, V, WA[a]	CR	Hard water, Nore river only	Water column, sediment	Y	High
	Artic alpine pea mussel (*Pisidium conventus*		CR	One or two lake sites (Donegal and Brandon, Kerry)	Benthic substrate	N	Low
	Iridescent pea mussel (*Pisidium pulchellum*)		EN	Calcareous lakes, streams, canals	Benthic substrate, water column	N	Medium
	Glutinous snail (*Myas glutinosa*)		EN	Lakes, streams, canals	Benthic substrate	Y	Medium
	Sand-bowl amber snail (*Quickella arenaria*)		EN	Sparsely vegetated flood plains of larger lakes	Benthic substrate	Y	High
	Desmoulin's whorl snail (*Vertigo moulinsiana*)	II, V, WA[a]	EN	Calcareous lowland, wetlands, fens and marshes with tall vegetation	Benthic substrate	Y	Medium
	Moitessier pea mussel (*Pisidium moitessierianum*)		EN	Slow-flowing, moderately calcareous rivers	Benthic substrate, sediment	Y	Medium
	False orb pea shell (*Pisidium pseudosphaerium*)		EN	Clean standing water, canals	Benthic substrate	Y	Medium
	Whirlpool ram's horn (Anisus vortex)		VU	Streams, rivers lakes, canals	Benthic substrate	Y	Medium
	Moss bladder snail (*Aplexa hypnorum*)		VU	Ditches, ponds, pools	Benthic substrate	Y	Medium
	Lilljeborg's pea mussel (*Pisidium lilljeborgii*)		VU	Deep clear water	Benthic substrate	N	Medium
	Beautiful grass snail (*Vallonia pulchella*)		VU	Flood plains of lakes and rivers	Benthic substrate	Y	High
	Marsh whorl snail (*Vertigo antivertigo*)		VU	Fens, lake shores and river banks	Benthic substrate	Y	High
	Lilljeborg's whorl snail (*Vertigo lilljeborgi*)		VU	Lakeshore flushes	Benthic substrate	N	Low
	Duck mussel (*Anodonta anatine*)		VU	Lowland rivers and lakes	Benthic substrate	Y	Medium

Table 4.3. Continued

Taxa	Species	Legal status under the HD	Conservation status	Habitat type	Feeding strategy	Occurrence in medium to high MP exposure catchments (Y/N)	Potential strength of pathway (high, medium, low)
Molluscs	Swan mussel (*Anodonta cygnea*)		VU	Lowland rivers and lakes	Benthic substrate	Y	High
	Lake orb mussel (*Musculium lacustre*)		VU	Vegetated margins of rivers	Benthic substrate	Y	High
	Swamp orb mussel (*Sphaerium nucleus*)		VU	Transition mires, turloughs	Benthic substrate	Y	High
Fish	European eel (*Anguilla anguilla*)		CR	All types of benthic habitats	Benthic substrate	N	Low
	Pollan (*Coregonas autumnalis pollan*)	V	EN	Found in upper and lower Shannon basins	Surface invertebrates, water column	Y	Medium
	Twaite shad (*Alosa fallax*)	II, V	VU	Feeding on Chironomid larvae	Benthic substrate	Y	Low
	Killarney shad (*Alosa fallax killarnensis*)	II, V	VU	Feeding on Chironomid larvae	Benthic substrate	N	Low
	Atlantic salmon (*Salmo salar*)	II, V[b]	VU[b]	Young feed on invertebrates	Water column	Y	Medium
	Arctic char (*Salvelinus alpinus*)		VU	Upland lakes, mostly in the west	Water column, substrate	N	Low
	River lamprey (*Lampettra fluviatilis*)	II, V	LC	Juveniles burrow in river beds	Water column, substrate	Y	Medium
	Brook lamprey (*Lampettra planeri*)	II	LC	Juveniles burrow in river beds	Water column, substrate	Y	Medium
Crustaceans	White-clawed crayfish (*Austropamobius pallipes*)	II, V	EN	Hard-water rivers, canals, lakes	Substrate	Y	High
Amphibians	Common frog (*Rana temporaria*)	V	LC	Widespread	Water column, substrate	Y	Low
	Common newt (*Triturus vulgaris*)	WA[a]	LC	Still water margins, midland and coastal habitats	Surface, water column, substrate	Y	Medium
Mammals	Eurasian otter (*Lutra lutra*)	II, IV WA[a]	NT	Highland and lowland lakes, rivers, streams	Fish, amphibians, birds, insects	Y	High

[a]WA indicates that the Wildlife Act, 1976 (S.I. 282/1980) is relevant to the legal status.

[b]Refers to freshwater locations.

MP, microplastic; HD, Habitats Directive.

