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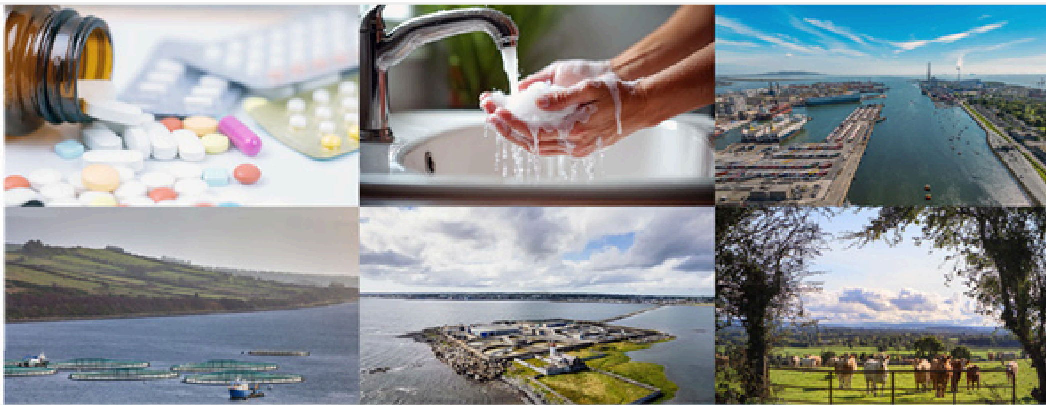
Assessment of the Environmental Contamination of Irish Soils and Sediments with Hazardous Chemicals (TERRAChem)

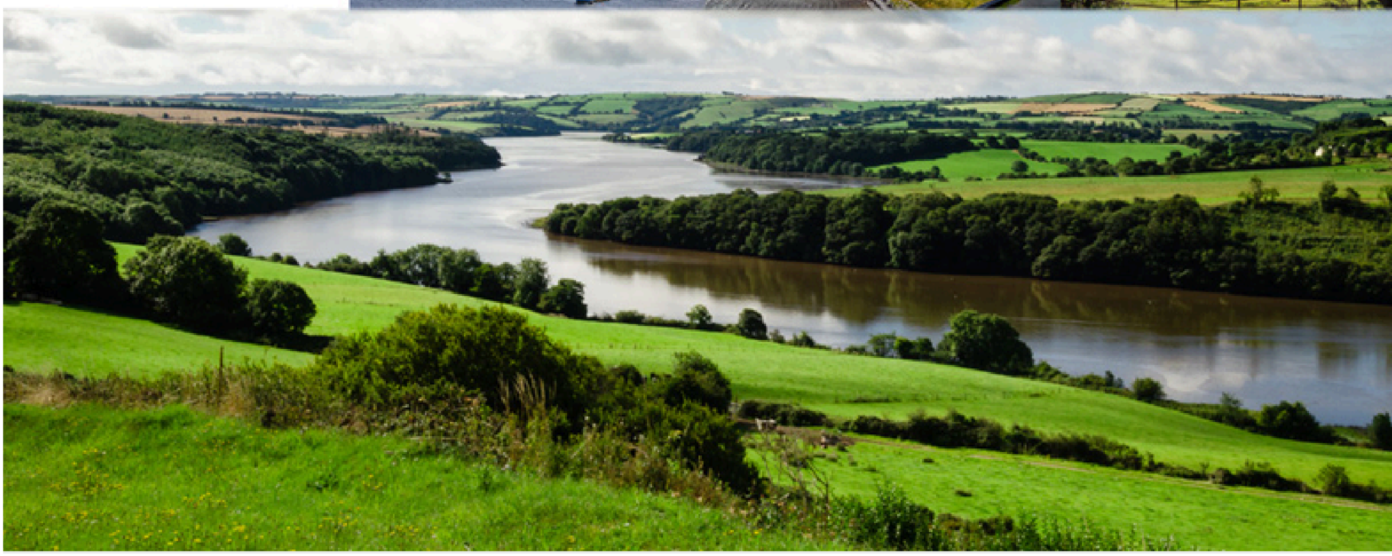
Authors: Marie Coggins, Martin Sharkey, Stuart Harrad, William A. Stubbings, Yulong Ma, Shijie Wang, Jingxi Jin and Mark G. Healy

Lead organisations: The University of Galway and the University of Birmingham

TERRAChem

CHEMICALS POLLUTANTS SOILS AND SEDIMENTS





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5. Office of Communications and Corporate Services

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What did the research aim to address?

The useofchemicals brings major societal and economic benefits, but problems arise when hazardous, persistent substances bioaccumulate with the potential to negatively impact human health and the environment. Examples include per- and polyfluoroalkyl substances (PFAS), flame retardants, polychlorinated biphenyls (PCBs), pharmaceuticals, UV filters, and insecticides, all of which have widespread commercial uses.

The TERRAChem project provides a baseline assessment of concentrations of legacy and emerging organic chemicals of concern in inland and coastal sediment samples collected across Ireland. The same target chemicals were also measured in biosolids from wastewater treatment plants.

Risk quotients were used to evaluate the ecotoxicological risks associated with the concentrations detected in sediment, by making comparisons with the predicted "no effect" concentration values for sediment that are promogulated by the Norman Network. Project data were used to identify potential contamination "hot spots" or locations with elevated concentrations of one or more contaminants. These locations may require inclusion in ongoing EPA monitoring programmes.

In addition, TERRAChem included a Best Practice review of legislative requirements and current approaches for monitoring organic chemicals in soils, sediments, and wastewater treatment plant–derived biosolids.

What did the research find?

Of the 92 target organic chemical sstudied, most were low risk but some, especially perfluorooctane sulfonate (PFOS), certain organophosphate esters (OPEs), pyrethroids and specific antibiotics, present a high ecotoxicological risk and warrant further investigation. Three potential contamination 'hot spots' were identified. The study presents new data of international significance for some of the target chemicals.

Concentrations of most brominated flame retardants (BFRs), OPEs, and PCBs in sediment were comparable to international data and pose low ecotoxicological risk. However, some OPEs including tris(1-chloro-2-propyl) phosphate, tris(2-ethylhexylphosphate, and certain PCBs were frequently detected at concentrations which represent moderate to high ecotoxicological risk. Similarly, the same chemicals and others were also found at relatively high concentrations in wastewater biosolids.

Concentrations of antibiotics in sediment present mostly a low ecotoxicological risk, with the exception of clarithromycin, which along with the antibiotic sulfamethoxazole, presents a high ecotoxicological risk. UV filters were detected in both sediments and biosolids at low overall levels compared to international reports, although sediment concentrations of 4-methylbenzylidene camphor, homosalate and ethylhexyl methoxycinnamate present a moderate ecotoxicological risk. Higher concentrations of antibiotics and UV filters in sediment were frequently detected downstream from wastewater emission points.

Of the 39 PFAS investigated, concentrations of PFOS exceed the relevant lowest predicted "no effect" concentration in sediment (PNECsed) in over half of the samples analysed, while those of the other target PFAS rarely if ever exceeded PNECs. Pyrethroids, specifically permethrin, cyfluthrin, cypermethrin, deltamethrin, λ-cyhalothrin were found at levels indicating high ecological risk in sediments, while those of anthelmintics (e.g. albendazole and fenbendazole) presented low to moderate risk but require further study due to limited available data.

How can the research findings be used?

- Acomprehensive baseline assessment of 92 target chemicals in sediment is provided which serves as the basis for conducting future long-term trend analysis for many of the target chemicals. Potential contamination 'hot spots' will assist in the development of a prioritisation list for future assessments in national monitoring programmes.
- The research supports the implementation of the EU Chemicals Strategy but also informs the inclusion of priority organic chemicals within the scope of future revisions of the Sewage Directive (86/278/EEC), the EU Soils strategy, and the Urban Wastewater Treatment Directive (2024/3019).
- Application of wastewater treatment plant biosolids to agricultural and is a widespread practice in Ireland. The data collected here will inform guidance in relation to these practices.
- Further research is needed to examine concentrations of organic chemicals in soil, particularly soil from land treated with wastewater treatment plant-derived biosolids.
- Results should inform the inclusion of new emerging chemicals in future risk profiling under OSPAR.

Project code: 2021-HE-1056

EPA RESEARCH PROGRAMME 2021–2030

Assessment of the Environmental Contamination of Irish Soils and Sediments with Hazardous Chemicals (TERRAChem)

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EPA Research Report

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Prepared by

The University of Galway and the University of Birmingham

Authors:

Marie Coggins, Martin Sharkey, Stuart Harrad, William A. Stubbings, Yulong Ma, Shijie Wang, Jingxi Jin and Mark G. Healy

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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This report is based on research carried out/data from February 2022 to January 2025. More recent data may have become available since the research was completed. More recent data may have become available since the research was completed.

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.

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Project Partners

Marie Coggins
School of Natural Sciences and the Ryan Institute
University of Galway
Galway H91 CF50
Ireland
Email: marie.coggins@universityofgalway.ie

Martin Sharkey
School of Natural Sciences and the Ryan Institute
University of Galway
Galway H91 CF50
Ireland
Email: martin.sharkey@universityofgalway.ie

Stuart Harrad
School of Geography, Earth and Environmental Sciences
University of Birmingham
Birmingham B15 2TT
UK
Email: s.j.harrad@bham.ac.uk

Mark G. Healy
College of Science and Engineering and the Ryan Institute
University of Galway
Galway H91 HX3
Ireland
Email: mark.healy@universityofgalway.ie

William A. Stubbings
School of Geography, Earth and Environmental Sciences
University of Birmingham
Birmingham B15 2TT
UK
Email: w.stubbings@bham.ac.uk

Yulong Ma
School of Geography, Earth and Environmental Sciences
University of Birmingham
Birmingham B15 2TT
UK
Email: y.ma.6@bham.ac.uk

Shijie Wang
School of Geography, Earth and Environmental Sciences
University of Birmingham
Birmingham B15 2TT
UK
Email: sxw597@student.bham.ac.uk

Jingxi Jin
School of Geography, Earth and Environmental Sciences
University of Birmingham
Birmingham B15 2TT
UK
Email: jxj193@student.bham.ac.uk

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Executive Summary

There is a limited body of research in Ireland investigating the degree of contamination of inland and transitional/coastal sediments with legacy and emerging chemicals of concern. The Assessment of the Environmental Contamination of Irish Soils and Sediments with Hazardous Chemicals (TERRAChem) project aimed to provide a status update on levels of hazardous chemicals in inland and transitional/coastal sediments and wastewater treatment plant-derived sewage sludges or biosolids that are intended for use as agricultural fertiliser. Samples were collected in 2023 and subsequently analysed for a range of hazardous chemicals, including halogenated flame retardants, chlorinated (and non-chlorinated) organophosphate esters (OPEs), perfluoroalkyl substances (PFASs), polychlorinated biphenyls, sunscreen agents (SSAs), antibiotics, anthelmintics and pyrethroids. Many of these chemicals are currently considered a threat to the aquatic or terrestrial environment and to animal and human health. Some are currently managed under the EU Water Framework Directive and others are restricted or banned under the Stockholm Convention or deemed to be emerging chemicals of concern as promulgated by the EU's Network of Reference Laboratories, Research Centres and Related Organisations for Monitoring of Emerging Environmental Substances (NORMAN network). To the authors' knowledge, this study presents the first data globally on concentrations in either sediments or biosolids for some PFASs, antibiotics and SSAs.

Average detection frequencies of 85% and 41% for all target chemicals were observed in biosolid and sediment samples, respectively. Flame retardant biosolid concentration data for polybrominated diphenyl ethers, in particular BDE-209 (or DecaBDE), and OPEs, particularly tris(2-butoxyethyl) phosphate and 2-ethylhexyl diphenyl phosphate, are at the higher end of those reported internationally. Higher concentrations of BDE-209 and tris(2-butoxyethyl) phosphate most likely reflect their lipophilic properties and tendency to accumulate in the organic-rich sludge, but also may reflect widespread historical use of BDE-209 in Ireland and its low propensity to break down over time.

Concentrations of polybrominated diphenyl ethers and OPEs in sediment were within the ranges reported internationally, with BDE-209 dominant, while those of polychlorinated biphenyls (with minor exceptions) were broadly similar to concentrations previously reported in Irish sediment. Reported concentrations in sediment, when compared with predicted no-effect concentration (PNEC) values promulgated by the NORMAN network, suggest most target contaminants present a moderate chronic ecotoxicological risk.

Antibiotic concentrations are presented for sediments only. Clarithromycin was the most frequently detected antibiotic and was present at higher concentrations than those reported internationally. In contrast, reported concentrations of all other target antibiotics are at the lower end of those reported internationally. All concentration data are below the "low risk" threshold when compared with NORMAN PNECs apart from clarithromycin and sulfamethoxazole, the concentrations of which represent a moderate ecotoxicological risk.

Concentrations of target PFASs are mostly at the lower end of concentrations reported internationally. However, perfluorooctane sulfonate concentrations exceed the PNEC value in most sediment samples, indicating a high ecotoxicological risk and warranting further investigation.

Concentrations of the pyrethroids resmethrin, cyfluthrin, permethrin, cypermethrin and deltamethrin in sediment were all at least one order of magnitude higher than those of other target pyrethroids. Cyfluthrin, followed by permethrin, was more prevalent in biosolids. Pyrethroid sediment concentrations were generally within the range reported worldwide. Comparison with NORMAN PNECs suggests that the concentrations of permethrin, cyfluthrin, cypermethrin, esfenvalerate and deltamethrin present a high ecotoxicological risk.

The SSA octocrylene was detected at the highest concentrations in sediment and biosolids, followed by homosalate. Although concentrations of SSAs in both sediment and biosolids are at the lower end of the

range reported in the few data sets available for the targeted SSAs, concentrations of 4-methylbenzylidene camphor, ethylhexyl methoxycinnamate (octinoxate) and homosalate present a moderate ecotoxicological risk based on current NORMAN PNECs.

TERRAChem presents the first European data set on anthelmintic concentrations in biosolids, with all target compounds detected in both sample types. Fenbendazole showed the highest detection frequency and concentration in sediments and was also dominant in biosolids. There is a scarcity of international data on anthelmintic concentrations, limiting the scope for comprehensive comparisons. Concentrations in TERRAChem sediments are markedly lower than those reported previously, while concentrations in biosolids are generally comparable with previous data for most compounds, with the exception of albendazole, which was lower in TERRAChem samples. Comparison with NORMAN PNEC values for albendazole and fenbendazole reveals a low to moderate ecotoxicological risk.

1 Introduction

1.1 Hazardous Organic Chemicals: Uses, Risks and Environmental Contamination

The use of synthetic chemicals is more ubiquitous today than at any point in history. Notwithstanding the benefits of such applications, issues arise when these chemicals enter the environment, particularly when contaminants display the capacity to persist, bioaccumulate, undergo long-range transboundary environmental transport and demonstrate adverse effects on the environment or human health. In response to this environmental challenge, the EU Water Framework Directive (WFD) (European Union, 2000) identified environmental quality standards (EQSs) for a number of priority chemical substances and, in 2013, a Surface Water Watch List was established to improve the availability of information on substances of concern. In addition, a number of international programmes designed to limit the use and environmental impact of these hazardous chemicals have been established. For example, the United Nations Environment Programme's Stockholm Convention on Persistent Organic Pollutants (UNEP, 2019) is an international treaty to protect human health and the environment from exposure to hazardous "persistent organic" chemicals – chemicals that can remain in the environment for long periods of time and bioaccumulate in fatty tissues. Persistent organic pollutants (POPs) controlled under the Stockholm Convention fall into one of three broad categories: pesticides (e.g. dichlorodiphenyltrichloroethane, or DDT), unintentionally produced POPs (e.g. dioxins) and intentionally produced POPs (e.g. perfluoroalkyl substances (PFASs) and polychlorinated biphenyls (PCBs)) (UNEP, 2019).

The European Chemicals Agency (ECHA; https://echa.europa.eu/) is the European regulatory agency responsible for implementing chemical legislation, including the Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH Regulation; Regulation EC No. 1907/2006) (ECHA, n.d.), which is the primary EU law intended to protect human health and the environment from risks posed by chemicals. Manufacturers and importers of chemicals are required to register their chemical substances with ECHA, which then evaluates the submitted data and, depending on the hazardous properties, authorises or restricts the substances' use. The authorisation process within REACH allows the identification of particularly hazardous substances or substances of very high concern (SVHCs). Chemicals designated as SVHCs include those classified as carcinogenic or mutagenic as well as those designated as persistent, bioaccumulative and toxic (PBT).

In 2019, the European Commission set out a road map known as the European Green Deal (European Commission, 2019), which is supported by many policy initiatives, including the 8th Environment Action Programme and the EU Chemicals Strategy for Sustainability (CSS) (European Commission, 2020). The CSS sets out a zero-pollution action plan aimed at protecting citizens and the environment, which includes phasing out the use of some chemicals (e.g. PFASs) and banning the use of others (e.g. mercury) where their use is deemed non-essential. Other actions within the CSS include proposals to introduce a "one substance, one assessment" approach for the safety assessment of chemicals used in products such as toys and food, and modernising standards on water quality, air quality, industrial emissions and chemicals.

For now, there are many legacy and currently used chemicals of concern circulating in the environment, and many knowledge gaps exist that prevent a full assessment of the risk they pose to the environment and human health. Common characteristics of many of the pollutants of concern are their persistence, potential to accumulate in organic-rich matrices, and high human and ecological toxicity. Such chemicals include PFASs, halogenated flame retardants (HFRs), PCBs, antibiotics, antiparasitic compounds, pesticides, including pyrethroid insecticides, and sunscreen agents (SSAs) and ultraviolet filters (UVFs) (European Commission, 2020; European Environment Agency, 2023). An overview of the common uses of and environmental pathways for these chemicals is presented in Table 1.1.

Table 1.1. Example hazard classifications, uses and environmental pathways for some of the legacy and commonly used chemicals currently in circulation in the environment

Substance group	Common legislative restriction/hazard label	Exemplar use	Potential environmental pathway
HFR	POP, SVHC, PBT	Flame retardant additive in electronics, furniture, insulation, vehicles, childcare articles	Leaching during use, landfilled waste, WWTP effluent
PFAS	POP, SVHC, PBT	Surfactant (dirt/water repellent) used in textiles, food packaging, aqueous fire-fighting foams	Leaching during use, landfilled waste, domestic wastewater, WWTP effluent
PCB	POP	Flame retardant and dielectric/coolant in electrical applications, dye contaminants	Leaching during use, landfilled waste, WWTP effluent
Antibiotic	H410	Human and veterinary pharmaceuticals	Domestic wastewater, agricultural run-off, WWTP effluent
Antiparasitic	H410	Human and veterinary pharmaceuticals	Domestic wastewater, agricultural run-off, aquaculture, WWTP effluent
SSA and UVF	H410	Personal care products	Domestic wastewater, WWTP effluent
Pyrethroid	H410	Pesticide/insecticide	Agricultural/horticultural run-off, aquaculture

H410, very toxic to aquatic life with long-lasting effects; WWTP, wastewater treatment plant.

1.2 Regulatory Requirements and International Actions for the Monitoring of Restricted Hazardous Organic Chemicals in the Environment

To date, few studies (Vickneswaran *et al*., 2023) have been conducted in Ireland with the aim of understanding the degree of contamination of the environment with legacy and emerging hazardous substances in sediments and soils and wastewater treatment plant (WWTP)-derived biosolids. Previous international research has shown that soils, sediments and WWTP biosolids are known reservoirs for persistent substances following environmental uptake and are therefore effective matrices to use in assessing the range of such substances and in conducting temporal monitoring of chemical contamination (Crompton, 2012; Huygens *et al*., 2022; Popoola *et al*., 2023). The following section provides an overview of current regulatory requirements for monitoring hazardous chemicals in soils, sediments and WWTP biosolids in Ireland.

1.2.1 Pollutants in sediments

The EU WFD, Directive 2000/60/EC, most recently amended by Directive 2014/101/EU (European Union, 2000, 2014), currently includes aquatic/biotic EQSs for 45 priority substances and other pollutants, including perfluorooctane sulfonate (PFOS), polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane and cypermethrin, all of which are within the scope of this research project. The list of priority substances in the WFD includes organohalogen compounds, organophosphate compounds and substances with PBT properties. Furthermore, since 2013, EU Member States have had to monitor their surface and transitional waters to improve the available information on the presence of WFD Watch List substances. The chemicals 2-ethylhexyl-4-methoxycinnamate (EHMC), ciprofloxacin, sulfamethoxazole, octocrylene (OC), benzophenone-3 (BP-3) and ofloxacin are all examples of previous Watch List chemicals included within the scope of this project. Monitoring programmes, as intended by the WFD, do not necessarily require the monitoring of sediments. No EQSs have been set for sediments, and sediments are only monitored for certain substances and for trend monitoring purposes (Directive 2008/105/EC, Article 16) (European Union, 2008), provided that the parameters are regularly monitored in other relevant matrices (i.e. water or biota). However, sediment and biota remain important matrices for the monitoring of certain substances with significant accumulation potential. In order to assess long-term presence of anthropogenic inputs, Member States should take measures, subject to Article 4 of Directive 2000/60/EC (European Union, 2000), with the aim of ensuring that existing levels of contamination in biota and sediments do not significantly increase.

The Drinking Water Directive (Directive (EU) 2020/2184) similarly establishes limits and guidelines for monitoring PFASs, heavy metals and certain other parameters in drinking water, but not in sediments (European Union, 2020). Beyond the EU requirements, OSPAR, an international organisation working to protect the marine environment of the north-east Atlantic Ocean, has possibly the most extensive assessment criteria defined for pollutants in marine sediments. Several concentration thresholds are defined for compounds such as PBDEs, dioxins, metals and other chemicals. For example, two assessment criteria are used for 10 PBDE congeners: the "Background Assessment Concentrations" or "BACs" were developed by OSPAR and the International Council for the Exploration of the Sea, while the Federal Environmental Quality Guidelines were developed under the Canadian Environmental Protection Act, 1999 (OSPAR, 2022a).

1.2.2 Pollutants in biosolids

The application of organic wastes from agriculture and stabilised biosolids from urban wastewater treatment facilities to agricultural land is widespread practice in Ireland (Huygens *et al*., 2022). Wastewater sludge and biosolids are subject to the provisions of the EU Sewage Sludge Directive (SSD) (Directive 86/278/EEC) (European Union, 1986), which was published over 40 years ago and does not include limits for the organic pollutants of concern today (Fehily Timoney, 2016; EPA, 2024a) but instead requires the monitoring of dry matter, organic matter, pH, nitrogen, phosphorus and some heavy metals (Cd, Cu, Ni, Pb, Zn, Hg and Cr). These regulations may change with the implementation of the revised EU Urban Wastewater Treatment Directive (European Union, 2024), which sets a requirement that by 2045 all micropollutants, including pharmaceuticals and cosmetics, be removed in WWTPs treating wastewater from all agglomerations with a population equivalent (PE) > 150,000. The current parameters (as per the SSD) are reflected in the nutrient management plans that must be submitted to local authorities and followed by entities that intend to use biosolids as agricultural fertilisers. In 2008, the Food Safety Authority of Ireland published a report on the food safety implications of spreading agricultural, municipal and industrial organic wastes on agricultural land (Food Safety Authority of Ireland, 2008). The report recommended that all untreated organic municipal and industrial wastes, including residual sludge from septic tanks, should not be allowed to be spread on agricultural land used for food production, in particular on land used for the production of "fresh food", as human pathogenic micro-organisms could potentially be incorporated into the human food chain. Organic wastes were also highlighted as a potential source of chemical contaminants in the food chain, especially organic chemicals that are capable of bioaccumulation in meat and dairy products. The report also highlighted that assessment of risks to food safety in the Irish context is currently impeded by a lack of Irish data. In Ireland, the Department of the Environment and Local Government (now the Department of Climate, Energy and the Environment) published a code of good practice for the use of biosolids in agriculture, which includes requirements for the routine monitoring (every 5 years) of chemicals such as PCBs, polychlorinated dibenzodioxins/furans and polycyclic aromatic hydrocarbons (Fehily Timoney, 2016).

In 2022, the European Commission's Joint Research Centre published a screening risk assessment on organic pollutants and the environmental impacts of sewage and sewage sludge management (Huygens *et al*., 2022). The study found that organic contaminants such as PCBs, long-chain PFASs and organophosphate compounds (which are included in the scope of this study) may pose significant risks to both humans and soil organisms. These risks are particularly concerning when such chemicals are present at concentrations typically found in sewage sludge applied to agricultural land. In addition to these compounds, pharmaceuticals and personal care products were also identified as potential threats to soil organisms. The report noted that humans may be a more vulnerable end point than soil organisms, as certain pollutants can accumulate in the body to levels that exceed acceptable risk thresholds. The study emphasised the need for further research, such as the work proposed in the Assessment of the Environmental Contamination of Irish Soils and Sediments with Hazardous Chemicals (TERRAChem) project, to measure pollutant concentrations in sludge. This would support more accurate risk assessments and help determine the relative contribution of sewage sludge compared with other sources of soil contamination. Importantly, the study also highlighted that commonly used biological sludge treatment methods do not reliably reduce priority pollutants to safe levels.

While the SSD is currently under review and likely to be revised in the coming years (Huygens *et al*., 2022), there are currently no requirements for monitoring POPs, SVHCs, PBT chemicals, persistent, mobile or toxic chemicals, or ecotoxic chemicals in sewage sludge or biosolids.

1.3 Chemicals of Emerging Concern and Emerging Substances of Concern

1.3.1 NORMAN network

The Network of Reference Laboratories, Research Centres and Related Organisations for Monitoring of Emerging Environmental Substances (NORMAN network; https://www.norman-network.com/) commenced in 2005. NORMAN defines both "emerging substances" – substances detected in the environment, although not currently routinely investigated in monitoring programmes, and whose fate, behaviour and toxicology are not well known – and "emerging pollutants" – which are similar to emerging substances, but with reliable data on their environmentally hazardous properties, and likely to be subject to restriction in the future.

NORMAN's Substance Database ("SusDat") (NORMAN network, n.d.a) lists a wide variety of emerging substances of concern (ESOCs), identified through its dedicated "Suspect List" where novel chemical, environmental and/or toxicological data on ESOCs are gathered and submitted by NORMAN network participants. Complementary to this is the dedicated EMPODAT chemical occurrence database, where data on ESOCs in different countries and a variety of different matrices, including soil, sediment and sewage, sludge can be submitted and openly accessed. NORMAN additionally includes the NORMAN Ecotoxicology Database (NORMAN network, n.d.b), which lists predicted no-effect concentrations (PNECs) for a wide range of ESOCs, values that can be used as preliminary indicators for prioritisation of chemicals based on suspected risk. In terms of chemicals of relevance to this current project (TERRAChem), these PNECs are largely established for freshwater and marine water as well as (to a slightly lesser extent) biota and sediments. These currently available data and the availability of a repository for established PNECs in the future are of key importance for prioritisation of ESOCs in various media in terms of risk and the necessity of regulatory efforts.

1.4 Objectives of the TERRAChem Project

The TERRAChem project aims to provide a status update on chemicals in Irish sediments, with a particular focus on potential hotspots (e.g. a sampling location with elevated concentrations of a contaminant). The project analyses sediments (riverine and coastal) from sites adjacent to potential pollutant sources, for example downstream from WWTPs or where large-scale industrial operations such as those based on the manufacture of pharmaceuticals or aquaculture occur. Finally, samples of biosolids derived from secondary or tertiary WWTPs that are intended for use as agricultural fertiliser are analysed.

Specific objectives of the TERRAChem project were to:

- complete a best practice review on the legislative requirements and best practices concerning monitoring of emerging chemicals of concern in soils, sediments and WWTP-derived biosolids across Europe;
- provide a baseline assessment of legacy and emerging hazardous organic chemicals (HFRs, PCBs, PFASs, SSAs, antibiotics, anthelmintics and pyrethroids) in inland and transitional/coastal sediments in Ireland;
- determine concentrations of these hazardous organic chemicals in WWTP-derived sludges intended for use as agricultural fertilisers (biosolids);
- identify priority chemicals and potential hotspots for ongoing monitoring due to elevated levels in both matrices, which may be indicative of moderate or high ecotoxicological risk.

2 Methods

2.1 Best Practice Review

The best practice review to identify the current legislative requirements and practices concerning the monitoring of soils, sediments and WWTP-derived biosolids for hazardous chemicals was subject to review and feedback from the TERRAChem project steering committee, and a final report was published (Sharkey *et al*., 2025a).

2.2 Sample Collection

Many of the sampling sites ($n = 46$) included in the TERRAChem study were part of the EPA National Monitoring programme. They were a mix of surveillance sites, designed to measure long-term trends in water chemistry, and operational/investigative sites, focused on identifying pressures impacting on water quality. The locations sampled (Figure 2.1)

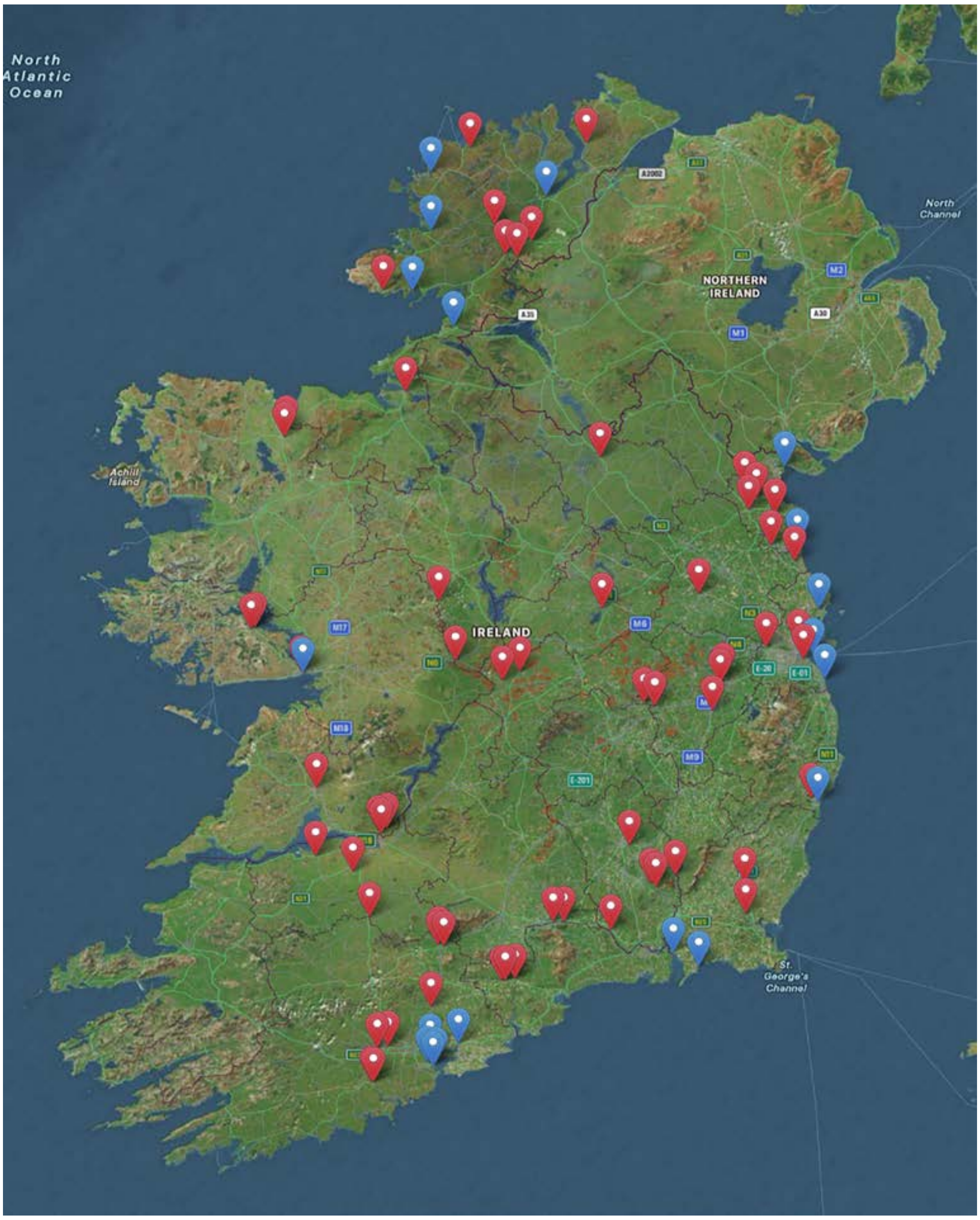

Figure 2.1. Locations sampled in the TERRAChem project in 2023: red pins indicate inland sediment sites and blue pins indicate transitional/coastal sites. Map adapted from https://irish.gridreferencefinder.com.

included sites where screening of potential chemical pollutants in water had been performed in previous work by the EPA as well as sites that lay at the outlets of some of the major Irish rivers.

An additional 16 locations were included in the sampling campaign. These sites were either adjacent to potential contamination sources, such as intensive agriculture or aquaculture, or were considered pristine background locations isolated from such sources.

The sampling campaign involved the collection of samples of inland and transitional/coastal sediments and WWTP-derived biosolids samples over the course of 2023. To extend the number of samples for the locations sampled in the TERRAChem project, an additional 39 transitional/coastal sediment samples (hereafter referred to as the historical samples) collected at 23 locations (Figure 2.2) by the Marine Institute under its WFD monitoring programme were made available to the project. The additional samples were collected over the period 2018–2022. A total of seven locations were sampled in both the 2023 and 2018–2022 sampling campaigns.

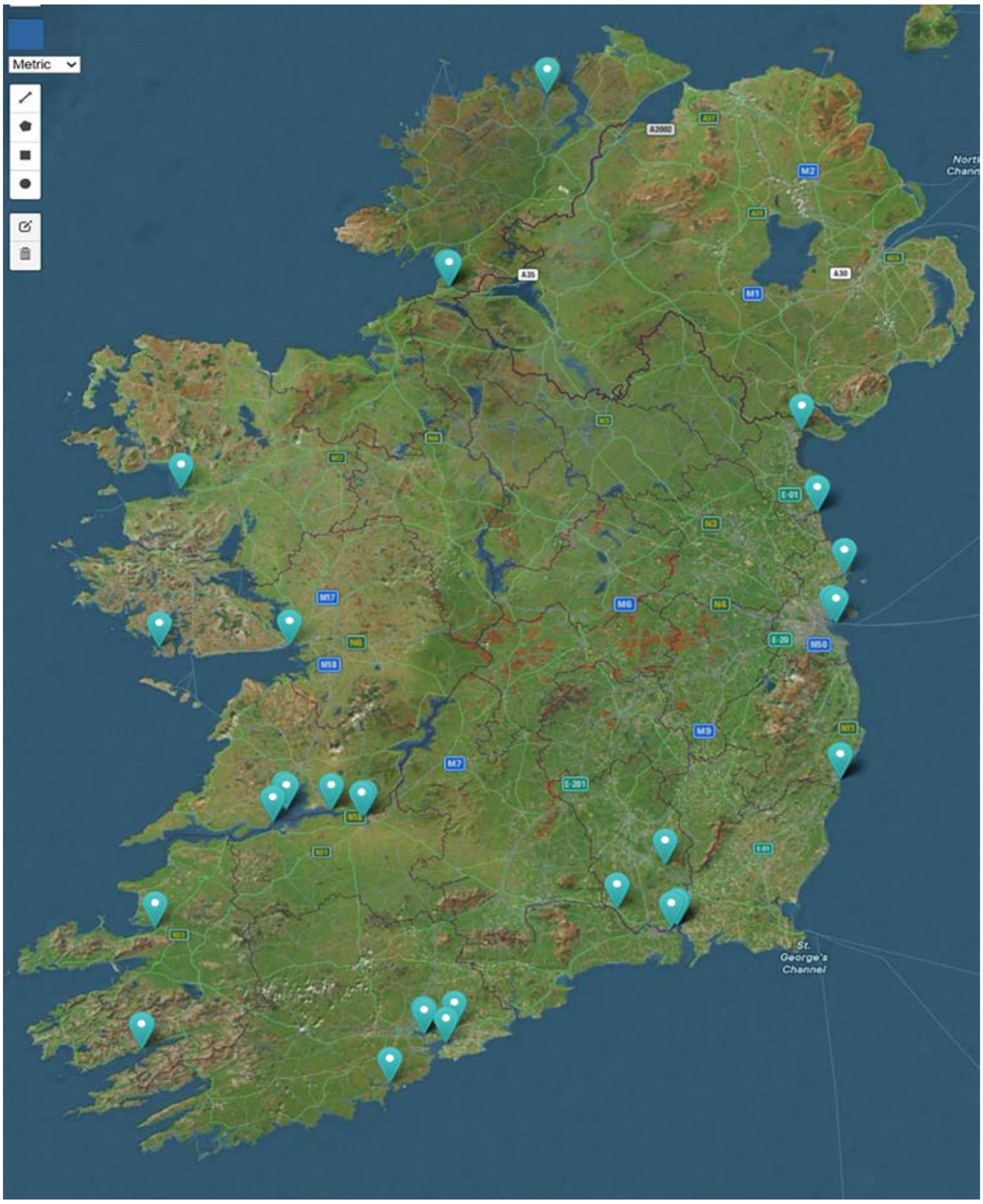

Figure 2.2. Locations sampled in the historical sampling campaign in 2018–2022: green pins indicate transitional/coastal sites. Map adapted from https://irish.gridreferencefinder.com.

2.2.1 Inland and transitional/coastal sediments in 2023 and 2018–2022

The TERRAChem (2023) inland and transitional/coastal sediment samples ($n=81$) were collected from a range of sites across Ireland, including rivers ($n=62$) and estuaries ($n=19$).