Table 4.4. Potential routes of microplastic exposure for some birds protected under the Birds Directive. Legal status as categorised by Annex number (I–III) and section (in brackets) (A,B). Conservation status refers to birds of conservation concern in Ireland (BoCCI; Lynas *et al.*, 2009)

Potential route of exposure	Common name	Scientific name	Legal status under the BD (Annex number)	Conservation status		Potential pathway	Feeding strategy
				Red	Amber		
Surface water	Pintail	*Anas acuta*	II(A), III(B)	X		Shallow water, lakes, ponds, flood plains	Dabbling
	Shoveler	*Anas clypeata*	II(A), III(B)	X		Turloughs, flood plains	Dabbling
	Teal	*Anas crecca*	II(A), III(B)		X	Lakes, pools, upland streams	Dabbling
	Widgeon	*Anas penelope*	II(A), III(B)		X	Lakes, pools	Dabbling
	Mallard	*Anas platyrhynchos*	II(A), III(A)			Lakes, pools	Dabbling
	Red-necked phalarope	*Phalaropus lobatus*	I	X		Unknown	Dabbling
Sub-surface water	Tufted duck	*Aythya fuligula*	II(A), III(B)		X	Lowland lakes, slow-flowing rivers, canals	Diving
	Pochard	*Aythya ferina*	II(A), III(B)	X		Large shallow eutrophic lakes	Diving
	Scaup	*Aythya marila*	II(B), III(B)			Large shallow eutrophic lakes (mostly coastal)	Diving
	Kingfisher	*Alcedo atthis*	I	X		Lowland lakes and rivers	Diving
Benthic/benthopelagic	Common scoter	*Melantita nigra*	II(II), III(B)	X		Lakes up to 20 m deep (bivalve molluscs)	Diving
	Water rail	*Rallus aquaticus*			X	Shallow water	Benthic feeder
	Snipe	*Gallinago gallinago*	II(A), III(B)		X	Shallow water	Mud in freshwater
Top trophic predator	Hen harrier	*Circus cyaneus*	I	X		Mostly lowlands	Terrestrial-based
	Golden eagle	*Aquila chrysaetos*	I	X		Mostly lowlands	Terrestrial-based

BD, Birds Directive.

Potential impact on protected molluscs

Bivalves are non-selective filter feeders and will therefore filter microplastics out of the passing water (Von Moos *et al*., 2012). It can therefore be assumed that freshwater bivalves may be impacted in locations with substantial densities of microplastics. Freshwater pearl mussels (*Margaratifera margaratifera*) have become increasingly threatened as a result of habitat loss; this species occurs in only 139 rivers in Ireland (IUCN, 2015) and the hard-water form *Margaratifera durrovensis* occurs only in the Nore catchment. They are suspension feeders that are similar to the marine species *Mytilus edulis* and *Modiolus modiolus* and can filter up to 50 L per day. Potential impacts from microplastics could occur through a variety of pathways. As *Margaratifera* spp. are very sensitive to chemical change, chemical toxicity may induce an inflammatory response if microplastics are present in sufficient densities. Such effects have been documented in *Mytilus edulis* during laboratory trials. Contamination of gravel substrates during the sedentary stage of *Margaratifera* spp. (when the mussels are two-thirds buried) could potentially cause toxicity and clogging of sediments, leading to reduced oxygen levels; this is a scenario that is well documented as detrimental to *Margaratifera*. Microplastic deposition will probably occur as waters recede from flood plains. The protected bivalve species present in these habitats and that are therefore at risk from microplastic pollution include the sand-bowl amber snail *Quickella arenaria* and the grass snail *Vallonia pulchella*. In turloughs, the species that may also be impacted include the swamp orb mussel, *Sphaerium nucleus* (Table 4.3).

Potential impact on some protected fish species

The lifestyle and feeding habits of some protected fish species increases their susceptibility to microplastic pollution. For example, the burrow behaviour of river lamprey *Lampetra fluviatilis* could increase its susceptibility to microplastic pollution from the benthos. Many species of freshwater fish consume invertebrates that could be vectors for microplastics.

Potential impact on protected birds

As birds occupy high trophic levels, their ingestion of microplastics could include direct as well as secondary ingestion from consumption of contaminated prey species (Verlis *et al*., 2013). Like all species, their potential levels of ingestion of microplastics and the types of microplastics ingested will depend on their feeding strategies and the characteristics of the water in which they feed (see Table 4.4). Although no impacts of microplastics on birds have been documented to date, it is logical that impacts may be similar to those associated with macroplastics in other species, including gut damage (Pierce at al., 2004), and chemical toxicity (Tanaka *et al*., 2013).