Grab surficial sediment samples (0–5 cm depth) were collected from riverine and transitional sites. Approximately 1 kg aliquots were collected from those sites that had a coarse (> 2 mm) grain size, and approximately 0.5 kg aliquots were collected from the sites that had finer grain sizes. Samples were collected using either stainless-steel digging implements or a Van Veen Grab sampler, which were both pre-cleaned before each sampling in a detergent wash and rinsed in triplicate with acetone, cyclohexane, methanol and distilled water. Samples were transferred to high-density polyethylene containers and transported to the laboratory, where they were homogenised and wet sieved to 2 mm before being transferred to 50 ml centrifuge tubes. The samples were sealed and stored at –80°C until freeze-drying, which was performed within 2 weeks of sampling.

Sampling procedures for the historical samples were similar to those outlined above, except that non-metallic sampling equipment was used. One significant difference regarding laboratory preparation prior to analysis from the 2023 TERRAChem samples was that samples were sieved through a 2 mm, 1 mm, 125 mm and 63 μm sieve using distilled water. The 63 μm fraction was dried and stored prior to contaminant analysis.

Further details on sample collection and preparation are included in the peer-reviewed publications emerging from this project (Ma *et al*., 2024; Sharkey *et al*., 2024a,b, 2025b; Wang *et al*., 2025).

2.2.2 Wastewater treatment plant-derived biosolids

In collaboration with Uisce Éireann (www.water.ie/), seven WWTP sites were selected for the collection of samples of biosolids used as agricultural fertilisers. Table 2.1 summarises relevant characteristics of the WWTPs sampled for biosolids. In total, 21 biosolid samples were collected from the seven WWTPs: three samples were collected from each site at 4-month intervals (January, May and September 2023) to assess any seasonal variations along with nuances relating to relative size/capacity and types of treatment occurring at each site. Biosolid samples were prepared for analysis in line with the procedures outlined for sediment samples in section 2.2.1, with further details available in the peer-reviewed publications emerging from the project (Ma *et al*., 2024; Sharkey *et al*., 2024a,b, 2025b; Wang *et al*., 2025).

2.3 Methods for Determining Analyte Concentrations

Unfortunately, due to analytical method issues related to matrix interferences and poor internal standard recoveries, antibiotic concentration data are not reported for biosolid samples. Quality assurance and control measures were undertaken for the chemical analyses to evaluate (1) laboratory contamination and (2) method reproducibility, and accuracy, measures comprised laboratory blanks and replicate analyses of standard/certified sediment reference materials or matrix spikes. Full information on the analytical methods used and the quality assurance and control data obtained for each group of contaminants (Table 2.2) is provided in the peer-reviewed publications emerging from this report (Ma *et al*., 2024; Sharkey *et al*., 2024a,b, 2025b; Wang *et al*., 2025).

Table 2.1. Summary characteristics of the WWTPs sampled in the TERRAChem study

WWTP site	PE band	Output flow band (m^3/day)	Type of biosolid treatment
WWTP 1	> 100,000	> 30,000	Advanced AD
WWTP 2	> 100,000	> 30,000	AD, TD
WWTP 3	> 100,000	> 30,000	AD, TD
WWTP 4	50,000–100,000	10,000–30,000	THP, AD
WWTP 5	2000–50,000	1000–10,000	AD, pasteurisation
WWTP 6	2000–50,000	1000–10,000	AD, TD
WWTP 7	2000–50,000	1000–10,000	LS

AD, anaerobic digestion; LS, lime stabilisation; TD, thermal drying; THP, thermal hydrolysis processing.

Table 2.2. A summary of the organic chemical contaminants measured in each sample type collected in the TERRAChem study

Sediment matrix	Chemical contaminant
Inland and transitional/coastal sediment and WWTP biosolid samples	Flame retardants: PBDEs (BDE-28, -47, -100, -99, -153, -154, -183, -209); OPEs (TCEP, TCIPP, TDCIPP, TBOEP, TEHP, TnBP, TBHP, EHDPP); PCBs (PCB-11, -28/31, -52, -101, -118, -153, -128 -180)
Inland and transitional/coastal sediment	Antibiotics: trimethoprim, azithromycin, roxithromycin, oxytetracycline, sulfamethoxazole, clarithromycin, lincomycin, sulfadiazine, erythromycin, difloxacin, enrofloxacin, norfloxacin, ofloxacin, levofloxacin, ciprofloxacin
Inland and transitional/coastal sediment and WWTP biosolid samples	PFASs: 11 perfluorocarboxylic acids (C4–C14), 10 perfluorosulfonic acids (C4–C13), 8 precursors (preFOS), 3 fluorotelomer sulfonates, 2 diPAPs, 5 “novel” PFASs
Inland and transitional/coastal sediment and WWTP biosolid samples	Anthelmintics: ivermectin, emamectin benzoate, albendazole, fenbendazole
Inland and transitional/coastal sediment and WWTP biosolid samples	Pyrethroids: bifenthrin, cyfluthrin, λ-cyhalothrin, esfenvalerate, permethrin, resmethrin, deltamethrin, cypermethrin
Inland and transitional/coastal sediment and WWTP biosolid samples	SSAs/UVFs: 2-ethylhexyl-4-methocycinnamate, benzophenone, homosalate, OC, 4-methylbenzylidene camphor

diPAP, polyfluoroalkyl phosphate diester; EHDPP, 2-ethylhexyl diphenyl phosphate; OPE, organophosphate ester; preFOS, perfluorooctane sulfonate precursors; TBHP, Bis-(2-ethylhexyl)tetrabromophthalate; TBOEP, tris(2-butoxyethyl) phosphate; TCEP, tris(2-chloroethyl) phosphate; TCIPP, tris(1-chloro-2-propyl) phosphate; TDCIPP, tris(1,3-dichloro-2-propyl) phosphate; TEHP, tris(2-ethylhexyl) phosphate; TnBP, tri-n-butyl phosphate.

2.4 Data Analysis and Risk Assessment

Further details of the statistical analysis undertaken on each of the data sets analysed are described in the project’s peer-reviewed publications (Ma *et al*., 2024; Sharkey *et al*., 2024a,b, 2025b; Wang *et al*., 2025). In summary, non-parametric statistical tests were used to make comparisons of mean concentrations determined with various metadata recorded (population density, sediment type, river flow speed and year of collection for sediments; PE, treatment type and month of collection for biosolids). For two sample means Mann–Whitney U tests were used, while Kruskal–Wallis H tests were used for testing differences between more than two sample sets (confidence interval of 95%, significance level (p) of 0.05). Where data were recorded to be below the limit of quantification (LoQ), proxy values were determined using LoQ × detection frequency (DF), according to Ali *et al*. (2012). A number of sample concentrations were close to the LoQ, which resulted in average concentrations for some pollutants being close to PNEC values; therefore, using LoQ × DF provided a more realistic estimate. Risk quotients (RQs) were employed to evaluate ecotoxicological risks for targeted compounds in sediment samples collected in inland and transitional/coastal sediments in 2023. RQs were calculated using equation 2.1:

$$RQ = \frac{MEC_{95}}{Lowest\ PNEC} \tag{2.1}$$

MEC_{95} is the 95th percentile concentration in sediment samples and $PNEC_{sed}$ is the PNEC for sediment in the NORMAN Ecotoxicology Database (NORMAN network, n.d.b). The degree of risk was assessed based on the resulting RQ: RQ > 1, high risk; 1 > RQ > 0.1, moderate risk; and RQ < 0.1, low risk. Sample locations that had pollutant concentrations that exceeded relevant $PNEC_{sed}$ values (RQ > 1) were considered potential hotspots for that pollutant. Threshold values for PNECs are generally derived for sediment with a particle size of < 2 mm and are therefore less appropriate for extension to risk assessment of concentrations in sediment with particle sizes of < 63 µm, which are likely to contain higher amounts of clay. The OSPAR assessment methodology (OSPAR, 2025) is more appropriate for sediment samples with particle sizes of < 63 µm; however, it differs from the PNEC approach. The OSPAR approach requires that concentrations be normalised to account for changes in the bulk physical composition of the sediment using total organic carbon content and/or a metal concentration (e.g. aluminium). Analytical standard deviations of the pollutant and normalised concentrations “uncertainties” are also required. In the TERRAChem study it was not possible to complete OSPAR risk assessments on the historical data (< 63 μm), and concentrations without risk assessment are therefore reported for the historical data. However, it should also be noted that for many of the pollutants reported in TERRAChem there are no OSPAR thresholds available.

3 Results

Tables 3.1–3.11 summarise the concentrations of the target chemicals analysed in the TERRAChem project that were detected in inland and transitional/coastal sediment samples and WWTP biosolid samples. Due to the methodological differences in how the samples were collected in 2023 and how the historical samples were prepared prior to analysis (sieving to 2 mm vs 63 µm), the data sets are presented separately.

For brevity, only those chemicals detected in > 25% of samples are presented. Summary statistics, including DFs, are presented; however, high DFs merely reflect the sensitivity of the analytical methods developed for the pollutants and should not be confused with RQ values, which better reflect ecotoxicological risk. Project data are available from the EPA and/or the University of Galway. Sample concentration data for legacy and emerging flame retardants (FRs), PCBs, organophosphate esters (OPEs), antibiotics, UVFs, pyrethroids, anthelmintics and PFASs have been published in the peer-reviewed literature (Ma *et al.*, 2024; Sharkey *et al.*, 2024a,b, 2025b; Wang *et al.*, 2025; Coggins *et al.*, 2026).

3.1 Concentrations of Legacy and Emerging Flame Retardants (µg/kg) in Sediments and Wastewater Treatment Plant-derived Biosolid Samples

Tables 3.1–3.3 summarise concentrations of PBDEs, OPEs and PCBs detected in sediment and WWTP-derived biosolid samples. In sediment samples collected in 2023, tri-n-butyl phosphate (TnBP),

Table 3.1. Summary of concentrations of brominated flame retardants, OPEs and PCBs (µg/kg dry weight) in inland and transitional/coastal sediment samples collected in 2023 (2.0 mm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)	$PNEC_{sed}$[a] (µg/kg)	RQ_{95}[b]
BDE-47	0.07	0.02	< LoQ–0.38	77.8	513	< 0.05
BDE-100	0.19	0.02	< LoQ–4.44	90.1	264	< 0.05
BDE-153	0.37	0.02	< LoQ–4.24	69.1	81.3	< 0.05
BDE-183	0.03	0.03	< LoQ–0.83	49.4	54.8	< 0.05
BDE-209	6.93	0.15	< LoQ–110	86.4	3553	< 0.05
TCEP	1.81	0.02	< LoQ–33.8	75.9	151	< 0.05
TCIPP	5.18	0.03	< LoQ–70.2	61.7	11.1	1.35
TDCIPP	0.70	0.01	< LoQ–15.3	88.9	20.5	0.08
EHDPP	0.88	0.01	< LoQ–23.7	95.1	2.24	0.95
TBOEP	27.6	0.1	< LoQ–214	71.6	842	0.09
TEHP	3.93	0.02	< LoQ–58.9	59.3	24.3	0.58
TnBP	0.24	0.02	< LoQ–3.19	97.5	542	< 0.05
TPHP	0.41	0.01	< LoQ–6.29	61.7	14.8	0.09
PCB-52	0.267	0.013	< LoQ–2.333	98.8	2.7	0.26
PCB-101	0.128	0.015	< LoQ–5.262	74.1	3.0	0.06
PCB-118	0.117	0.013	< LoQ–2.010	72.8	0.6	0.45
PCB-153	0.179	0.025	< LoQ–4.773	75.3	40	< 0.05
PCB-138	0.181	0.045	< LoQ–4.582	66.7	7.9	< 0.05
PCB-180	0.091	0.021	< LoQ–1.366	70.4	12	< 0.05

[a]PNECs in sediment extracted from the NORMAN Ecotoxicology Database in 2024.

[b]RQ_{95} = RQs based on the 95th percentile concentration.

BDE-209, decabromodiphenyl ether; TBOEP, tris(2-butoxyethyl) phosphate; TCEP, tris(2-chloroethyl) phosphate; TCIPP, tris(1-chloro-2-propyl) phosphate; TDCIPP, tris(1,3-dichloro-2-propyl) phosphate; TEHP, tris(2-ethylhexyl) phosphate; TnBP, tri-n-butyl phosphate; TPHP, triphenyl phosphate.

Table 3.2. Summary of concentrations of brominated flame retardants, OPEs and PCBs (μg/kg dry weight) in transitional/coastal sediment samples collected between 2018 and 2022 (63 mm sediment fraction)

Chemical	Mean concentration (μg/kg)	LoQ (μg/kg)	Range (μg/kg)	DF (%)
BDE-47	0.09	0.02	<LoQ–0.44	61.5
BDE-100	0.22	0.02	0.06–0.71	100
BDE-153	0.92	0.02	<LoQ–7.30	94.9
BDE-209	48.4	0.15	0.52–258	100
TCEP	1.22	0.02	<LoQ–5.24	53.8
TCIPP	7.83	0.03	<LoQ–25.9	87.2
TDCIPP	0.48	0.04	<LoQ–3.90	92.3
EHDPP	2.01	0.01	0.23–14.0	100
TBOEP	76.2	0.10	32.4–167	100
TEHP	6.29	0.02	<LoQ–32.6	92.3
TnBP	0.99	0.02	<LoQ–6.55	84.6
TPHP	1.07	0.01	<LoQ–33.1	28.2
PCB-11	0.080	0.016	<LoQ–1.362	43.6
PCB-28/31	0.078	0.008	<LoQ–0.808	35.9
PCB-52	0.562	0.013	0.095	100
PCB-101	0.140	0.015	0.026	100
PCB-118	0.254	0.013	0.108	100
PCB-153	0.317	0.025	0.090	100
PCB-138	0.336	0.045	0.046	100
PCB-180	0.137	0.021	0.044	100

TBOEP, tris(2-butoxyethyl) phosphate; TCEP, tris(2-chloroethyl) phosphate; TCIPP, tris(1-chloro-2-propyl) phosphate; TDCIPP, tris(1,3-dichloro-2-propyl) phosphate; TEHP, tris(2-ethylhexyl) phosphate; TnBP, tri-n-butyl phosphate; TPHP, triphenyl phosphate.

2-ethylhexyl diphenyl phosphate (EHDPP), BDE-100, tris(1,3-dichloro-2-propyl) phosphate (TDCIPP) and decabromodiphenyl ether (BDE-209) were the FRs with the highest DFs; among PCBs, PCB-52 had the highest DF. Tris(2-butoxyethyl) phosphate (TBOEP) was present in the highest concentration, followed by tris(1-chloro-2-propyl) phosphate (TCIPP) and BDE-209.

Unlike the FRs and PCBs, most PCB congeners were detected at higher concentrations in transitional/coastal sediments than in inland sediments (p-value: PCB-11, -52, -101, -153, -138 $<<0.05$; PCB-180 $= 0.051$; PCB-28, -118 > 0.05).

In the historical sediment samples, BDE-209 and BDE-100 had 100% DFs, followed by BDE-153 with 95% DFs. EHDPP and TBOEP had DFs of 100%, and all PCBs apart from PCB-11 and PCB-28/31 had 100% DFs.

Biosolid samples had 100% DFs for all PBDEs (apart from BDE-28), OPEs and PCBs (apart from PCB-28/31 and PCB-11 (95% DF)). BDE-209 and TBOEP were found at the highest concentrations in the biosolid samples (Table 3.3).

3.2 Concentrations of Perfluoroalkyl Substances in Sediments and Wastewater Treatment Plant-derived Biosolid Samples

Concentrations of PFASs detected in sediment and biosolid samples are summarised in Tables 3.4–3.6. All target PFASs were detected in both sediments and biosolids. The most frequently detected PFASs in sediments (2023) were perfluorobutanesulfonic acid (PFBS) (67%), followed by perfluoro-n-undecanoic acid (PFUdA) and PFOS. PFAS DFs for the historical data were higher, with the chemicals perfluorohexanoic acid (PFHxA), perfluorooctanoic acid (PFOA), perfluorodecanoic acid (PFDA), PFUdA and PFOS having 100% DFs. PFOA was the PFAS with the highest reported mean concentration.

Table 3.3. Summary of concentrations of brominated flame retardants, OPEs and PCBs (µg/kg dry weight) in WWTP-derived biosolid samples

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
BDE-28	1.37	0.37	<LoQ–9.07	66.7
BDE-47	17.74	0.20	3.90–51.8	100
BDE-100	15.9	0.20	4.34–40.7	100
BDE-99	41.2	1.9	7.57–217	100
BDE-153	5.26	0.20	0.26–14.7	100
BDE-154	2.57	0.30	0.33–9.12	100
BDE-183	1.72	0.30	0.10–6.33	100
BDE-209	3160	1.5	908–7700	100
TCEP	57.6	0.2	29.7–126	100
TCIPP	338	0.3	87.0–915	100
TDCIPP	49.3	0.4	6.30–358	100
EHDPP	423	0.1	34.87–1320	100
TBOEP	1410	1.0	267–4460	100
TEHP	900	0.2	292–1670	100
TnBP	66.9	0.2	3.48–319	100
TPHP	42.1	0.1	6.15–165	100
PCB-11	0.369	0.016	<LoQ–1.319	95.2
PCB-28/31	0.596	0.008	<LoQ–4.896	28.6
PCB-52	22.75	0.013	6.374–39.93	100
PCB-101	0.758	0.015	0.437–1.380	100
PCB-118	1.332	0.013	0.480–2.946	100
PCB-153	1.713	0.025	0.707–3.952	100
PCB-138	1.907	0.045	0.567–3.648	100
PCB-180	1.002	0.021	0.356–1.830	100

TCEP, tris(2-chloroethyl) phosphate; TEHP, tris(2-ethylhexyl) phosphate; TnBP, tri-n-butyl phosphate; TPHP, triphenyl phosphate.

In the biosolid samples, many target PFASs had DFs of 100% (PFHxA, perfluoroheptanoic acid, PFDA, perfluorohexane sulfonate (PFHxS) and PFOS).

3.3 Concentrations of Antibiotics (µg/kg) in Sediment Samples

Concentrations of the antibiotics targeted in this study in inland and transitional/coastal sediments are summarised in Tables 3.7 and 3.8. As explained in section 2.3, no data are available for antibiotics in biosolid samples. At least one antibiotic was detected in all sediment samples, with clarithromycin displaying the highest DF (87%) in the 2023 data, and levofloxacin displaying the highest DF in the historical data.

3.4 Concentrations of Sunscreen Agents/Ultraviolet Filters (µg/kg) in Sediments and Wastewater Treatment Plant-derived Biosolid Samples

Summary concentrations of SSAs/UVFs detected in sediment and biosolid samples are presented in Tables 3.9–3.11. All target chemicals were detected in both sediments and biosolids. The most frequently detected SSA/UVF was 4-methylbenzylidene camphor (4-MBC), followed by OC and then homosalate (HMS), in inland and transitional/coastal sediments, and OC was present in the highest concentrations. Similarly high DFs for 4-MBC, BP-3 and OC were found in the historical data. In terms of concentration, OC was also the UVF with the highest mean concentration in the historical data.