Potential trophic transfer of microplastics

The transfer of microplastic pollution across trophic levels has been proven in marine ecosystems between mussels and crabs (Watts *et al*., 2016). The similarity between ecological niches and feeding strategies for species in marine and freshwater environments would suggest that trophic transfer should also occur in freshwater ecosystems. In the water column, planktonic crustaceans such as ostracods and water fleas (*Daphnia magna*) may ingest microplastics (Imhof *et al*., 2013) and then be consumed by planktivorous fish. Some species may be particularly effective vectors for microplastic pollution. For example, the minnow *Phoxinus phoxinus* feeds on plant debris, molluscs and crustaceans in the sediments and is an important component of the diet of larger fish and of many water birds. Minnows are consumed by predatory fish, such as pike (*Esox lucius*). The Eurasian Otter (*Lutra lutra*) is a top predator of freshwater systems (Reid *et al*., 2013) that feeds on a variety of insects, mussels, fish, amphibians and birds. An assessment of otter spraints in the Corrib catchment confirmed the presence of pike and perch (*Perca fluviatilis*) (Breathnach and Fairley, 1993), both species found to have ingested microplastics in studies of Lough Corrib (Figure 4.4; O'Connell, 2015).

4.4 Legislative Implications

The EU Directives relevant to the consideration of microplastic pollution are those implemented to protect human health (Table 4.5) and protect habitats and species (Table 4.6).

4.5 Discussion

As further research is carried out, more definitive assessments of impacts will be published. Based

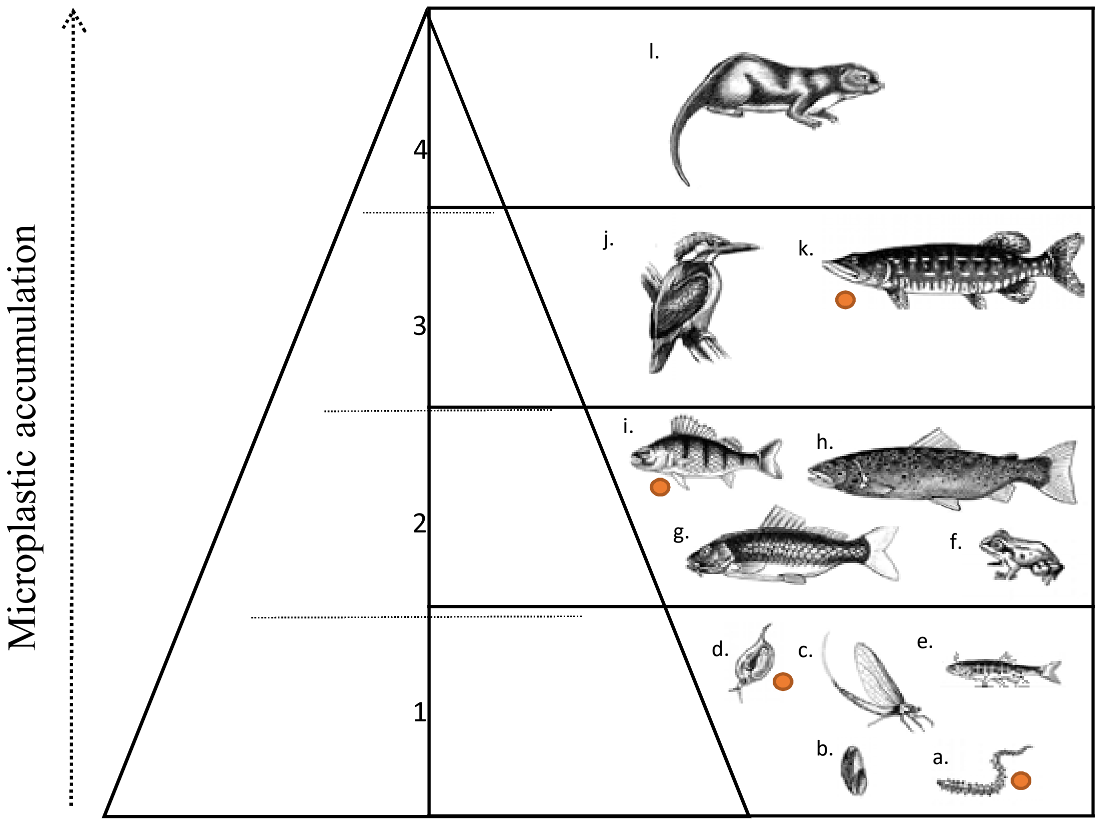

Figure 4.4. Infographic diagram representing the accumulation of microplastics through the trophic levels, using sample species that are potentially affected by microplastic pollution; (a) blackworm; (b) freshwater pearl mussel; (c) mayfly; (d) water flea; (e) minnow; (f) frog; (g) carp; (h) brown trout; (i) perch; (j) kingfisher; (k) pike; and (l) otter. Orange spheres indicate species previously confirmed to contain microplastics. The four zones are specified as follows: (1) large numbers of species, potentially feeding directly on microplastics on the surface or in the sediments; (2) biota that may feed in zone 1; (3) predators that feed on biota in zones 2; and (4) mammals that feed upon biota in zones 2 and 3.

Table 4.5. Legislation relevant to microplastic pollution affecting human health

Legislation	Relevance to microplastic pollution	Potential implications
European Drinking Water Directive (98/83/EC)	Must protect against all potential sources of contamination	Yes
EU Bathing Water Directive (2006/7/EC)	A BWP is required for all designated EU waters, containing details on possible types of pollution that could have a negative impact on human health as a result of bathing (Keswani *et al*., 2016)	Yes

on current knowledge, only potential impacts from microplastics can be defined. However, this study shows that the most likely pathway for microplastic pollution to reach humans in Ireland is through the consumption of water that is abstracted for public and private water supplies. Unfiltered private wells and public water supplies carry the highest risk of microplastic pollution.

Potential impacts of microplastic pollution to humans are possible and these will most probably be localised in the gut, with some possible effects to the immune system. The transfer of organic contaminants that may have been absorbed into the microplastics into the human body is also possible.

Habitats and species are both highly susceptible to microplastic pollution and there is a possibility that the potential impacts will arise from cumulative rather than from episodic exposure. Cumulative impacts will encompass both habitat degradation and potential effects on species viability through, for example,

Table 4.6. Legislation relevant to microplastic pollution affecting priority species and habitats

Legislation	Relevance to microplastic pollution	Potential implications
Habitats Directive (92/43/EEC)	Protection of habitats potentially affected by microplastic pollution	Yes
Birds Directive (2009/147/EC)	Protection of bird species potentially impacted by microplastic pollution	Yes
Water Framework Directive (2000/60/EC)	Identification and monitoring of anthropogenic pressures; requirement to maintain "good status"	Yes
Marine Strategy Framework Directive (2008/56/EC)	Prevention of litter inputs and reduction of litter in the marine environment	Yes

the deposition of microplastics, the leeching of organic pollutants and plasticisers, the degradation of microplastics, ingestion and the species acting as vectors for the bioaccumulation of microplastics up the food chain.

While potential impacts have been discussed within this chapter in order to calculate a more precise impact and subsequent risk to humans, habitats and species, risk assessment should be carried out using empirical data collected from the field as has been carried out for other freshwater pollutants (Albering *et al*., 1999).

To assess the potential impact on humans and species fully, the abundance of microplastics should be measured in water abstraction areas and efficacy of treatment systems should be investigated further; until then it will not possible to determine the likelihood of impacts from microplastics.

5 Risk Appraisal of Potential Impacts of Microplastics on Human Health and Protected Species

5.1 Overview

The potential risks posed by microplastic pollution to human health and to protected species were assessed using information gathered regarding potential sources, pathway, fates and impacts to humans and species, as described in Chapters 2 and 3 of this report.

5.2 Risk Appraisal Approach

The risk rating is calculated as the “likelihood of impact” score multiplied by the “severity of consequence” score (Table 5.1).

This analysis involved the following steps:

- development of consequence scores;
- development of likelihood scores; and
- assignment of risk categories for humans and species.

The risk assessment was carried out for selected protected species. For assessment of impacts to humans, a compilation of very high- to low-risk scenarios were compiled, as little is known regarding the pathway for humans or the inputs required to perform this analysis.

5.3 Potential Risk of Impact to Humans

5.3.1 Methodology

The factors determining the consequence score for human health are described in Table 5.2. As there is no evidence to date from the literature to determine significant or major consequences, only minor and moderate consequences will be used. Factors affecting the likelihood of impact are listed in Table 5.3. However, it should be noted that the proportion of the

Table 5.1. Likelihood and risk rating scores used to calculate the risk rating

Likelihood	Consequence				
	1: Negligible	2: Minor	3: Moderate	4: Significant	5: Major
1: Rare	1	2	3	4	5
2: Unlikely	2	4	6	8	10
3: Possible	3	6	9	12	15
4: Likely	4	8	12	16	20
5: Almost certain	5	10	15	20	25

Risk rating: green, low; yellow, medium; orange, high; red, very high.