Table 3.4. Summary of concentrations of PFASs (µg/kg dry weight) in inland and transitional/coastal sediment samples collected in 2023 (2.0 mm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)	$PNEC_{sed}$[a] (µg/kg)	RQ_{95}[b]
PFBA	0.12	0.006	<LoQ–1.5	53	166	<0.05
PFHxA	0.02	0.003	<LoQ–0.18	37	7602	<0.05
PFOA	0.02	0.002	<LoQ–0.20	26	6.1	<0.05
PFDA	0.01	0.001	<LoQ–0.09	35	3.5	<0.05
PFuDA	0.004	0.001	<LoQ–0.047	65	103.3	<0.05
PFDoA	0.01	0.001	<LoQ–0.01	53	485	<0.05
PFTrDA	0.003	0.001	<LoQ–0.032	46	940	<0.05
PFTeDA	0.01	0.001	<LoQ–0.252	27	954	<0.05
PFBS	0.11	0.002	<LoQ–8.344	67	2166	<0.05
PFHxS	0.002	0.001	<LoQ–0.038	27	100.5	<0.05
PFOS	0.06	0.001	<LoQ–2.182	59	0.0067	19.5
FOSA	0.002	0.001	<LoQ–0.025	27	5.7	<0.05
N-EtFOSA	0.002	0.001	<LoQ–0.024	36	3.46	<0.05
N-EtFOSE	0.003	0.001	<LoQ–0.031	31	337	<0.05
4:2 FTS	0.007	0.004	<LoQ–0.050	41	77.5	<0.05
6:2 FTS	0.006	0.002	<LoQ–0.053	32	4.7	<0.05
8:2 diPAP	0.01	0.002	<LoQ–0.074	58	481	<0.05
Gen-X	0.01	0.01	<LoQ–0.06	39	29.5	<0.05
NaDONA	0.007	0.002	<LoQ–0.06	51	NA	NA

[a]PNECs in sediment extracted from the NORMAN Ecotoxicology Database in 2024.

[b]RQ_{95} = RQs based on the 95th percentile concentration.

4:2 FTS, 1H,1H,2H,2H-perfluorohexane sulfonate; 6:2 FTS, 1H,1H,2H,2H-perfluorooctane sulfonate; 8:2 diPAP, bis(1H,1H,2H,2H-perfluorodecyl)phosphate; FOSA, perfluoro-1-octanesulfonamide; Gen-X, 2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid; NA, not available; NaDONA, sodium dodecafluoro-3H-4,8-dioxanonanoate; N-EtFOSA, n-methylperfluoro-1-octansulfonamide; N-EtFOSE, 2-(n-ethylperfluoro-1-octanesulfonamido)-ethanol; PFBA, perfluoro-n-butanoic acid; PFDoA, perfluorododecanoic acid; PFHxS, perfluorohexane sulfonate; PFTeDA, perfluoro-n-tetradecanoic acid; PFTrDA, perfluorotridecanoic acid; PFUdA, perfluoro-n-undecanoic acid.

Higher concentrations of UVFs were detected in WWTP-derived biosolids than in sediment samples. The UVF OC, followed by HMS, was present in the highest concentrations in the biosolid samples.

3.5 Concentrations of Pyrethroids (µg/kg) in Sediment and Biosolid Samples

Concentrations of the eight pyrethroids measured in sediment and biosolid samples are summarised in Tables 3.12–3.14. The most frequently detected pyrethroid in sediment was resmethrin, at 100% DF, followed by permethrin, cyfluthrin and cypermethrin. The maximum concentration detected in sediment was of cypermethrin at 76.1 µg/kg, followed by permethrin at 74.5 µg/kg.

In the WWTP-derived biosolid samples, 100% DFs were observed for all target pyrethroids. Cyfluthrin (1740 µg/kg) and permethrin (485 µg/kg) were the pyrethroids detected at the highest concentrations.

3.6 Concentrations of Anthelmintics (µg/kg) in Sediments and Wastewater Treatment Plant-derived Biosolid Samples

Concentrations of the four anthelmintics measured in sediment and biosolid samples are summarised in Tables 3.15–3.17. The most frequently detected anthelmintic in sediment was fenbendazole (86.4%), followed by emamectin benzoate (69.1%). Slightly higher DFs for all four anthelmintics were found in the historical data. In terms of concentration, fenbendazole was also the chemical with the highest mean concentration in the historical data.

The maximum concentration detected for all target chemicals in biosolid samples was 5.87 µg/kg for fenbendazole.

Table 3.5. Summary of concentrations of PFASs (µg/kg dry weight) in transitional/coastal sediment samples collected between 2018 and 2022 (63 µm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
PFBA	0.05	0.003	<LoQ–0.18	82
PFHxA	0.06	0.00013	0.01–0.29	100
PFOA	0.14	0.0008	0.01–0.61	100
PFDA	0.11	0.0006	0.02–0.33	100
PFUdA	0.03	0.0002	0.002–0.08	100
PFDoDA	0.02	0.0006	<LoQ–0.07	85
PFTrDA	0.01	0.0005	<LoQ–0.04	49
PFTeDA	0.003	0.0003	<LoQ–0.03	33
PFBS	0.003	0.0011	<LoQ–0.03	44
PFHxS	0.003	0.0003	<LoQ–0.03	39
PFOS	0.08	0.0003	0.01–0.39	100
FOSA	0.002	0.0004	<LoQ–0.02	26
N-EtFOSA	0.002	0.0003	<LoQ–0.01	33
N-EtFOSE	0.005	0.0004	<LoQ–0.04	44
4:2 FTS	<0.004	0.0010	<LoQ–0.63	78
8:2 diPAP	0.03	0.0013	<LoQ–0.18	49
HFPO-DA/Gen-X	0.01	0.0052	<LoQ–0.06	39
NaDONA	0.007	0.0008	<LoQ–0.06	86

4:2 FTS, 1H,1H,2H,2H-perfluorooctane sulfonate; 8:2 diPAP, bis(1H,1H,2H,2H-perfluorodecyl)phosphate; FOSA, perfluoro-1-octanesulfonamide; HFPO-DA/Gen-X, 2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid; NA, not available; NaDONA, sodium dodecafluoro-3H-4,8-dioxanonanoate; N-EtFOSA, n-methylperfluoro-1-octansulfonamide; N-EtFOSE, 2-(n-ethylperfluoro-1-octanesulfonamido)-ethanol; PFBA, perfluoro-n-butanoic acid; PFDoA, perfluorododecanoic acid; PFDoDA, perfluorododecanoic acid; PFHxS, perfluorohexane sulfonate; PFTeDA, perfluoro-n-tetradecanoic acid; PFTrDA, perfluorotridecanoic acid; PFUdA, perfluoro-n-undecanoic acid.

Table 3.6. Summary of concentrations of PFASs (µg/kg dry weight) in WWTP-derived biosolid samples

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
PFBA	0.41	0.0300	<LoQ–1.1	82
PFHxA	0.64	0.0264	0.05–2.5	100
PFOA	0.41	0.0076	<LoQ–1.7	86
PFDA	1.20	0.0124	0.17–4.8	100
PFUdA	0.41	0.0023	<LoQ–2.1	91
PFDoDA	0.32	0.0065	<LoQ–0.86	86
PFTrDA	0.02	0.0048	<LoQ–0.10	29
PFTeDA	0.05	0.0027	<LoQ–0.23	48
PFBS	3.11	0.0105	<LoQ–65	52
PFHxS	0.12	0.0061	0.0208–0.31	100
PFOS	8.20	0.0055	1.4–53	100
FOSA	0.28	0.0044	<LoQ–1.1	91
N-EtFOSA	0.03	0.0035	<LoQ–0.19	33
N-EtFOSE	0.43	0.0037	<LoQ–1.4	86
4:2 FTS	0.26	0.0222	<LoQ–1.7	67
6:2 FTS	0.40	0.0099	<LoQ–4.2	62
8:2 diPAP	0.38	0.0128	<LoQ–2.0	71
HFPO-DA/Gen X	0.12	0.0516	<LoQ–0.44	38
NaDONA	0.241	0.0082	<LoQ–0.9477	85.7

4:2 FTS, 1H,1H,2H,2H-perfluorohexane sulfonate; 6:2 FTS, 1H,1H,2H,2H-perfluorooctane sulfonate; 8:2 diPAP, bis(1H,1H,2H,2H-perfluorodecyl)phosphate; FOSA, perfluoro-1-octanesulfonamide; HFPO-DA/Gen-X, 2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid; NaDONA, sodium dodecafluoro-3H-4,8-dioxanonanoate; N-EtFOSA, n-methylperfluoro-1-octansulfonamide; N-EtFOSE, 2-(n-ethylperfluoro-1-octanesulfonamido)-ethanol; PFBA, perfluoro-n-butanoic acid; PFDoDA, perfluorododecanoic acid; PFHxS, perfluorohexane sulfonate; PFTeDA, perfluoro-n-tetradecanoic acid; PFTrDA, perfluorotridecanoic acid; PFUdA, perfluoro-n-undecanoic acid.

Table 3.7. Summary of concentrations of antibiotics (µg/kg dry weight) in inland and transitional/coastal sediment samples collected in 2023 (2.0 mm sediment fraction)

Antibiotic	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)	$PNEC_{sed}$[a] (µg/kg)	RQ_{95}[b]
Azithromycin	0.185	0.093	<LoQ–5.39	38.8	40.8	<0.05
Clarithromycin	6.65	0.411	<LoQ–78.5	87.2	269	0.10
Sulphamethoxazole	0.077	0.047	<LoQ–0.977	33.3	3.67	0.09
Ciprofloxacin[c]	<LoQ	5.04	<LoQ–7.76	1.27	1.49	1.48

[a]PNECs in sediment extracted from the NORMAN Ecotoxicology Database in 2024.

[b]RQ_{95} = RQs based on the 95th percentile concentration.

[c]Based on a single sample that was ≥ the analytical method LoQ.

Table 3.8. Summary of concentrations of antibiotics (µg/kg dry weight) in transitional/coastal sediment samples collected between 2018 and 2022 (63 µm sediment fraction)

Antibiotic	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
Clarithromycin	1.92	1.54	<LoQ–12.9	35.9
Levofloxacin	0.22	0.047	<LoQ–1.99	43.6

Table 3.9. Summary of concentrations of SSAs/UVFs (µg/kg dry weight) in inland and transitional/coastal sediment samples collected in 2023 (2.0 mm sediment fraction)

SSA/UVF	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)	$PNEC_{sed}$[a] (µg/kg)	RQ_{95}[b]
4-MBC	1.87	0.143	<LoQ–10.69	93	14.4	0.40
BP-3	0.19	0.020	<LoQ–3.759	61	122	<0.05
OC	3.66	0.127	<LoQ–31.79	62	606	<0.05

[a]PNECs in sediment extracted from the NORMAN Ecotoxicology Database in 2024.

[b]RQ_{95} = RQ based on the 95th percentile of the maximum measured environmental concentration.

Table 3.10. Summary of concentrations of SSAs/UVFs (µg/kg dry weight) in transitional/coastal sediments collected between 2018 and 2022 (63 mm sediment fraction)

SSA/UVF	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
4-MBC	4.51	0.14	1.95–9.77	100
BP-3	0.82	0.02	0.30–1.78	100
OC	6.59	0.13	<LoQ–46.5	79.5

Table 3.11. Summary of concentrations of SSAs/UVFs (µg/kg dry weight) in WWTP-derived biosolid samples

SSA/UVF	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
4-MBC	13.91	0.714	4.596–30.04	100
BP-3	1.28	0.102	<LoQ–7.77	47.6
OC	666	0.637	90.06–1875	100
EHMC	12.65	0.175	<LoQ–63.87	42.9
HMS	456	7.092	122.0–914.4	100

Table 3.12. Summary of concentrations of pyrethroids (µg/kg dry weight) in inland and transitional/coastal sediments collected in 2023 (2.0 mm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)	$PNEC_{sed}$[a] (µg/kg)	RQ_{95}[b]
Resmethrin	3.65	0.8	0.23–22.5	100	18.3	0.68
Bifenthrin	0.07	0.3	<LoQ–1.73	64.2	105,078	0
λ-cyhalothrin	0.11	0.2	<LoQ–1.07	74.1	0.2	1.57
Permethrin	8.53	0.3	<LoQ–74.5	97.5	0.8	34.84
Cyfluthrin	8.07	0.6	<LoQ–68.5	95.1	0.5	51.36
Cypermethrin	7.12	0.3	<LoQ–76.1	93.8	0.2	244
Esfenvalerate	0.60	0.2	<LoQ–5.5	82.7	0.0045	455
Deltamethrin	1.55	0.3	<LoQ–11.6	61.7	0.0046	1425

[a]$PNEC_{sed}$ = PNECs in sediment extracted from the NORMAN Ecotoxicology Database in 2024.

[b]RQ_{95} = RQs based on the 95th percentile concentration.

Table 3.13. Summary of concentrations of pyrethroids (µg/kg dry weight) in transitional/coastal sediments collected between 2018 and 2022 (63 mm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
Resmethrin	0.73	0.127	<LoQ–2.09	92.3
Bifenthrin	0.05	0.009	<LoQ–0.28	79.5
λ-cyhalothrin	0.10	0.016	<LoQ–1.71	94.9
Permethrin	9.06	0.011	3.84–16.7	100
Cyfluthrin	8.89	0.128	4.17–21.0	100
Cypermethrin	9.51	0.060	4.60–31.0	100
Esfenvalerate	0.54	0.034	<LoQ–4.25	89.7
Deltamethrin	2.22	0.326	<LoQ–10.9	94.9

Table 3.14. Summary of concentrations of pyrethroids (µg/kg dry weight) in WWTP-derived biosolid samples

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
Resmethrin	13.4	0.8	2.16–48.8	100
Bifenthrin	2.31	0.3	0.51–6.43	100
λ-cyhalothrin	8.79	0.2	0.23–60.7	100
Permethrin	265	0.3	43.1–485	100
Cyfluthrin	1027	0.6	540–1740	100
Cypermethrin	143	0.3	28.0–360	100
Esfenvalerate	121	0.2	11.5–294	100
Deltamethrin	215	0.3	25.6–672	100

Table 3.15. Summary of concentrations of anthelmintics (µg/kg dry weight) in inland and transitional/coastal sediment samples collected in 2023 (2.0 mm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)	$PNEC_{sed}$[a] (µg/kg)	RQ_{95}[b]
Ivermectin	0.066	0.003	<LoQ–0.367	65.4	NA	NA
Emamectin benzoate	0.051	0.001	<LoQ–0.434	69.1	NA	NA
Albendazole	0.072	0.002	<LoQ–0.760	38.3	7.65	0.03
Fenbendazole	0.198	0.006	<LoQ–1.428	86.4	8.41	0.10

[a]$PNEC_{sed}$ = PNECs for sediment extracted from the NORMAN Ecotoxicology Database in 2024.
[b]RQ_{95} = RQs based on the 95th percentile concentration.
NA, not available.

Table 3.16. Summary of concentrations of anthelmintics (µg/kg dry weight) in transitional/coastal sediment samples collected between 2018 and 2022 (63 µm sediment fraction)

Chemical	Mean concentration (µg/kg)	LoQ (µg/kg)	Range (µg/kg)	DF (%)
Ivermectin	0.112	0.003	<LoQ–0.35	92.3
Emamectin benzoate	0.042	0.001	<LoQ–0.27	76.9
Albendazole	0.189	0.002	<LoQ–1.24	97.4
Fenbendazole	0.471	0.007	0.061–2.88	100

Table 3.17. Summary of concentrations (μg/kg dry weight) of anthelmintics in WWTP-derived biosolid samples

Chemical	Mean concentration (μg/kg)	LoQ (μg/kg)	Range (μg/kg)	DF (%)
Ivermectin	0.60	0.03	0.24–2.27	100
Emamectin benzoate	0.02	0.01	<LoQ–0.04	66.7
Albendazole	0.36	0.02	0.20–0.94	100
Fenbendazole	0.91	0.03	<LoQ–5.87	85.7

4 Discussion

A total of 92 chemical contaminants were analysed in samples collected from inland and transitional/coastal sediments and from biosolids derived from WWTPs at various sites across Ireland. Although historical sediment samples were made available to the project by the Marine Institute, there were insufficient sample replicates per location over multiple years to support a robust temporal analysis of each of the target chemicals at each of the locations sampled. However, the TERRAChem study does provide a baseline assessment for 92 chemical contaminants at 97 sites on which future trend monitoring could be performed. The historical samples were sieved to a 63 mm mesh size and therefore are not directly comparable with samples collected in 2023; samples sieved to the smaller mesh size are likely to contain higher pollutant concentrations due to the greater surface-to-mass ratio. Average DFs for target chemicals of 85% and 41% were observed for biosolid and sediment samples, respectively. Results for each target chemical group are discussed in the following section.

4.1 Flame Retardants and Polychlorinated Biphenyls in Inland and Transitional/Coastal Sediments

In the 2023 samples, no significant differences were observed between concentrations detected in inland and transitional/coastal sediment samples for any of the brominated flame retardants (BFRs) or OPEs. In contrast, many PCB congeners were detected at higher concentrations in transitional/coastal sediments than in inland sediments, likely to be due to decreased usage recently and the washing-out of PCBs from rapidly moving inland waters to transitional/coastal waters. Two coastal sites had elevated PCB concentrations, perhaps related to local industrial activity, although there were no obvious local sources. Samples collected near WWTP discharge points did not have higher concentrations of target chemicals than samples taken from remote areas ($p > 0.05$), concurring with previous UK research findings (Martinez-Carballo *et al*., 2007; Onoja *et al*., 2023). Although the TERRAChem data set is limited by small sample numbers (thus limiting the ability to conduct robust statistical analysis), population density showed little significance in terms of sediment concentration, even for those chemicals for which there were statistically significant differences observed between sites (tris(2-ethylhexyl)phosphate (TEHP), tris(2-chloroethyl) phosphate (TCEP) and EHDPP).

Pollutant mean concentrations were higher in historical samples than in the samples collected in 2023, most likely due to the smaller particle size of the sediment. For sites with data for 4 consecutive years, concentrations of OPE were relatively consistent, suggesting constant emissions to the environment (Sharkey *et al*., 2024a).

4.2 Flame Retardants in Wastewater Treatment Plant-derived Biosolid Samples

BDE-209 and TBOEP were found at the highest concentrations in biosolids; BDE-209 has previously been reported as the most prevalent BFR in Irish waste furniture and electronics (Harrad *et al*., 2019, 2023a) and landfill leachate (Harrad *et al*., 2020, 2023b). Moreover, TBOEP was the OPE detected at the highest average concentration in UK river sediment (Onoja *et al*., 2023). No clear trend between the type of influent stream and resultant levels of any FR could be established. Again, small sample numbers limit the ability to identify trends in the data collected.

The impact of sludge treatment processes, anaerobic digestion and thermal drying was not shown to result in significantly higher or lower levels than other treatment types. Data analysis was limited by small sample numbers; however, typical treatment methods are not designed to remove such chemicals. Significant trends were, however, observed related to the PE of the WWTPs. For several BFRs and PCBs, higher concentrations were frequently detected in samples collected from "medium"-sized plants (PE of 50,000–100,000), while for OPEs higher concentrations were found in samples from the larger plants (PE > 100,000). Results show (see Figure A3.1) that the highest concentrations of some target chemicals occurred in samples collected in September, which is possibly related to higher rainfall during this period. Higher rainfall amounts can significantly affect influent to WWTPs, either by diluting the incoming wastewater or by causing storm overflows that result in wastewater being diverted from the treatment process as the plant capacity is exceeded (Tipper *et al*., 2024).

4.2.1 Comparisons with international data

PBDE concentrations reported in WWTP-derived biosolids in this study are for some congeners at the high end of those reported internationally (e.g. BDE-209) and for others are within the range of reported concentrations (e.g. BDE-47, BDE-100, BDE-99) (a detailed comparison is provided in Sharkey *et al*., 2024a, and in Tables A2.1 and A2.2). Concentrations are comparable with those reported for Australia, the UK and South Korea (Lee *et al*., 2014; McGrath *et al*., 2020; Rigby *et al*., 2021) and lower than levels found in the USA (Venkatesan and Halden, 2014). The OPE concentrations reported in this study exceed those reported internationally; TBOEP and EHDPP are the dominant congeners, and the profile differs significantly from that reported for China, Spain and the USA (Cristale *et al*., 2016; Gao *et al*., 2016; Wang *et al*., 2019). While concentrations exceed those in the UK (Stevens *et al*., 2003), the profile of the measured OPEs is similar – characterised by high concentrations of TCIPP with relatively low levels of TCEP, triphenyl phosphate and TDCIPP. PCB concentrations in Irish biosolids fall within the middle to lower range of values reported globally. Although many commercial mixtures contain combinations of the seven PCB congeners analysed in this study (excluding PCB-11), the reason for the relatively high concentration of PCB-52 remains unclear. Studies of indoor environments in the UK have also reported elevated levels of PCB-52 compared with other congeners (Currado and Harrad, 1998). It is important to acknowledge that differences in sampling and analytical methodologies between studies may introduce minor discrepancies in the data; however, direct comparisons are made here in the absence of a standardised approach.

Concentrations in sediment reported in this study exceed the environmental background concentrations for inland and transitional/coastal sediments reported by OSPAR (OSPAR, 2022a), but are within the range reported internationally for BFRs and OPEs. For many of the target PBDE congeners, TERRAChem concentrations are significantly lower than those previously reported, for example in data from Japan (BDE-209, BDE-47), the Netherlands (BDE-209) and the UK (BDE-209) (Brandsma *et al*., 2015; Matsukami *et al*., 2015; Gianci *et al*., 2019). Total PBDEs (ΣPBDEs) are slightly higher than those reported in other parts of Europe (Gianci *et al*., 2019), while concentrations of OPEs exceed those reported for Greece, the Netherlands, the USA and Japan (Brandsma *et al*., 2015; Matsukami *et al*., 2015; Giulvio *et al*., 2017; Sutton *et al*., 2019), but are lower than those reported for Germany (the Elbe), Austria and Spain (Stachel *et al*., 2005; Martinez-Carballo *et al*., 2007; Cristale *et al*., 2013). The dominance of the BDE-209 congener in Irish samples most likely reflects its widespread use up to its banning in 2019 (UNEP, 2019). Concentrations of OPEs in Irish and UK sediments are similar in terms of congener profile and magnitude, likely to be due to similar fire safety standards (De Boer *et al*., 2024). PCB concentrations in sediments reported in this study are comparable to those previously submitted to OSPAR (OSPAR, 2024), with most values falling below the Background Assessment Criteria and Environmental Assessment Criteria. Overall, concentrations in Ireland are relatively low compared with other European countries, although a few sites show slightly elevated concentrations of PCB-101 and PCB-118, exceeding the Environmental Assessment Criteria thresholds.

4.2.2 Ecotoxicological risk assessment – flame retardant and polychlorinated biphenyl concentrations in sediment samples

RQ values based on MEC_{95} concentrations for each compound show moderate risk in sediments for PCB-52, PCB-118, TEHP and EHDPP ($0.1 < RQ < 1$) and high risk for TCIPP ($RQ > 1$). At a number of individual sites TCIPP, EHDPP and PCB-118 are present at concentrations associated with moderate or high risk (60%, 54% and 71%, respectively). While other compounds exceed the low-risk quotient at some sites, these higher values are primarily due to a limited number of samples exhibiting elevated concentrations of multiple chemicals, suggesting potential point-source pollution at these locations. TDCIPP is also one of the more dominant (mean concentration of 7.83 µg/kg) OPEs measured in the historical samples. Given the results of the PNEC risk assessment (< 2 mm sediment data), future studies should explore additional risk assessment approaches for this chemical using the 63 mm sediment concentration data.

4.3 Perfluoroalkyl Substances in Inland and Transitional/Coastal Sediments

To the authors' knowledge, this study presents the first global report of the concentrations of five PFASs in freshwater and transitional/coastal sediments. These include perfluoroundecanesulfonic acid (7.4%), perfluorododecanesulfonic acid (8.6%), perfluorotridecane sulfonate (7.4%) and 9-chlorohexadecafluoro-3-oxanonane-1-sulfonate (2.5%) (DFs indicated in parentheses; they include only 2023 data). Other novel PFASs such as sodium dodecafluoro-3H-4,8-dioxanonanoate (NaDONA), perfluoro-4-ethylcyclohexanesulfonate and 2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid (Gen-X) were found at low concentrations and with low DFs across most sediment samples, with the exception of two sediment sites where markedly higher relative abundances of Gen-X (59% and 69% of Σ_{39}PFAS) were detected (0.27 µg/kg and 0.37 µg/kg). This suggests the potential presence of unidentified local sources of Gen-X at these locations. There was no significant difference between either concentrations or relative abundance (expressed as %ΣPFAS$_{39}$) of any individual PFAS in inland and transitional/coastal sediments; this suggests that similar sources and source strengths impact both sediment types and that hydrological factors such as salinity are not a major influence on benthic PFAS contamination. A caveat is that for PFOA the difference in concentrations (averages of 0.02 µg/kg and 0.006 µg/kg dry weight in riverine and transitional/coastal sediments) was near-significant ($p = 0.07$) and its relative contribution to ΣPFCAs in riverine sediments (average = 12.5%) exceeded significantly ($p = 0.02$) that in estuarine sediments (2.7%). While lower concentrations of other contaminants have previously been attributed to flocculation-deposition of sediment, controlled by salinity with increasing proximity to the coast, it is unclear why this would apply to PFOA only; it may perhaps be due to the low DF for PFOA (26%).

There was no significant correlation ($p > 0.05$) between PFAS concentrations and PE for any of the target PFASs, with the exception of perfluorododecanoic acid, where the correlation was driven by two of the most contaminated samples, collected in the Dublin area. The origin of the elevated perfluorododecanoic acid concentrations in these samples remains uncertain. Although no significant correlations between river flow rate and the concentrations of most PFASs were found, notable positive correlations were observed for perfluorononanoic acid, perfluorotridecanoic acid, PFOS, 2-(n-ethylperfluoro-1-octanesulfonamido)-ethanol, 1H,1H,2H,2H-perfluorooctane sulfonate, bis(1H,1H,2H,2H-perfluorodecyl)phosphate and NaDONA. One possible explanation for the higher concentrations at faster river flow rates could be increased run-off from land during periods of heavy precipitation. One historical transitional/coastal sediment sample collected in 2021 was dominated by 11-chloroeicosafluoro-3-oxaundecane-1-sulfonate (2.6 ng/g and 90% of S$_{39}$PFAS in that sample), suggesting a potential local source of emissions at this site.

4.4 Perfluoroalkyl Substances in Wastewater Treatment Plant-derived Biosolids

There was a notable difference in PFAS patterns between biosolid and sediment samples, suggesting that WWTP-derived biosolids are just one of many sources of PFASs in Irish sediment. In the sediment profile, perfluorocarboxylic acids (PFCAs) dominate (51% S$_{39}$PFAS); in comparison, in biosolids, PFCAs are present at, on average, 26% S$_{39}$PFAS, with SPFSAs the main contributing group (37% S$_{39}$PFAS). PFOS was the dominant PFSA in biosolids (90% SPFSAs), compared with just 51% SPFSAs in sediment. Perfluoroheptanoic acid and PFDA were also present at higher concentrations than commonly reported; similarly to PFOA, this is most likely due to their higher octanol-water partitioning coefficient (logK_{ow}) values, which indicate a stronger tendency to partition into organic-rich matrices such as biosolids. The relationship between the PEs served by each WWTP, seasonal precipitation patterns and PFAS concentrations in biosolids was examined, but no significant correlations ($p < 0.05$) were found. Similarly, no clear impact of sludge treatment technologies on PFAS concentrations was observed across the WWTPs studied. However, this does not imply that the treatment technologies were ineffective, as PFAS inputs to each WWTP will vary substantially. Overall, PFAS concentrations in WWTP biosolids appear to be determined by the complex interplay of many factors; understanding these factors will require further detailed investigations.

4.4.1 Comparisons with international data

Overall, sediment concentrations recorded in this study are at the lower end of those reported internationally, including data reported for PFCAs and PFSAs from France (Macorps *et al*., 2023) and Spain (Campo *et al*., 2016; Pignotti *et al*., 2017). Data recorded for sediments contaminated due to the use of aqueous film-forming foam at a location in Sweden (Mussabek *et al*., 2019) provide the only comparator data in Europe for perfluoro-1-octanesulfonamidoacetic acids, n-ethylperfluoro-1-octanesulfonamidoacetic acid, n-methylperfluoro-1-octanesulfonamidoacetic acid, n-methylperfluoro-1-octansulfonamide, n-methylperfluoro-1-octansulfonamide, 2-(n-ethylperfluoro-1-octanesulfonamido)-ethanol and 2-(n-methylperfluoro-1-octanesulfonamido)-ethanol. Perfluoro-1-octanesulfonamide and n-methylperfluoro-1-octansulfonamide were detectable in TERRAChem samples and non-detectable in the Swedish study (Mussabek *et al*., 2019).

WWTP-derived biosolid concentration data for PFCAs, PFHxS, PFOS and perfluorooctane sulfonate precursors are at the low end of concentrations reported globally. Concentrations of 3 fluorotelomer sulfonates (FTSs), polyfluoroalkyl phosphate diesters (diPAPs) and neutral PFASs are in the middle of the range reported globally, while concentrations of PFBS fall within the higher end of the range. A more detailed comparison of the TERRAChem PFAS data with previously reported global data is available in Ma *et al*. (2024) and in Tables A2.3 and A2.4.

4.4.2 Ecotoxicological risk assessment – perfluoroalkyl substances in sediment samples

The RQ values for each of the target PFAS in both sets of sediment samples were in the low-risk category (RQ < 0.1) for all chemicals but PFOS, for which the PNEC of 0.0067 µg/kg was exceeded in 52% of samples collected (RQ_{95} value of 19.5; see Table 3.2). PFOS is also characterised by a high DF (100%) and is the PFAS with the third highest concentration (after PFOA and PFDA) in the historical data; it therefore warrants inclusion in future risk assessments more suited to particle sizes < 63 mm.

4.5 Antibiotics in Inland and Transitional/Coastal Sediments

No significant differences in antibiotic concentrations were observed between inland and transitional/coastal sediments. Additionally, no significant correlations were found between antibiotic levels and either the population size of the surrounding area or water velocity. At least one antibiotic was detected above the method's limit of detection (LoD) in all samples, and in 77 out of 80 samples at least one antibiotic was quantified above the method's LoQ. Clarithromycin was the most frequently detected antibiotic (87.2%), followed by azithromycin (38.8%), sulfamethoxazole (33.3%) and trimethoprim (20.5%).

Wastewater discharges from human or animal sources are considered the primary route of antibiotic entry into the environment (Carvalho and Santos, 2016). In this study, samples collected within 0.1 km of wastewater discharge points exhibited significantly higher total antibiotic concentrations (49.3 ± 24.7 µg/kg) than those collected within 5 km (4.7 ± 3.8 µg/kg). An exception to this trend was the detection of high clarithromycin concentrations (> 10 µg/kg) in two outlier samples ($p > 0.02$) taken at two sites located further away from known discharge sources, most likely related to local anthropogenic sources. Samples collected at intermediate distances (0.1–5 km) showed moderate contamination (9.0 ± 9.7 µg/kg), with elevated concentrations generally associated with high PEs, wastewater treatment discharges and other anthropogenic sources.

Comparing sediment concentrations with the distribution profiles reported for Irish river waters (O'Flynn, 2024) and WWTP effluents (Rodriguez-Mozaz *et al*., 2020), clarithromycin is much more abundant in sediment samples, while sulfamethoxazole is more prevalent in water samples. Differences across environmental matrices are most likely due to the $\log K_{ow}$ of the compounds; sulfamethoxazole is more hydrophilic ($\log K_{ow}$ = 0.7–0.89) than clarithromycin ($\log K_{ow}$ = 1.7–3.16). The low ecotoxicological risk for the majority of antibiotic residues assessed in sediment therefore may not translate to an equivalent risk in other environmental compartments. The partitioning behaviour of antibiotics should therefore be taken into consideration in future antibiotic residue assessment and monitoring programmes.

4.5.1 Comparisons with international data

Concentrations of antibiotics in Irish sediments appear to be at the lower end of the range reported for other European countries, apart from clarithromycin, which was detected at higher DFs and concentrations than in many previous reports. It should be noted that the available comparison data from France and Spain (Feitosa-Felizzola and Chiron, 2009; Da Silva *et al.*, 2011) were collected over 15 years ago and, since then, global antibiotic usage has increased (Browne *et al.*, 2021). Concentrations reported in this study are also at the lower end of the range reported for the USA (Kim and Carlson, 2006); however, that study was completed between 2003 and 2005, and antibiotic use has increased significantly since (a comparison of TERRAChem antibiotic data with previous published studies is available in Sharkey *et al.* (2024b) and in Table A2.5).

4.5.2 Ecotoxicological risk assessment – antibiotic concentrations in Irish sediments

For most of the samples analysed, antibiotic concentrations were below the "low risk" threshold when compared with available $PNEC_{sed}$ values. Exceptions included clarithromycin and sulfamethoxazole, for which several samples fell into the "moderate risk" category ($0.1 < RQ < 1$). Only a single sample exceeded the 0.1 RQ threshold for azithromycin, enrofloxacin and ciprofloxacin. In the case of ciprofloxacin, one sample concentration surpassed both the method's LoQ and the PNEC, while 18% of samples exceeded the method's LoD. These findings suggest that a follow-up study using a more sensitive analytical technique is needed to more accurately assess the environmental risk posed by ciprofloxacin. Future monitoring programmes should include antibiotics identified as posing a moderate or high ecotoxicological risk. The measurement strategy should also account for the partitioning preferences of individual species into different environmental matrices, as this is a key factor in assessing environmental risk.

4.6 Organic Ultraviolet Filters in Inland and Transitional/Coastal Sediments

There was no significant difference between UVF concentrations detected in the 2023 inland and transitional/coastal sediment concentrations ($p < 0.05$). The UVF OC was present in the highest concentrations, followed by HMS and 4-MBC, with 4-MBC the most frequently detected (DF = 93%). The Cosmetics Products Regulation (European Union, 2009) specifies an allowable concentration in cosmetics of 9–10% for OC, up to 10% for EHMC and 0.5–6.0% for BP-3. Until recently, HMS and 4-MBC were permitted at 4% and 10%, respectively. Similarly to previous studies (Ramos *et al.*, 2016; Duis *et al.*, 2022), the sample sites in our study that were downstream of or adjacent to (within 0.5 km of) urban wastewater sites or sewage treatment emission points (EPA, 2024b) had significantly higher sediment concentrations of ΣUVFs ($p < 0.01$). However, elevated concentrations were also seen in a few samples from areas isolated from these sources, suggesting that other diffuse sources may contribute to environmental uptake. Higher concentrations of UVFs were found in the historical samples; similarly to the 2023 data, OC was dominant in terms of mean concentration (6.6 mg/kg).

4.7 Organic Ultraviolet Filters in Wastewater Treatment Plant-derived Biosolids

Similarly to the sediment samples, the highest concentrations detected in biosolid samples were that of UVF OC (average concentration 666 µg/kg), followed by HMS (average concentration 456 µg/kg). 4-MBC, although the third-most prevalent UVF detected in sediment samples, was present at much lower levels in biosolids (compared with OC and HMS). Although limited by low sample numbers, statistical analysis showed no significant trends in the relationships between UVF biosolid concentration and date of sample collection, PE or treatment technologies.

4.7.1 Comparisons with international data

Among the five UVFs analysed in sediment, EHMC and BP-3 are the most widely used organic UVFs in the cosmetics industry (Chayada *et al*., 2021; Menzie *et al*., 2022; Pniewska and Kalinowska, 2024); however, the concentrations of both EHMC and BP-3 recorded in this study are low compared with both those of the other target UVFs in this study and those reported in previous similar research (Gago-Ferrero *et al*., 2011a; Peng *et al*., 2017; Li *et al*., 2022; Costa *et al*., 2024). A comparison between previous reports of UVF concentrations in sediment and WWTP-derived biosolids is presented in Tables A2.6 and A2.7. OC sediment concentrations reported in this study are lower than those reported internationally, for example in China (Li *et al*., 2022), Norway (Langford *et al*., 2015) and Spain (Gago-Ferrero *et al*., 2011a). HMS concentrations are within the range of those reported in China (Li *et al*., 2022) and lower than those reported for Admiralty Bay, Antarctica (Costa *et al*., 2024).

Despite the elevated levels of OC and HMS in Irish biosolids, concentrations of almost all UVFs determined (to the authors' knowledge there has only been one previous report of HMS in WWTP-derived biosolids) are low compared with data reported internationally (Plagellat *et al*., 2006; Nieto *et al*., 2009; Gago-Ferrero *et al*., 2011b; Liu *et al*., 2011; Mao *et al*., 2020). This, coupled with the generally lower levels observed in sediments, points to lower use of UVF-based products in Ireland compared with the EU average (Statista, 2024). Given the dearth of data on UVFs in our environment, along with recent restrictions (HMS and 4-MBC) at the EU level due to concerns regarding aquatic toxicity, further environmental monitoring of HMS is recommended.

4.7.2 Ecotoxicological risk assessment – ultraviolet filters in sediment samples

Calculated RQs for inland and transitional/coastal sediment data suggest that 4-MBC, EHMC (despite a low DF compared with the other UVFs) and HMS present a moderate ecotoxicological risk based on current $PNEC_{sed}$ values published by the NORMAN network. Concentrations of both OC and BP-3 suggest low ecotoxicological risk in Irish sediments. However, both compounds are included in the WFD Watch List, highlighting the need for continued environmental monitoring. Should future work lead to a revision of existing $PNEC_{sed}$ values, additional risk assessments may be warranted.