Table 5.2. Consequence scores for impacts on human health

Score	Consequence	Descriptor	Determining factor
1	Negligible	Absence of health impacts	No evidence from literature
2	Minor	Minor health implications (irritant)	Evidence from scientific literature, showing irritation to the gut as a result of fluids interacting with the gut wall[a]
3	Moderate	Moderate health implications	Uptake of < 1% into the lymphatic system[b]
4	Significant	Serious health implications	No evidence from scientific literature
5	Major	Life-threatening health implications	No evidence from scientific literature

[a]**Powell *et al*. (2007).**

[b]**Hussain *et al*. (2001).**

Table 5.3. Likelihood scoring of impacts on human health

Factors affecting likelihood of impact	Score	Source data
Exposure in abstraction waters		
Very high	3	Exposure scores as calculated in Chapter 3, based on the presences of landfill, medical devices industries, precision engineering companies, UWWTPs and sludge spreading; distribution of species from http://maps.biodiversityireland.ie/
High	2	
Medium	1	
Water treatment processes		
No treatment (private wells)	3	*Twort's Water Supply* (6th Edition) (Ratnayaka *et al*., 2009); *Drinking Water Report* (EPA, 2014b)
Disinfection only public water supply	3	
Slow sand filtration (public water supplies and most group water schemes)	2	
Public water supplies treated using settlement and filtration	1	
Bathing		
Bathing area located within 3 km of area with high exposure to microplastics	1	GIS layers: Bathing Water Locations, (supplied by EPA, 2015)
Bathing area with low exposure to microplastics	0	Exposure maps (see Chapter 3) showing UWWTPs, landfill sites and microplastic-associated industries

population drinking from the various abstraction points and bathing in the various bathing areas has not been determined.

5.3.2 Results

Consumption of water from private wells or private group water schemes with no treatment has a high potential associated risk to human health (Table 5.4); this also applies to public water supplies that are treated only by disinfection. As approximately 10% of the population in Ireland is currently receiving water from unregulated supplies, there is a possibility that much of this is untreated. As some of the public water abstraction areas in Ireland, from which 80% of the population receives their water, occur in areas with potential microplastic exposure, there may be a risk to a large proportion of the population, particularly if the supplies are not filtered. However, with little knowledge regarding the impacts, pathways and environmental occurrence of this pollutant, further research is required to further substantiate this initial assessment of the potential risks.

5.4 Potential Risk of Impact to Protected and Red List Species

5.4.1 Methodology

A selection of protected and Red List species thought to be affected by microplastic pollution were chosen from Tables 4.3 and 4.4. For the development of the consequence scores (Table 5.5), examples from the effects of microplastic pollution on similar species determined during laboratory trials were used. Likelihood scores were developed for molluscs, fish, amphibians, mammals and birds (Table 5.6). The total likelihood of impact was calculated by summing the likelihood scores, and the frequency and description of these score can be seen in Table 5.6. The risk ranking was then calculated using Table 5.1 to achieve the final table of potential risk (Table 5.7).

5.4.2 Results

It has been determined that there is a potentially high risk to the critically endangered pearl mussel, *Margaratifera margaratifera* and *Margaratifera durrovensis*, and a medium risk to several species, including the Atlantic salmon, *Salmo salar*, the otter, *Lutra lutra*, and the white-clawed crayfish, *Austropamobius pallipes*, as well as several bird species, all of which are protected under the Habitats Directive (Table 5.8). The high risk assignment for *Margaratifera* spp. is because of the body of literature on the occurrence, retention and effects of microplastics on the similar marine species *Mytilus edulis*, with relevance to its life cycle, as described in Chapter 4, and its occurrence in the catchments identified as having potentially high exposure in this study. Although the protected dabbling birds and the benthic feeders are also potentially at risk,

Table 5.4. Potential risk category scenarios for human health

Risk scenario	Description
Very High	As no serious impacts have been recorded as a result of the ingestion of microplastics, it is not likely that life-threatening illnesses would occur
High	Consumption of water from private wells and group water schemes without treatment in areas of very high microplastic exposure; consumption of public water supplies that are not filtered
Medium	Consumption of water from private wells and group water schemes without treatment in areas of high microplastic exposure
	Consumption of water from public water supplies (without treatment) from source areas of high microplastic exposure
	Bathing in areas close to areas of very high microplastic exposure, particularly that resulting from UWWTPs (floating microplastics)
Low	Consumption of water from public water supplies (without filtration/treatment) abstracted from areas of medium microplastic exposure
	Consumption of water from private wells and group water schemes without treatment in areas of low to medium microplastic exposure
	Bathing close to areas of low microplastics exposure, particularly that from UWWTPs (floating microplastics)

Table 5.5. Consequence scores for protected species

Score	Consequence	Descriptor	Determining factor
1	Negligible	Absence of health impacts	No evidence from the literature of any impacts from similar taxa
2	Minor	Minor effects (inflammation)	Evidence from the literature from laboratory trials for similar taxa
3	Moderate	Reduced feeding	Evidence from the literature from laboratory trials for similar taxa
4	Significant	Toxicity, tumour formation	Evidence from the literature from laboratory trials for similar taxa
5	Major	Fatality	Evidence from the literature from laboratory trials for similar taxa

Table 5.6. Factors for determination of likelihood scores for protected/Red List species

Factors affecting likelihood of impact	Score	Source data
Exposure		
Very high	3	Exposure scores as calculated in Chapter 3, based on the presences of landfill sites, medical devices industries, precision engineering companies, UWWTPs and areas of sludge spreading; distribution of species from http://maps.biodiversityireland.ie/
High	2	
Medium	1	
Hydrological conditions		
Occupies lowlands for part of its life cycle	1	*Ireland Red List No. 5: Amphibians, Reptiles and Freshwater Fish* (King *et al.*, 2011); distribution of species from http://maps.biodiversityireland.ie/
Occupies lowlands for most of its life cycle	2	
Very-slow-flowing rivers	1	
Flood plains	2	
Occupies water bodies with high retention times (still water, lakes, ponds)	2	
Feeding strategy		
Filter feeders	2	*Ireland Red List No. 5: Amphibians, Reptiles and Freshwater Fish* (King *et al.*, 2011)
Benthic feeders	2	
Surface water feeders	1	
Pelagic feeders	1	
Top trophic level feeders	3	

Table 5.7. Likelihood scores resulting from likelihood calculation

Likelihood of Impact	Resulting likelihood score	Frequency	Description
0	1	Rare	This will probably never happen
0–2	2	Unlikely	This may occur but is unlikely
2–4	3	Possible	This may happen occasionally
4–6	4	Likely	This will probably occur or recur
6–8	5	Almost certain	This is very likely to occur

Table 5.8. Potential microplastics risk categories for some protected species listed in the Habitats Directive (HD), the Birds Directive (BD) and the Red List

Protected species	Low	Medium	High	Very high
Lake orb mussel (*Musculium lacustre*) (VU)	X			
Sand-bowl amber snail (*Quickella arenaria*) (EN)	X			
Swan mussel (*Anodonta cygnea*) (VU)				
Swamp orb mussel (*Sphaerium nucleus*) (VU)		X		
Desmoulin’s whorl snail (*Vertigo moulinsiana*) (HD)		X		
Freshwater pearl mussel *Margaratifera margaratifera*) (HD)			X	
Nore freshwater pearl mussel (*Margaratifera durrovensis*) (HD)			X	
River lamprey (*Lampettra fluviatilis*) (HD)		X		
Brook lamprey (*Lampettra planeri*) (HD)		X		
Atlantic salmon (*Salmo salar*) (HD)		X		
Eurasian otter (*Lutra lutra*) (HD)		X		
White-clawed crayfish (*Austropamobius pallipes*) (HD)		X		
Pollan (*Coregonas autumnalis pollan*)		X		
Twaite shad (*Alosa fallax*) (HD)		X		
Pintail (*Anas acuta*) (BD)	X			
Shoveler (*Anas clypeata*) (BD)	X			
Tufted duck (*Aythya fuligula*) (BD)	X			
Pochard (*Aythya farina*) (BD)	X			
Scaup (*Aythya marila*) (BD)	X			
Common scoter (*Melantita nigra*) (BD)	X			
Snipe (*Gallinago gallinago*) (BD)	X			
Hen harrier (*Circus cyaneus*) (BD)		X		
Golden eagle (*Aquila chrysaetos*) (BD)		X		
Kingfisher (*Alcedo atthis*) (BD)		X		

EN, endangered; VU, vulnerable.

birds occupying higher trophic regions are deemed to have a potentially higher risk, as they may ingest microplastics that have accumulated through the food chain.

5.5 Conclusions

- Human health could be at risk from microplastic pollution. Further knowledge on the abundances of microplastics in our surface and ground freshwater systems and on the efficacy of treatment systems in removing microplastics is imperative to verify these risks.
- Twenty four species of molluscs, fish, birds, mammals and crustaceans have been identified as being potentially at risk from microplastic pollution in Ireland.
- A failure to protect these species from emerging anthropogenic pressures may risk violation of legislation, in particular the WFD (2000/60/EC) and the MSFD (2008/56/EC).

6 Study Conclusions and Recommendations

6.1 Overview

Combatting plastic litter has become a priority of the G7 leaders, who have acknowledged it as posing a "global challenge, directly affecting marine and coastal life and ecosystems and potentially human health" (G7 Summit, 2015). The aim of this study was to improve our understanding of the environmental fate and risks posed by microplastics in Irish freshwater systems, thereby informing policy development and implementation. This was carried out through a desk-based assessment of potential sources of microplastics, the development of a conceptual model describing potential fates, assessing the potential impacts to humans, protected and priority species in Ireland and the combination of all this knowledge to assess the potential risks to humans and biota. The main conclusions and recommendations are presented below.