4.8 Pyrethroids in Inland and Transitional/Coastal Sediments

Of the eight pyrethroids analysed in this study, resmethrin, cyfluthrin, permethrin, cypermethrin and deltamethrin were present in the highest concentrations, at least one order of magnitude higher than the other target pyrethroids, and at DFs exceeding 90%. There was no significant difference between concentrations (of both $\sum_8$ pyrethroids and individual target chemicals) detected in inland and transitional/coastal sediment samples, and the pyrethroid profile for each sediment type was similar – with cyfluthrin at 31.4%, permethrin at 28.2% and cypermethrin at 21.0% in transitional/coastal sediments, and permethrin at 29.0%, cyfluthrin at 25.7% and cypermethrin at 25.2% in riverine sediments – which suggests that these are the mostly frequently used pyrethroids in Ireland and also warrant further investigation. A positive correlation was found between the degree of flow attenuation provided by rivers and lakes (Flow Attenuation from Reservoirs and Lakes Index) (EPA, 2024b) and concentrations of the pyrethroids resmethrin ($r = 0.513$, $p < 0.001$) and cypermethrin ($r = 0.274$, $p < 0.039$) only, suggesting that stable river flow may be an important factor in allowing the accumulation of both insecticides in sediment. Concentrations of cypermethrin were negatively correlated ($r = -0.333$, $p = 0.011$) with average rainfall amounts, suggesting that higher rainfall leads to lower accumulation of this insecticide in sediments. Meanwhile, concentrations of λ-cyhalothrin ($r = 0.266$, $p < 0.016$) and cyfluthrin ($r = 0.277$, $p < 0.012$) were positively correlated with population size, suggesting that anthropogenic activities are a likely source of environmental contamination for both. Similarly to the 2023 data, in the historical sediment data, cyfluthrin, permethrin and cypermethrin dominate in terms of concentration. At three sites where more than 3 years of data were available, concentrations of Σ_8 pyrethroids were significantly lower ($p = 0.042$) than in the previous years.

4.9 Pyrethroids in Wastewater Treatment Plant-derived Biosolids

Similarly to the other chemicals investigated in this study, pyrethroid concentrations in biosolid samples exceed significantly those in sediment samples. All target pyrethroids were detected with 100% DF in the WWTP-derived biosolid samples. Of all the target pyrethroids investigated, the insecticide cyfluthrin was present in the highest concentrations (average: 1027 µg/kg), followed by permethrin (average: 265 µg/kg). In contrast to the concentration profile of the sediment data, which had an almost equal distribution of cyfluthrin, permethrin and cypermethrin, in biosolids cyfluthrin accounts for 57.2% of Σ_8 pyrethroids, followed by permethrin at 14.7% and deltamethrin at 12.0%. Σ_8 pyrethroid concentrations at four sites were higher in winter (January), which may be due to reduced volatilisation of these chemicals during this period due to cooler temperatures. Σ_8 pyrethroid concentrations (across the winter, spring/summer and autumn sampling periods) were positively correlated with factors such as PE and flow band but, regardless of the treatment process, there was no correlation between Σ_8 pyrethroid concentration and rainfall amount.

4.9.1 Comparisons with international data

Most previous studies on pyrethroid concentrations in inland or transitional/coastal sediments have been conducted in the USA or China, with limited data available for Europe – published data on resmethrin are especially scarce (a comparison with previous reported data is provided in Table A2.8). Published data (median concentrations) for resmethrin from the USA (Hladik and Kuivila, 2012) are within the range reported in the current study. Concentrations of permethrin, cyfluthrin, cypermethrin and esfenvalerate are within the range of or, in some cases, slightly higher (cyfluthrin, esfenvalerate and cypermethrin) than those reported for the USA (Amweg *et al.*, 2006; Hladik and Kuivila, 2012), and concentrations are slightly higher than values reported for China (Cheng *et al.*, 2017, who also included permethrin, cypermethrin and deltamethrin). However, concentrations for the other target pyrethroids, such as bifenthrin and λ-cyhalothrin, are lower than those reported in the USA (Amweg *et al.*, 2006) and China (You *et al.*, 2008). Concentrations reported for Europe, specifically the UK (Long *et al.*, 1998, who also included permethrin and cypermethrin, and House *et al.*, 2000, who included permethrin) and Denmark (Kronvang *et al.*, 2003, who included λ-cyhalothrin, esfenvalerate and deltamethrin), are higher than the values reported in TERRAChem samples.

Previous studies on pyrethroids in WWTP-derived biosolids tended to focus on a few target insecticides, mainly permethrin, unlike the current study. Concentrations of permethrin are within the range reported for biosolid samples in Switzerland (Kupper *et al.*, 2006) and are significantly higher than those reported much earlier in the UK (Rogers *et al.*, 1989).

4.9.2 Ecotoxicological risk assessment – pyrethroid concentrations in sediment

The RQ values for measured concentrations of permethrin, cyfluthrin, cypermethrin, esfenvalerate and deltamethrin fell into the high-risk category (RQ > 1.0) in 97.5%, 93.8%, 91.4%, 82.7% and 61.7% of samples, respectively. As higher concentrations for four of these pyrethroids (excluding esfenvalerate) are reported in historical data, an appropriate risk assessment on these pyrethroids is required. Detectable concentrations of resmethrin and λ-cyhalothrin were deemed moderate risk in 50.6% and 59.3% of samples, respectively, and concentrations of bifenthrin were categorised as low risk (RQ < 0.1).

4.10 Anthelmintics in Inland and Transitional/Coastal Sediments

All target chemicals were detected in sediment samples, with the highest DF and concentration reported for fenbendazole. There was no significant difference between concentrations in inland and transitional/coastal sediment types and no observed correlations between concentration and type of water body, speed of water therein or nearby population density. While previous studies have shown anthropogenic activities to have a greater impact on environmental concentrations than agricultural activities (Chen *et al.*, 2021), due to limited sample numbers within TERRAChem it was not possible to investigate possible sources of contamination in any great detail.

4.11 Anthelmintics in Wastewater Treatment Plant-derived Biosolids

All target anthelmintics were detected in biosolid samples, with two chemicals, ivermectin and albendazole, detected in 100% of samples. Previous studies on the distribution, fate and removal efficiency of anthelmintics in WWTPs (Zhao *et al*., 2024) have shown that concentrations of anthelmintics in biosolids are significantly correlated with $\log K_{ow}$, promoting the accumulation of macrocyclic lactones such as ivermectin, which have higher $\log K_{ow}$ values than other anthelmintic classes. The same study also reported that removal of anthelmintics in the WWTP process mainly occurs in the biodegradation phase of the treatment process via sedimentation adsorption to the biosolid and photolysis (Chen *et al*., 2021). There was no clear correlation between concentrations of anthelmintics in TERRAChem biosolid samples and sludge treatment type.

4.11.1 Comparisons with international data

There have been limited reported studies internationally on anthelmintic concentrations in either inland or transitional/coastal sediments, and so these data reported in TERRAChem are, to the authors' knowledge, the first reported for Ireland and, for some target chemicals, for Europe. Comparisons were made with a Chinese study that reported sediment data from the Tuojiang River, which flows through six cities in south-west China, with TERRAChem samples collected in 2019 (Chen *et al*., 2021). Concentrations of the target chemicals ivermectin, albendazole and fenbendazole in the TERRAChem data are significantly lower than in the Chinese data. In the Chinese study, albendazole was one of the more dominant anthelmintics, followed by fenbendazole, which was present at concentrations over 300 times higher than reported in the TERRAChem study.
The biosolid concentration data reported in the TERRAChem study are within the range reported by Zhao *et al*. (2024) for two WWTPs in Chengdu, China, where the treatment processes investigated included anaerobic-anoxic-aerobic treatment and a cyclic activated sludge system. In that study, similarly to the TERRAChem study, albendazole and fenbendazole were the two dominant anthelmintics detected in sludge samples collected from both sludge treatment processes. Concentrations reported for fenbendazole and ivermectin were within the range of concentrations reported in the TERRAChem samples. TERRAChem albendazole concentrations are lower than those reported by Zhao *et al*. (2024). For further details regarding anthelmintic data, please refer to Coggins *et al*. (2026).

4.11.2 Ecotoxicological risk assessment – anthelmintic concentrations in sediment

The NORMAN network has published $PNEC_{sed}$ values for only two of the anthelmintics studied in the TERRAChem project – albendazole and fenbendazole – and reported concentrations represent a low to moderate ecotoxicological risk.

5 Conclusions and Recommendations

The TERRAChem project measured a range of legacy and emerging hazardous organic chemicals in inland and transitional/coastal sediment samples collected from sites across Ireland. Most of the same contaminants were also measured in samples of WWTP-derived biosolids from seven Irish WWTPs. The chemicals within the purview of the TERRAChem project have either recently been restricted under the Stockholm Convention (UNEP, 2019), are priority hazardous substances within the EU WFD (European Union, 2000), are European Commission Watch List chemicals or have been flagged as ESOCs by the NORMAN network. The TERRAChem study provides a first baseline assessment of the degree of contamination of the Irish environment for some of the chemicals and new data for the others, and provides a first baseline assessment of legacy chemicals and chemicals of emerging concern in WWTP-derived biosolids in Ireland. Using the PNEC risk assessment approach for sediment data collected in 2023, Figure 5.1 summarises the chemicals that have RQ values of > 1.0 and present a high ecotoxicological risk. Of the 92 chemicals analysed in the TERRAChem study, 9 chemicals (2 OPEs, PFOS and 6 pyrethroids) present a high ecotoxicological risk and warrant further investigation. The RQ values for five target pyrethroids and PFOS exceeded the high-risk threshold (RQ > 1.0) at most (both riverine and estuarine) sediment sampling sites surveyed in 2023. Of the 81 sites sampled, 3 potential contamination hotspots were identified: Galway Harbour, the Barrow River at Graiguenamanagh and the Tolka River at Drumcondra. In addition to elevated RQ values for pyrethroids and PFOS, these sites also exhibited RQ values > 1.0 for other target chemicals, including PCBs at the Barrow River site (an RQ value of 1.0 for both PCB-28/31 and PCB-52); chlorinated OPEs and other OPEs at the Tolka River site (RQs = 1.0 and 2.0 for TCIPP and EHDPP, respectively); and OPEs, PCBs and antibiotics (in silty sediment) at Galway Harbour (RQs = 2.0, 11.0, 1.0, 2.0, 2.0, 3.0 and 3.0 for TEHP, EHDPP, PCB-28/31,PCB-52, PCB-101, PCB-118 and ciprofloxacin, respectively).

The main findings are the following:

- Concentrations of targeted BFRs, OPEs and PCBs in sediment samples are broadly in line with those reported internationally. Reported concentrations, for the most part, suggest a low ecotoxicological risk when compared with $PNEC_{sed}$ values promulgated by the NORMAN network. However, concentrations of TCIPP, EHDPP,

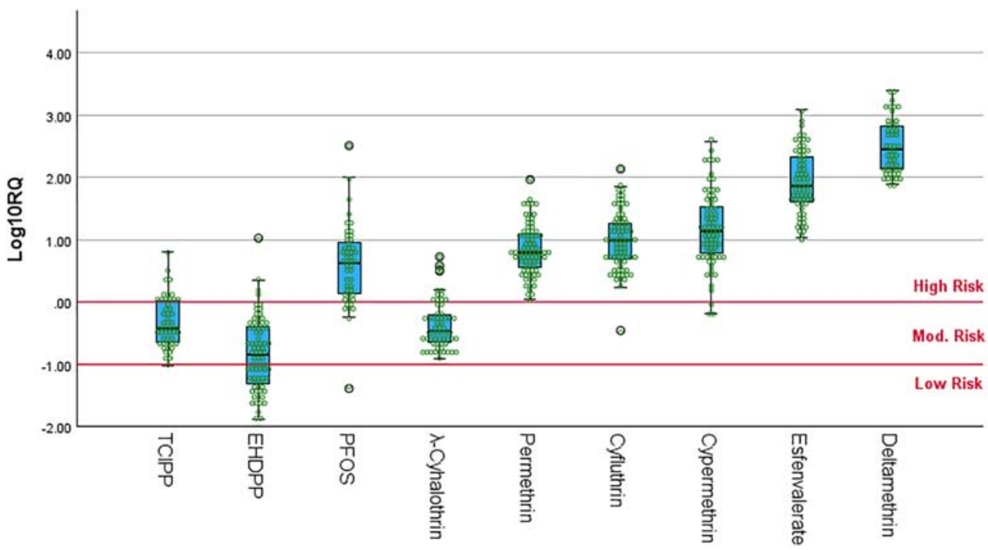

Figure 5.1. Target chemicals that had RQ values > 1.0 in some or most of the inland and coastal sediment samples collected in 2023. Log10RQ, log10 relative quantity; Mod., moderate.

TEHP, PCB-118 and PCB-52 were considered to represent a moderate to high ecotoxicological risk at over half of the sites surveyed and thus warrant further investigation in national monitoring programmes. Concentrations of the same chemicals in WWTP-derived biosolid samples are at the high end of those reported internationally. Elevated concentrations of BDE-209, TBOEP, TCIPP and TEHP were detected both in sediment and biosolid samples, suggesting that these legacy and replacement chemicals are in use across Ireland and are finding their way into the Irish environment. Although the concentration data for biosolids are limited by small sample sizes, they suggest that concentrations may be influenced by seasonal factors and that higher influent volumes to WWTPs may affect final biosolid concentration. However, further studies are required to fully elucidate the impact of seasonality on biosolid concentrations.

- TERRAChem provides novel data on the antibiotics difloxacin and levofloxacin in Irish sediments. Clarithromycin was the most frequently detected antibiotic and was present in higher concentrations than previously reported internationally. Concentrations of all other targeted antibiotics in sediment samples are at the lower end of those reported internationally. High concentrations were detected in samples collected in the immediate vicinity (within 0.1 km) of wastewater emission points and near other potential anthropogenic sources. While no data on antibiotics in biosolids were obtained, higher concentrations of antibiotics are present in sediments downstream from WWTP emission points. Concentrations of the targeted antibiotics suggest a low ecotoxicological risk, with the exception of the concentrations reported for clarithromycin and sulfamethoxazole. Given the projected ecotoxicological risk associated with the concentrations reported for these two antibiotics, both warrant further investigation in national monitoring programmes.
- TERRAChem provides a first assessment of concentrations for five organic UVFs in Irish inland and transitional/coastal sediment and WWTP-derived biosolid samples. Concentrations of these contaminants are at the low end of those reported internationally for both sediments and biosolids. Despite this, levels detected suggest a moderate ecotoxicological risk for hydroxyethyl methyl cellulose, 4-MBC and HMS in sediments, with higher concentrations of UVFs frequently detected in sediments directly adjacent to or downstream from wastewater emission points.
- TERRAChem presents, to the authors' knowledge, the first global report on the concentrations of five PFAS compounds in freshwater and transitional/coastal sediments. Concentrations of one of the 39 PFAS congeners investigated, PFOS, exceeded the relevant $PNEC_{sed}$ values in over half of the sediment samples analysed; the other target PFASs rarely if ever exceeded PNECs. PFCAs were the most abundant PFAS detected in sediments, and PFSAs were the most abundant in biosolids.
- TERRAChem presents, to the authors' knowledge, the first pyrethroid concentration data (both sediment and WWTP-derived biosolids) for Ireland and new data for Europe, of which there have been few reported to date. Concentrations are mostly comparable with those reported internationally, with sediment concentrations of permethrin, cyfluthrin, cypermethrin, esfenvalerate and deltramethrin falling into the category of high ecotoxicological risk and thus warranting further investigation in an environmental monitoring programme.
- TERRAChem presents, to the authors' knowledge, the first anthelmintic sediment and biosolid data for Europe. Among the target chemicals analysed, fenbendazole is the dominant chemical in both sample types. Globally, there are limited data available on anthelmintics in sediments or biosolids. Of the compounds investigated in this study, only two have $PNEC_{sed}$ values reported by the NORMAN network, which, when compared with TERRAChem concentrations, indicate a low to moderate ecotoxicological risk associated with albendazole and fenbendazole. Additional research is necessary to better understand the potential environmental risks posed by these substances.

Based on our findings, the following recommendations are made:

- The scope of the current EPA environment monitoring programme needs to be broadened to include sediment and soil sampling, prioritising the inclusion of the hazardous chemicals with concentrations that suggest high ecotoxicological risk, for example deltamethrin, PFOS and others falling into the moderate to high ecotoxicological risk categories, as defined by the NORMAN network $PNEC_{sed}$ values. The TERRAChem project, although limited by sample numbers, also identifies potential pollutant hotspots that warrant further investigation in future programmes.

- As the OSPAR risk assessment approach differs from the approach used in the TERRAChem project and is currently limited primarily to legacy pollutants, it is recommended that the contaminant risk conclusions in TERRAChem are considered in future risk profiling under OSPAR. This may require the development of new risk thresholds for contaminants not currently included in routine OSPAR monitoring programmes.
- Research should be conducted to investigate and fully characterise the level of contamination and possible sources of those hazardous chemical contaminants at sites where reported concentrations approach or exceed available $PNEC_{sed}$ values.
- The objective of the current study was to measure levels of organic pollutants in a sample of WWTP-derived biosolids. Future research should investigate pollutant concentrations in both influent and effluent wastewater, as well as sludge/biosolids, over a longer sampling period, so that pathways of retention and loss can be fully quantified. Such studies should also determine the efficacy of the various sludge treatment processes for the relevant pollutants.
- A follow-up study is needed to assess how spreading of WWTP biosolids on agricultural land impacts the concentrations of hazardous chemicals in soil and whether it acts as a secondary diffuse source through run-off.
- Since the current study did not examine soil contamination, bioconcentration, bioaccumulation or biomagnification potential, future research should explore the uptake of the analysed chemicals in the terrestrial food chain.
- Ongoing periodic assessments, like those conducted in the TERRAChem project, can be used to identify emerging issues and provide a means of assessing general trends in concentrations as these harmful substances are phased out. Such assessments will also provide a means of evaluating the efficacy of actions taken to reduce environmental contamination with chemical contaminants.

Further investment in advanced wastewater and sludge treatment technologies, including quaternary treatment in the treatment of both the solid and liquid fractions, is needed to address both legacy contaminants and emerging chemicals of concern.

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Appendix 1 List of Peer-reviewed Publications Emerging from the Research Described in this Report

Coggins, A.M., Sharkey, M., Healy, M.G., Harrad, S. and Wang, S. (2026). Concentrations of anthelmintics in Irish sediments and wastewater treatment plant derived biosolids from Ireland. *Environmental Contamination: Causes and Solutions*, accepted for publication June 2026.