6.2 Conclusions

1. The principle microplastic sources identified were industry, landfill, UWWTPs, DWWTPs and sewage sludge/biosolids derived from UWWTPs.
2. Manufacturing industries involved in the primary production of polymers, regulated under the IPPC licensing scheme, were found to emit microplastics to sewer. Manufacturing industries involved in the machining of microplastics (particularly the plastics recycling industry) were found to emit high quantities to sewer and have high potential as a diffuse source for surface waters through surface run-off.
3. UWWTPs were identified as receptors of the cumulative abundance of microplastics arising from industry, landfill and household waste. Partitioning of microplastics results in 90% being incorporated into the sewage sludge that is mostly land-spread in Ireland. A separate study carried out during the lifetime of this project (2015-CCRP-SS.6) suggested that treatment of sewage sludge affects the abundance of microplastics.
4. An assessment of potential microplastic exposure in Ireland revealed very high exposure in the Slaney and Suir catchments and high exposure in the Barrow, Nore and Shannon Lower catchments resulting from the spreading of sewage sludge and the presence of UWWTPs. An assessment of the Slaney catchment revealed a potential for most of the microplastic inputs from the land spreading of biosolids to be deposited to the riverbed.
5. Potential impacts to human health were identified as a result of consumption of contaminated drinking water, with the highest risk being from untreated water (wells, some private group schemes and unfiltered public supplies) with some potential for microplastics to pass through public water supply filtration systems. This was verified through the identification of microplastics at one public water supply (2015-CCRP-SS.6).
6. There are potential risks to protected habitats and species in Ireland. The pearl mussel (*Margaratifera margaratifera*) and the Nore pearl mussel, (*Margaratifera durrovensis*) are both protected under the HD and are classified as critically endangered under the ICUN Red List, which represents the highest risk. Some protected fish species, including the salmon (*Salmo salar*), the river lamprey (*Lampettra fluviatilis*) and the brook lamprey (*Lampettra planeri*), were also found to be at risk. In the higher trophic levels, the protected otter (*Lutra lutra*) and the kingfisher (*Alcedo atthis*) will probably consume and accumulate microplastics from lower trophic levels.
7. Failure to protect these species may result in a breach of compliance to several EU legislations.

6.3 Recommendations

6.3.1 *Current knowledge gaps*

In order to address the current knowledge gaps, further scientific research is of paramount importance. Knowledge gaps of particular concern include two phases, as follows:

(a) *Phase 1: Identification of pathways into freshwater*

As the majority of microplastics will probably be land spread as biosolids derived from UWWTPs, the following questions should be addressed:

1. What are the pathways of microplastics entrained in sewage sludge on agricultural land?
2. Could agricultural land be a sink for microplastics?
3. What are the mechanisms by which leaching and translocation occur?
4. What is the potential for surface run-off and vertical translocation of microplastic particles and associated pollutants?
5. What are the key factors in determining pathways?
6. Do translocation rates vary between polymer types and sizes, and environmental factors?
7. What are the interactions between microplastics and co-existing pollutants in sewage sludge?

Based on this information, the following questions can be asked:

1. What are the exposure rates of microplastics entrained in sewage sludge to ground water and surface waters in Ireland?
2. Are the specifications detailed in the *Code of Good Practice for the Use of Biosolids in Agriculture* sufficient for preventing contamination of surface and ground waters with microplastics and are these specifications sufficient to comply with Irish and EU legislation?

The outputs of this suggested research will be able to further inform specific potential changes to policy that can be be defined as "good practice" to comply with EU legislation and in particular the EU Directive (86/278/EEC) on the protection of the environment in relation to soil where sewage sludge is currently used in agriculture.

Phase 2: Transport of microplastics in freshwater systems

In addition to defining potential pathways into freshwater systems, it is of paramount importance to understand the environmental fate of microplastics within freshwater systems.

1. Can factors deemed important in transport and deposition of microplastics determine abundances in Irish freshwater systems?
2. How do transport and deposition mechanisms of rivers and lakes vary with meteorological conditions and what implications does this have for the fate of microplastics on a temporal basis?
3. Under which conditions could monitoring be most effective?
4. Has trophic transfer resulted in bioaccumulation of microplastics within the freshwater food web?
5. Are organisms adversely affected?
6. Based on abundances in water abstraction areas and efficacy of water treatment regimes, what are the risks of human consumption?
7. What are the impacts of microplastics on human health?

The outputs of this suggested research will be able to further inform policy decisions regarding the possible requirement for inclusion of microplastics in temporal monitoring programme under the WFD and whether there is a need for the development of further legislation to regulate the input of microplastics from various sources, possibly in the form of an amendment to drinking water regulations.