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Appendix 2 Comparison of Concentrations of Selected Contaminants Monitored in the TERRAChem Study with Previously Reported Data

Table A2.1. Comparison of TERRAChem BFR data for Irish inland and transitional/coastal sediments with previously reported data (mean, median and range, µg/kg)

Source/location	Mean/median/range	BDE-28	BDE-47	BDE-100	BDE-99	BDE-153	BDE-154	BDE-183	BDE-209
TERRAChem study (Ireland), inland and transitional/coastal, *n* = 81	Mean	<LoD	0.07	0.19	0.28	0.37	0.04	0.08	6.93
	Median	<LoD	0.04	0.04	<LoD	0.05	<LoD	<LoD	0.79
	Range	–	<LoD–0.38	<LoD–4.44	<LoD–2.95	<LoD–4.24	<LoD–0.30	<LoD–0.83	<LoD–110.07
Gianci *et al*. (2019) (UK), river, *n* = 45	Mean	0.4	0.2	–	0.8	0.03	–	0.1	174
	Median	<0.2	<0.03	–	0.5	<0.01	–	0.05	148
	Range	<0.2–4.0	<0.03–2.5	<0.05–4.4	<0.05–4.4	<0.01–0.6	–	<0.01–0.7	0.03–535
Giulivo *et al*. (2017) (Adige, Italy), river, *n* = 20	Mean	0.01	0.28	0.14	0.52	–	–	<LoD	1.27
	Median	<LoD	0.22	0.14	0.28	–	–	<LoD	0.62
	Range	<LoD–0.12	0.08–0.89	<LoD–0.48	<LoD–2.49	–	–	<LoD	<LoQ–8.90
Giulivo *et al*. (2017) (Evrotas, Greece), river, *n* = 12	Mean	<LoD	0.43	0.14	0.52	<LoD	<LoD	<LoD	0.44
	Median	<LoD	0.36	0.145	0.625	<LoD	<LoD	<LoD	<LoQ
	Range	<LoD	<LoD–1.34	<LoD–0.31	<LoD–0.99	<LoD	<LoD	<LoD	<LoQ–2.43
Giulivo *et al*. (2017) (Sava, Slovenia, Croatia, Bosnia and Herzegovina and Serbia), river, *n* = 20	Mean	<LoD	0.35	0.23	1.25	<LoD	<LoD	<LoD	3.55
	Median	<LoD	0.37	0.17	1.20	<LoD	<LoD	<LoD	1.75
	Range	<LoD	<LoD–1.20	<LoD–1.39	<LoD–7.71	<LoD	<LoD	<LoD	<LoQ–13.30
Brandsma *et al*. (2015) (Netherlands), transitional/coastal, *n* = 3	Mean	–	–	–	–	–	–	–	43
	Median	–	–	–	–	–	–	–	9.7
	Range	–	–	–	–	–	–	–	8.5–111
Sutton *et al*. (2019) (USA), transitional/coastal, *n* = 10	Mean	0.04	0.30	0.11	0.11	0.07	0.02	0.03	0.91
	Median	0.02	0.31	0.12	0.12	0.08	0.02	0.02	0.77
	Range	<LoD–0.18	0.06–0.62	<LoD–0.27	<LoD–0.27	0.02–0.13	<LoD–0.05	<LoD–0.07	0.11–2.78
Matsukami *et al*. (2015) (Japan), river, *n* = 8	Mean	0.06	0.44	0.03	0.35	0.24	0.05	1.40	83.24
	Median	0.02	0.04	<LoQ	0.04	0.08	<LoD	0.75	12.00
	Range	<LoD–0.26	<LoD–2.00	<LoD–0.14	<LoD–1.60	<LoD–1.00	<LoD–1.27	<LoD–5.80	0.09–320

"–", data unavailable.

Source: Reproduced from Sharkey *et al*. (2024a) with kind permission from Elsevier.

Table A2.2. Comparison of TERRAChem OPE data for Irish inland and transitional/coastal sediments with previously reported data (mean, median and range, μg/kg)

Source/location	Mean/median/range	TBOEP	TnBP	TCIPP	TEHP	TCEP	EHDPP	TPHP	TDCIPP
TERRAChem Study (Ireland), inland and transitional/coastal, *n* = 81	Mean	27.6	0.25	5.19	3.93	1.83	0.88	0.41	0.24
	Median	24.5	0.14	2.24	1.15	1.13	0.28	0.27	0.04
	Range	<LoD–214	<LoD–3.19	<LoD–70.2	<LoD–58.9	<LoD–33.8	<LoD–23.7	<LoD–23.7	<LoD–15.3
Onoja *et al.* (2023) (UK), freshwater, *n* = 4	Mean	37	6.3	9.5	–	4.8	3.3	2.0	2.0
	Median	–	–	–	–	–	–	–	–
	Range	6.0–170	0.02–73	0.02–37	–	0.3–22	0.02–29	0.1–26	0.03–8.0
Martinez-Carballo *et al.* (2007) (Danube, Schwechat, Liesing, Austria), river sediment, *n* = 4	Mean	–	–	382.25	43.1	40.0	–	41.08	<LoD
	Median	–	–	697.5	84	< LoQ	–	2.15	<LoD
	Range	–	–	<LoD–1300	<LoD–140	<LoQ–160	–	<LoD–160	<LoD
Tan *et al.* (2016) (Pearl River Delta, China), river and estuary, *n* = 52	Mean	–	4.78	15.72	13.05	12.58	1.17	18.60	1.28
	Median	–	2.10	9.45	10.0	6.25	0.59	3.50	0.33
	Range	–	ND–37.0	0.91–185.0	0.86–56.0	ND–58.0	ND–5.10	ND–253.0	ND–10.0
Stachel *et al.* (2005) (Germany/Czechia), river and estuary, *n* = 37	Median	–	4.9	57	–	7.4	–	–	7.9
	Range	–	< 1–23	5.9–311	–	< 1–41	–	–	< 1–93
Giulivo *et al.* (2017) (Adige, Italy), river, *n* = 20	Mean	1.57	–	14.93	5.83	2.52	37.31	1.04	0.46
	Median	0.28	–	7.75	2.81	1.62	13.65	0.42	ND
	Range	ND–9.98	–	0.53–53.70	ND–35.10	0.33–19.00	4.27–288.0	ND–9.69	ND–6.86
Giulivo *et al.* (2017) (Evrotas, Greece), river, *n* = 12	Mean	1.10	–	1.53	1.22	0.59	1.61	0.15	0.54
	Median	–	–	ND	0.46	ND	ND	ND	ND
	Range	–	–	ND–7.62	ND–4.73	ND–2.27	ND–6.39	ND–0.67	ND–2.96
Giulivo *et al.* (2017) (Sava, Slovenia, Croatia, Bosnia and Herzegovina and Serbia), river, *n* = 20	Mean	2.69	–	6.27	3.53	0.48	2.14	ND	0.04
	Median	1.98	–	5.53	3.35	0.34	ND	ND	ND
	Range	ND–11.0	–	ND–14.70	0.33–7.73	ND–2.32	ND–8.48	ND	ND–0.39
Brandsma *et al.* (2015) (Netherlands), transitional/coastal, *n* = 3	Mean	9.5	–	3.6	1.5	0.5	0.3	0.6	0.6
	Median	7.0	–	1.8	0.8	0.4	0.2	0.5	0.3
	Range	<LoD–19.6	–	1.7–7.3	0.4–3.3	<LoD–1.0	<LoD–0.7	<LoD–1.0	<LoD–1.4
Cristale *et al.* (2013) (Spain), river, *n* = 21	Mean	–	3.25	72.1	28.44	2.87	18.19	6.35	6.06
	Median	–	<LoD	29.0	9.5	<LoD	17.00	2.90	8.20
	Range	–	<LoD–13.0	<LoD–365	<LoD–290	<LoD–9.70	<LoD–63.0	<LoD–23.0	<LoD–12.0
Sutton *et al.* (2019) (USA), transitional/coastal, *n* = 10	Mean	–	0.67	0.68	10.12	0.03	0.40	2.32	1.05
	Median	–	0.57	0.54	8.21	<LoD	0.28	1.85	0.96
	Range	–	0.35–1.2	0.26–1.6	2.28–19.9	<LoD–0.13	<LoD–1.47	0.44–7.49	0.73–1.97
Matsukami *et al.* (2015) (Japan), river, *n* = 8	Mean	–	–	0.94	–	0.22	0.22	6.30	0.50
	Median	–	–	<LoD	–	<LoD	<LoD	3.00	<LoD
	Range	–	–	<LoD–4.50	–	<LoD–2.00	<LoD–2.00	<LoD–38.0	<LoD–2.50

“–”, data unavailable; ND, not detected; TPHP, triphenyl phosphate.

Source: Reproduced from Sharkey *et al.* (2024a) with kind permission from Elsevier.

Table A2.3. Comparison of TERRAChem selected PFAS data for Irish inland and transitional/coastal sediments with previously reported data (range, µg/kg dry weight)

Location/source	PFBA	PFHxA	PFOA	PFDA	PFDoDA	PFTrDA	PFBS	PFHxS	PFOS	FOSA	N-EtFOSA	4:2-FTS	6:2-FTS	8:2 diPAP	Gen-X	NaDONA
Ireland, 2023 (TERRAChem)	<0.006–1.5	<0.003–0.18	<0.002–0.20	<0.001–0.09	<0.001–0.10	<0.001–0.03	<0.002–8.3	<0.001–0.04	<0.001–2.2	<0.001–0.03	<0.001–0.01	<0.004–0.05	<0.002–0.05	<0.002–0.08	<0.01–0.06	<0.002–0.06
Ireland, 2018–2022 (TERRAChem)	<0.006–0.18	0.01–0.29	0.01–0.61	0.02–0.33	<0.001–0.07	<0.001–0.04	<0.002–0.03	<0.001–0.03	0.01–0.39	<0.001–0.02	<0.001–0.01	<0.004–0.016	<0.002–0.63	<0.002–0.18	<0.01–0.06	<0.002–0.06
France (Macorps *et al.*, 2023)	<0.43–0.74	<0.24–1.2	<0.05–0.58	<0.06–0.46	<0.05–0.77	<0.06–1.1	<0.03	<0.02–0.16	<0.1–6.0	<0.02–0.11	<0.01–0.15	<0.02	<0.12–2.1	<0.71	<0.05	<0.006
Spain (Campo *et al.*, 2016)	2.7–10.7	ND	ND–6.7	ND–1.7	ND	ND	ND–29	ND	ND–9.8	ND	NM	NM	NM	NM	NM	NM
North Sea and Baltic Sea (Joerss *et al.*, 2019)	ND–0.54	ND–0.057	ND–0.65	0.0062–0.30	ND–0.143	0.0051–0.10	ND	ND–0.16	ND–0.39	ND–0.078	NM	ND	ND–0.40	NM	ND	ND
China (Wang *et al.*, 2019)	0.26–0.50	0.19–0.30	ND	ND	ND	ND	ND	ND–0.18	0.51–2.2	0.61–0.91	NM	NM	NM	NM	NM	NM
Spain (Pignotti *et al.*, 2017)	NM	ND–3.7	ND–12	ND	ND–4.0	ND	ND–4.8	ND–1.5	ND–22.6	ND	NM	NM	NM	NM	NM	NM
USA (Bai and Son, 2021)	ND–2.2	1.8–20	ND	ND	ND–19	ND–14	ND–29	ND–21	ND	NM	NM	NM	NM	NM	NM	NM
Pearl River Delta, China (Chen *et al.*, 2021)	ND	ND	ND–0.015	ND	ND	ND	ND	ND	0.014–0.14	NM	NM	NM	NM	NM	NM	NM
South Korea (Lam *et al.*, 2014)	NM	ND–0.05	ND–0.28	ND–0.08	ND–0.13	NM	NM	ND–0.01	0.01–0.48	NM	NM	NM	NM	NM	NM	NM
Sweden, AFFF-impacted site (Mussabek *et al.*, 2019)	<0.6–1.3	<0.5–3.7	ND	ND	ND	ND	<0.5–1.6	<0.5–13	<0.5–64	ND	ND	NM	ND	NM	NM	NM
North Carolina, USA (Shimizu *et al*, 2022)	NM	NM	0.04–0.51	NM	NM	NM	NM	NM	0.08–2.8	NM	NM	NM	NM	NM	0.08–1.7	NM
Yellow River, China (Zhao *et al.*, 2020)	0.05–0.34	0.013–0.19	3.2–7.8	1.3–2.4	0.59–1.6	NM	ND–0.44	NM	0.19–0.71	NM	NM	NM	NM	NM	NM	NM
China, ocean sediments (Zhong *et al.*, 2021)	ND–0.045	ND–0.062	0.045–2.8	0.01–0.21	0.002–0.041	0.003–0.02	0.006–0.034	0.002–0.095	0.002–0.558	0.002–0.012	NM	0.004–0.10	NM	NM	0.018–0.45	NM
South Korea (Lee *et al.*, 2020)	NM	<0.002–0.064	<0.005–0.513	<0.005–0.123	<0.005–0.039	<0.005–0.086	<0.002–0.024	<0.002–0.059	<0.005–0.330	<0.002–0.007	NM	NM	NM	<0.01–0.087	NM	NM
Hai River, China (Li *et al.*, 2020)	ND–0.76	ND–0.12	0.011–0.39	0.004–0.15	ND–0.10	ND–0.09	ND–0.015	ND–0.058	0.005–0.62	ND–0.076	NM	ND–0.043	ND–0.031	NM	NM	NM
Bohai Bay, China (Zhao *et al.*, 2020)	0.15–0.60	ND–0.88	0.20–1.00	ND–0.38	ND–0.10	NM	ND	ND–0.15	ND–0.20	NM	ND–0.09	ND	ND–0.20	ND	ND	ND

4:2 FTS, 1H,1H,2H,2H-perfluorohexane sulfonate; 6:2 FTS, 1H,1H,2H,2H-perfluorooctane sulfonate; 8:2 diPAP, bis(1H,1H,2H,2H-perfluorodecyl)phosphate; AFFF, aqueous film-forming foam; FOSA, perfluoro-1-octanesulfonamide; ND, not detected; N-EtFOSA, n-methylperfluoro-1-octansulfonamide; NM, not measured in study; PFBA, perfluoro-n-butanoic acid; PFDoDA, perfluorododecanoic acid; PFTrDA, perfluorotridecanoic acid.

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Table A2.4. Comparison of TERRAChem PFAS concentrations in Irish biosolids with previously reported data (range, µg/kg dry weight)

Location/source	PFBA	PFHxA	PFOA	PFDA	PFDoDA	PFTrDA	PFBS	PFHxS	PFOS	FOSA	N-EtFOSA	4:2-FTS	6:2-FTS	8:2 diPAP	Gen-X	NaDONA
Ireland, 2023 (TERRAChem)	<0.06–1.1	0.05–2.5	<0.015–1.7	0.17–4.8	<0.013–0.86	<0.01–0.10	<0.02–65	0.02–0.31	1.4–53	<0.009–1.1	<0.007–0.19	<0.044–1.7	<0.02–4.2	<0.03–2.0	<0.1–0.44	<0.02–0.95
Australia (Coggan *et al.*, 2019)	ND–4.1	ND–13	ND–25	ND–26	ND–20	ND–1.8	ND–9.3	ND–17	ND–90	NM	NM	NM	ND–2.7	NM	NM	NM
Germany (Stahl *et al.*, 2018)	NM	<LoQ–16.4	<LoQ–51	<LoQ–43	<LoQ–29.1	<LoQ–31.6	<LoQ–112	ND–95	ND–700	NM	NM	NM	NM	NM	NM	NM
Switzerland (Alder and van der Voet, 2015)	0.8–49	0.7–91	1.0–87	0.9–73	NM	NM	0.1–28	0.1–27	4.0–2400	NM	NM	NM	NM	NM	NM	NM
Spain (Campo *et al.*, 2016)	NM	6.2	11.8	86.4	0.1	2.1	19.5	ND	135	NM	NM	NM	NM	NM	NM	NM
Denmark (Bossi *et al.*, 2008)	NM	NM	0.7–19.7	1.2–32	NM	NM	NM	0.4–11	9.5–156	NM	NM	NM	NM	NM	NM	NM
Greece (Stasinakis *et al.*, 2013)	NM	<0.22–62	<0.36–19.4	<0.26–9.6	<0.46–9.8	NM	<0.06	<0.06–18	0.58–17	NM	NM	NM	NM	NM	NM	NM
Sweden (Fredriksson *et al.*, 2022)	<0.6	1.4–8.2	1.3–44	<0.1–69	<0.5–22	<0.5–40	<0.1	0.1–2.5	6.2–26	<0.1–4.1	<0.5	<0.1	<0.3–2.5	<0.5–24	NM	NM
USA (Venkatesan and Halden, 2014)	1.2–3.2	2.5–11.7	11.8–70	6.9–59	4.5–26	NM	NM	NM	<0.8–68	NM	NM	NM	NM	NM	NM	NM
South Korea (Seo *et al.*, 2019)	NM	1.2–4.5	5.2–10.9	10–13	3.8–6.5	NM	0.98–37	0.1–66	4.6–62	NM	NM	NM	NM	NM	NM	NM
Thailand (Kunacheva *et al.*, 2011)	NM	0.3–100	11.3–136	3.8–328	ND–311	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
China (Li *et al.*, 2010)	ND–131	0.35–118	9.2–76	0.33–6.2	0.4–4.5	NM	ND–2.6	ND–3.1	28–135	NM	NM	NM	NM	NM	NM	NM
Canada (Lakshminarasimman *et al.*, 2021)	<2.1	<2.1–8.3	<2.1–23	<2.1–54	<2.1–10	NM	<4.1–11	<4.1	<4.1–27	NM	NM	NM	NM	NM	NM	NM
Nigeria (Sindiku *et al.*, 2013)	NM	0.01–0.25	0.02–0.42	0.009–0.6	0.009–0.28	NM	0.01–0.14	0.01–0.04	0.01–0.54	NM	NM	NM	NM	NM	NM	NM
Kenya (Chirikona *et al.*, 2015)	NM	<0.1–0.57	0.03–0.35	<0.03–0.34	0.01–0.26	NM	NM	<0.04–0.83	<0.07–0.67	NM	NM	NM	NM	NM	NM	NM
Czechia (Semerád *et al.*, 2020)	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	<1.4	<1.6	NM	NM	0.3–1.2	<0.7

4:2 FTS, 1H,1H,2H,2H-perfluorohexane sulfonate; 6:2 FTS, 1H,1H,2H,2H-perfluorooctane sulfonate; 8:2 diPAP, bis(1H,1H,2H,2H-perfluorodecyl)phosphate; FOSA, perfluoro-1-octanesulfonamide; ND, not detected; N-EtFOSA, n-methylperfluoro-1-octansulfonamide; NM, not measured in study; PFBA, perfluoro-n-butanoic acid; PFDoDA, perfluorododecanoic acid; PFTrDA, perfluorotridecanoic acid.