6.3.2 Investigation into feasibility of interventions at source

It is recommended that interventions should occur where feasible at all point and diffuse sources of microplastics. It is important, therefore, to obtain knowledge on the technical and economic feasibility of the implementation of such measures. Based on the knowledge attained during this study and using the ethos of the precautionary principle (Rogers *et al*., 1997), changes within manufacturing industry that could be investigated include:

- replacement of machining by moulding where possible;
- changes in processes in the recycling industry, e.g. washing of the plastic material prior to shredding;

- re-use of waste plastics/microplastics;
- regulation on importing plastic waste with unknown contamination levels for recycling;
- reduction in the allowable amounts of suspended solids (mg/L) going to sewer;
- installation/maintenance of filters for waste water emitted to sewer and storm water drains; and
- changes in the licensing system, whereby not only the primary producers of plastics but also those industries involved in the machining of plastics are regulated by the EPA (IPPC licensing).

6.3.3 Further investigation into sources and transport routes to freshwater systems

Although this study investigated some of the important sources of microplastics, there are other sources, such as littering, that could not be investigated within the given time frame of this study. Therefore, it is recommended that further research looks into the following areas: microplastics that are generated through littering, urban storm drainage systems as a transport route for microplastics and the influence of population densities on microplastic loadings.

6.3.4 Dissemination of findings

In addition to research recommendations, it is important to make findings of this study available to other stakeholders, including monitoring and environmental managers. In particular, Figure 2.10 is important in showing the potential sources of microplastics in Ireland that could be important for river basin district management plans under the WFD.

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Abbreviations

AD	Anaerobic digestion
BD	Birds Directive
BWP	Bathing water profile
COA	Certificate of authorisation
CRO	Companies Registration Office
DWWTP	Domestic waste water treatment plant
ELV	End-of-life vehicle
EPA	Environmental Protection Agency
FTIR	Fourier transform infrared spectroscopy
GES	Good environmental status
GIS	Geographic information system
GMIT	Galway-Mayo Institute of Technology
HD	Habitats Directive
HDPE	High-density polyethylene
IFFPG	Irish Farm Film Producers Group
IPPC	Integrated Pollution Prevention and Control
LDPE	Low-density polyethylene
MSFD	Marine Strategy Framework Directive
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
PE	Population equivalent
PET	Polyethylene terephthalate
POP	Persistent organic pollutants
PVC	Polyvinyl chloride
SME	Small to medium-sized enterprise
TD	Thermal drying
UWWTP	Urban waste water treatment plant
WEEE	Waste electrical and electronic equipment
WFD	Water Framework Directive
WWTP	Waste water treatment plant

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Scope, Fate, Risks and Impacts of Microplastic Pollution in Irish Freshwater Systems

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Anne Marie Mahon, Rick Officer, Róisín Nash and Ian O'Connor

Plastic litter has become a priority of the G7 leaders, which in 2015 acknowledged it as posing a "global challenge, directly affecting marine and coastal life and ecosystems and potentially human health". The aim of this study was to improve the understanding of the environmental fate and risks posed by microplastics in Irish freshwater systems, thereby informing policy development and implementation. This was carried out through a desktop assessment of potential microplastics sources, development of a conceptual model describing potential fates, assessing the potential impacts to humans, protected and priority species in Ireland and combining all of this knowledge gained to assess the potential risks to humans and priority species in Irish freshwater systems.

Identifying Pressures

Principle microplastics pressures were identified as industry, landfill, urban waste water treatment plants (UWWTPs), domestic waste water treatment plants and sewage sludge/biosolids derived from UWWTPs. Manufacturing industries involved in the primary production of polymers, as well as those involved in machining of plastics, were found to emit microplastics to sewer and have high potential as a diffuse source to surface waters via surface run-off. UWWTPs were identified as receptors of the cumulative abundance of microplastics arising from industry, landfill and household waste. Partitioning of microplastics results in the majority of microplastics being incorporated into the sewage sludge, which is mostly land spread in Ireland.

Informing Policy

Potential Implications of microplastic pollution for various legislations were recognised including for the WEEE Directive (2012/19/EU), Packaging Directive (94/62/EC as amended), Waste Framework Directive (2008/98/EC), End-Of-Life Vehicles Directive (2000/53/EC) and the Landfill Directive (1999/31/EEC). In addition, the treatment and use of sewage sludge with MP pollution may have implications for the EU directive (86/278/EEC) which governs the application of sewage sludge to agricultural land. Upon entry to the environment, the potential for a compliance risk was identified for the Habitats Directive (92/43/EEC), the Birds Directive (2009/147/EC), the Water Framework Directive (2000/60/EC), the European Drinking Water Directive (98/83/EC) and the EU Bathing Water Directive (2006/7/EC).

Developing Solutions

This study helped to address a knowledge gap which existed regarding the sources of microplastics from land-based sources. Recommendations were made to move closer to solutions and, in some cases, solutions were offered. Particularly for the manufacturing industry, several recommendations were made with regard to industry processes which could reduce microplastic leakage. This initial study forms a solid basis for further investigations into the sources, fate and transport of microplastics through freshwater systems as well as the possible inclusion of microplastics into monitoring strategies.

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