Table A2.5. Comparison of TERRAChem antibiotic mean concentrations for Irish inland and transitional/coastal sediments with previously reported data (µg/kg dry weight)

Location	Trimethoprim	Ciprofloxacin	Enrofloxacin	Ofloxacin	Azithromycin	Clarithromycin	Erythromycin	Roxithromycin	Sulfamethoxazole	Sulfadiazine
Ireland, 2023 (TERRAChem) ($n=80$)	0.170	< 5.04	< 0.977	< 0.355	0.093	6.650	< 0.156	< 0.333	0.077	< 0.074
Italy, 2019–2021 ($n=26$)	–	< 17.1	–	–	7.099	0.285	1.219	–	–	–
Poland, 2011–2013 ($n=61$)	1.851	–	–	–	–	–	0.135	–	20.11	–
Spain, 2009 ($n=20$)	0.270	–	–	–	–	1.408	2.718	–	–	0.430
France, 2008–2009 ($n=12$)	–	–	–	–	130.4	1.71	–	–	–	–
Kenya, 2019 ($n=9$)	1.678	12.49	–	–	–	–	–	–	8.311	–
Argentina, 2016 ($n=10$)	< 0.8	–	–	6.0	3.2	0.96	–	< 0.1	< 0.6	< 0.7
Hong Kong, 2016 ($n=20$)	–	0.986	–	0.355	–	–	–	0.279	0.267	–
China (Bohai Sea), 2014 ($n=35$)	–	12.9	19.9	7.6	–	–	–	2.5	–	–
China (Shanghai), 2012 (n not provided)	–	–	3.2	4.1	–	–	10.2	1.9	0.2	0.4
China (north east), 2011 ($n=94$)	1.187	40.05	0.177	20.07	–	–	–	4.267	< 0.65	0.713
USA, 2003–2005 ($n=20$)	–	–	–	–	–	–	–	2.1	1.6	–

References in descending order: Pizzini *et al*. (2024); Siedlewicz *et al*. (2018); Da Silva *et al*. (2011); Feitosa-Felizzola and Chiron (2009); Kairigo *et al*. (2020); Valdés *et al*. (2021); Deng *et al*. (2018); Liu *et al*. (2016); Chen and Zhou (2014); Zhou *et al*. (2011); Kim and Carlson (2006). The year stated denotes the collection date as opposed to journal article publication date. Note that no comparison data were available for levofloxacin and difloxacin.

"–", data unavailable.

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Table A2.6. Comparison of TERRAChem UVF concentrations in Irish inland and transitional/coastal sediments with previously reported data

Source/location	Mean/median/range/DF	EHMC	4-MBC	BP-3	HMS	OC
TERRAChem, Ireland (*n* = 81)	Mean (μg/kg)	< LoQ	1.87	0.19	2.35	3.66
	Median (μg/kg)	< LoQ	1.09	0.06	< LoQ	1.82
	Range (μg/kg)	< LoQ–0.99	< LoQ–10.7	< LoQ–3.76	< LoQ–32.0	< LoQ–31.8
	DF (%)	9.9	92.6	60.5	21.0	61.7
Li *et al*. (2022), Tianging, China (*n* = 59)	Mean (μg/kg)	–	–	–	–	–
	Median (μg/kg)	1.56	1.47	–	2.04	–
	Range (μg/kg)	0.625–10.3	0.359–8.91	–	< 1.45–25.8	1.03–175
	DF (%)	–	–	–	–	–
Costa *et al*. (2024), Admiralty Bay, Antarctica (*n* = 17)	Mean (μg/kg)	5.23	< LoQ	9.70	19.7	20.2
	Median (μg/kg)	3.60	< LoQ	< LoQ	5.00	11.5
	Range (μg/kg)	< LoQ–26.2	< LoQ	< LoQ–86.0	< LoQ–251	< LoQ–93.8
	DF (%)	76.5	0	35.3	88.2	93.8
Gago-Ferrero *et al*. (2011a), Ebro, Spain (*n* = 20)	Mean (μg/kg)	4.85	< LoQ	4.60	–	240
	Median (μg/kg)	< LoD	< LoQ	< LoQ	–	62.0
	Range (μg/kg)	< LoQ–42.0	< LoQ	< LoQ	–	< LoQ–2400
	DF (%)	20.0	0	35.0	–	95
Peng *et al*. (2017), Pearl River Delta, China (*n* = 27)	Mean (μg/kg)	3.36	–	0.44	–	6.9
	Median (μg/kg)	1.30	–	0.32	–	1.04
	Range (μg/kg)	< LoQ–22.4	–	0.14–1.07	–	0.05–91.7
	DF (%)	81.5	–	100	–	100
Tovar-Salvador (2023), Atacama, Chile (*n* = 36)	Mean (μg/kg)	0.36	0.05	0.08	0.28	4.79
	Median (μg/kg)	–	–	–	–	–
	Range (μg/kg)	ND–2.52	ND–1.61	ND–0.5	ND–1.06	ND–33.4
	DF (%)	> 71	> 11	> 71	> 71	> 70
Langford *et al*. (2015), Norway (*n* = 5)	Mean (μg/kg)	–	–	–	–	–
	Median (μg/kg)	–	–	< LoD	–	–
	Range (μg/kg)	8.5–19.8	–	< LoD	–	< LoQ–82.1
	DF (%)	–	–	–	–	–

"–", data unavailable; ND, not detected.

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Table A2.7. Comparison of TERRAChem UVF concentrations in Irish biosolids with previously reported data

Source/location	Mean/median/range/DF	EHMC	4-MBC	BP-3	HMS	OC
TERRAChem, Ireland	Mean (µg/kg)	12.7	13.9	1.28	453	666
	Median (µg/kg)	<LoQ	14.3	<LoQ	413	393
	Range (µg/kg)	LoQ–63.9	4.60–30.0	LoQ–7.77	122–914	90.1–1890
	DF (%)	42.9	100	47.6	100	100
Liu *et al*. (2011), Adelaide, Australia ($n=3$)	Mean (µg/kg)	31.9	250	74.0	–	138.4
	Median (µg/kg)	–	–	–	–	–
	Range (µg/kg)	–	–	–	–	–
	DF (%)	–	–	–	–	–
Gago-Ferrero (2011b), Catalonia, Spain ($n=15$)	Mean (µg/kg)	1489	1896	52.7	–	–
	Median (µg/kg)	1220	1630	ND	–	–
	Range (µg/kg)	610–3350	730–3830	ND–790	–	–
	DF (%)	100	100	6.7	–	–
Nieto *et al*. (2009), Tarragona, Spain ($n=3$)	Mean (µg/kg)	–	–	17.7	–	1450
	Median (µg/kg)	–	–	20	–	1800
	Range (µg/kg)	–	–	10–20	–	700–1840
	DF (%)	–	–	100	–	100
Plagellat *et al*. (2006), Switzerland (nationwide) ($n=28$)	Mean (µg/kg)	1780	110	–	–	5510
	Median (µg/kg)	1580	100	–	–	3450
	Range (µg/kg)	150–4980	10	–	–	700–27,700
	DF (%)	100	390	–	–	100
Mao *et al*. (2020), Changsha, China ($n=5$)	Mean (µg/kg)	–	–	1.94	–	–
	Median (µg/kg)	–	–	1.43	–	–
	Range (µg/kg)	–	–	ND–4.33	–	–
	DF (%)	–	–	60.0	–	–

"–", data unavailable; ND, not detected.

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Table A2.8. Comparison of TERRAChem pyrethroid concentrations (range and median (µg/kg dry weight)) in Irish sediments with previously reported data

Source/location	Range/ median	Resmethrin	Bifenthrin	λ-Cyhalothrin	Permethrin	Cyfluthrin	Cypermethrin	Esfenvalerate	Deltamethrin
TERRAChem (2023), Ireland	Range	0.23–22.5	ND–1.73	ND–1.07	ND–74.5	ND–68.5	ND–76.1	ND–5.5	ND–11.6
	Median	2.27	0.03	0.07	5.09	4.80	2.78	0.33	1.31
TERRAChem (2018–2022), Ireland	Range	ND–2.09	ND–0.28	ND–1.71	3.84–16.7	4.17–21.0	4.60–31.0	ND–4.25	ND–10.9
	Median	0.61	0.04	0.05	7.87	7.40	8.45	0.23	1.74
Bonwick *et al*. (1995), UK	Range	NM	NM	NM	ND–335	ND	NM	NM	NM
	Median	NM	NM	NM	214	ND	NM	NM	NM
Long *et al*. (1998), UK	Range	NM	NM	NM	ND–5451	NM	ND–1140	NM	ND
	Median	NM	NM	NM	15	NM	ND	NM	ND
House *et al*. (2000), UK	Range	NM	NM	NM	50–300	NM	NM	NM	NM
	Median	NM	NM	NM	NA	NM	NM	NM	NM
Kronvang *et al*. (2003), Denmark	Range	NM	NM	ND–30	ND	NM	NM	ND–10	ND–50
	Median	NM	NM	NA	ND	NM	NM	NA	NA
Feo *et al*. (2012), Spain	Range	ND	ND	ND	ND	ND	8.27–71.9	ND	ND
	Median	ND	ND	ND	ND	ND	NA	ND	ND
Peris *et al*. (2022), Spain	Range	NM	NM	NM	NM	NM	ND–327	NM	NM
	Median	NM	NM	NM	NM	NM	NA	NM	NM
Hladik and Kuivila (2012), USA	Range	ND–18.8	ND–30.1	ND–0.3	ND–180	ND–14.6	ND–21.8	NM	ND–12.1
	Median	ND	0.6	ND	ND	ND	ND	NM	ND
Amweg *et al*. (2006), USA	Range	NM	ND–429	ND–10.7	ND–172	ND–60.4	ND–30.6	ND–4.4	ND–57.0
	Median	NM	NA	NA	NA	NA	NA	NA	NA
Anderson *et al*. (2006), USA	Range	NM	NM	ND–59.4	ND–107	NM	NM	ND–32.6	NM
	Median	NM	NM	9.25	ND	NM	NM	ND	NM
Ensminger *et al*. (2011), USA	Range	NM	ND–74.4	ND–8.98	ND	ND–4.19	ND	ND	ND
	Median	NM	2.9	ND	ND	ND	ND	ND	ND
Harwood *et al*. (2013), USA	Range	NM	1.2–329	ND–11.0	ND–58	ND–32	ND–36	NM	NM
	Median	NM	6.95	1.42	3.3	ND	ND	NM	NM
Holmes *et al*. (2008), USA	Range	NM	2.19–219	ND–24.2	ND–97.8	ND–127	ND–30.4	ND–6.90	ND–9.31
	Median	NM	13.5	ND	23.9	6.53	ND	ND	ND
Phillips *et al*. (2010), USA	Range	NM	24.7–172	2.5–9.7	13.8–53.1	ND–67.5	ND–102	NM	NM
	Median	NM	86.0	4.77	32.1	ND	18.8	NM	NM
Phillips *et al*. (2012), USA	Range	NM	ND–375	ND–125	ND–1279	ND–214	ND–499	ND–5.5	NM
	Median	NM	ND	1.45	ND	ND	3.25	2.1	NM
Weston *et al*. (2013a), USA	Range	NM	ND–32.2	ND–11.7	ND–158	ND–3.0	ND–6.7	ND–203	ND
	Median	NM	ND	ND	ND	ND	ND	ND	ND

Table A2.8. Continued

Source/location	Range/ median	Resmethrin	Bifenthrin	λ-Cyhalothrin	Permethrin	Cyfluthrin	Cypermethrin	Esfenvalerate	Deltamethrin
Weston *et al*. (2013b), USA	Range	NM	ND–35.5	ND–4.2	ND–12.8	ND–7.7	ND–5.4	NM	NM
	Median	NM	1.8	ND	ND	ND	ND	NM	NM
You *et al*. (2008), USA	Range	NM	ND–52.5	ND–6.55	ND–107	ND–38.5	ND–33.0	ND–5.56	ND–7.86
	Median	NM	4.21	ND	4.26	ND	ND	ND	ND
Ding *et al*. (2010), USA	Range	NM	ND–46	ND–25	ND–51	ND	ND	ND	ND
	Median	NM	3.4	ND	ND	ND	ND	ND	ND
Emert *et al*. (2023), USA	Range	NM	ND–0.82	ND–5.33	ND–3.57	NM	NM	ND–9.41	NM
	Median	NM	0.52	1.82	0.83	NM	NM	3.78	NM
Miranda *et al*. (2008), Brazil	Range	NM	NM	ND–5.0	ND–7.0	NM	ND	NM	ND–20.0
	Median	NM	NM	1.65	3.5	NM	ND	NM	ND
Allinson *et al*. (2015), Australia	Range	NM	ND–59	NM	ND–34	NM	NM	NM	NM
	Median	NM	ND	NM	ND	NM	NM	NM	NM
Xue *et al*. (2008), China	Range	NM	NM	NM	NM	NM	ND–0.009	NM	ND–0.524
	Median	NM	NM	NM	NM	NM	0.006	NM	0.345
Hu *et al*. (2015), China	Range	NM	NM	0.04–6.40	ND–3.4	ND–5.7	ND–7.6	NA	ND–0.19
	Median	NM	NM	0.35	0.38	1.6	1.75	NA	ND
Qi *et al*. (2015), China	Range	NM	ND	0.03–0.06	0.06–0.15	ND	ND–0.04	ND–0.03	ND
	Median	NM	ND	0.04	0.12	ND	ND	ND	ND
Wang *et al*. (2012), China	Range	NM	ND–0.062	ND–0.064	ND–108	ND–0.203	ND–11.3	ND–187	ND–0.334
	Median	NM	0.002	0.005	0.937	0.004	0.082	0.182	0.026
Li *et al*. (2011), China	Range	NM	ND–135	ND–13.2	ND–91.4	ND–2.83	1.44–219	ND–15.7	ND–83.3
	Median	NM	ND	0.65	1.53	ND	18.3	ND	ND
Sun *et al*. (2015), China	Range	NM	ND–1.76	ND–7.44	ND–48.5	NM	ND–29.8	ND–4.08	NM
	Median	NM	0.02	0.03	0.39	NM	0.25	0.04	NM
Yi *et al*. (2015), China	Range	NM	0.63–3.48	9.87–90.7	20.4–132	ND–5.77	18.0–130	NM	ND–227
	Median	NM	1.81	14.0	71.1	ND	115	NM	0.39
Cheng *et al*. (2017), China	Range	NM	0.38–6.54	0.29–1.87	0.88–35.4	ND	0.14–20.4	ND	ND–1.29
	Median	NM	1.17	0.59	8.66	ND	2.46	ND	0.36
Gu *et al*. (2024), China	Range	NM	0.12–5.59	NM	ND–9.85	NM	ND–25.4	NM	13.8–476
	Median	NM	NA	NM	NA	NM	NA	NM	NA
Chai *et al*. (2023), China	Range	NM	5.96–10.12	1.77–3.77	NM	NM	4.02–6.14	NM	7.68–28.6
	Median	NM	NA	NA	NM	NM	NA	NM	NA
Liu *et al*. (2022), China	Range	NM	ND–55.6	0.23–78.3	ND–10.2	ND–1.02	1.37–198	ND–7.32	ND–14.5
	Median	NM	4.67	4.07	0.62	ND	9.92	0.63	0.16

NA, not available; ND, not detected; NM, not measured in study.

Appendix 3 Flame Retardant Concentrations versus Collection Month

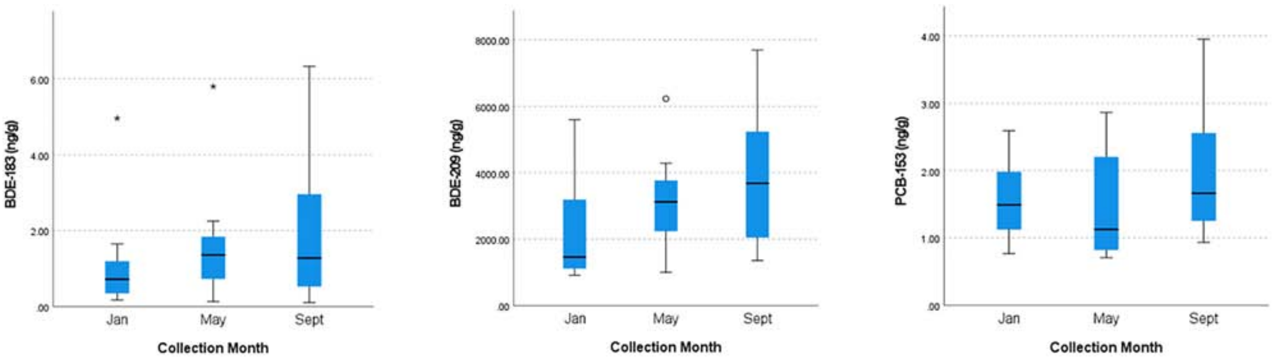

Figure A3.1. FR/PCB concentrations versus collection month for three target chemicals, showing higher variance in concentrations for samples collected in September. Data extracted from Sharkey *et al*. (2024a), with kind permission from Elsevier.

Abbreviations

4-MBC	4-methylbenzylidene camphor
BFR	Brominated flame retardant
BP-3	Benzophenone-3
CSS	Chemicals Strategy for Sustainability
DF	Detection frequency
ECHA	European Chemicals Agency
EHDPP	2-ethylhexyl diphenyl phosphate
EHMC	2-ethylhexyl-4-methoxycinnamate
ESOC	Emerging substance of concern
EQS	Environmental quality standard
FR	Flame retardant
FTS	Fluorotelomer sulfonate
Gen-X	2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid
HFR	Halogenated flame retardant
HMS	Homosalate
LoD	Limit of detection
$\log K_{ow}$	Octanol-water partitioning coefficient
LoQ	Limit of quantification
NaDONA	Sodium dodecafluoro-3H-4,8-dioxanonanoate
NORMAN	Network of Reference Laboratories, Research Centres and Related Organisations for Monitoring of Emerging Environmental Substances
OC	Octocrylene
OPE	Organophosphate ester
PBDE	Polybrominated diphenyl ether
PBT	Persistent, bioaccumulative and toxic
PCB	Polychlorinated biphenyl
PE	Population equivalent
PFAS	Perfluoroalkyl substance
PFBS	Perfluorobutanesulfonic acid
PFCA	Perfluorocarboxylic acid
PFDA	Perfluorodecanoic acid
PFHxA	Perfluorohexanoic acid
PFHxS	Perfluorohexane sulfonate
PFOS	Perfluorooctane sulfonate
PFUdA	Perfluoro-n-undecanoic acid
PNEC	Predicted no-effect concentration
POP	Persistent organic pollutant
RQ	Risk quotient
SSA	Sunscreen agent
SSD	Sewage Sludge Directive
SVHC	Substance of very high concern
TBOEP	Tris(2-butoxyethyl) phosphate
TCEP	Tris(2-chloroethyl) phosphate
TCIPP	Tris(1-chloro-2-propyl) phosphate
TDCIPP	Tris(1,3-dichloro-2-propyl) phosphate

TEHP	Tris(2-ethylhexyl) phosphate
TERRAChem	Assessment of the Environmental Contamination of Irish Soils and Sediments with Hazardous Chemicals
TnBP	Tri-n-butyl phosphate
UVF	Ultraviolet filter
WFD	Water Framework Directive
WWTP	Wastewater treatment plant

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
> Sceitheadh fuíolluisce uirbigh;
> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
> Foinsí radaíochta ianúcháin;
> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
> 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 um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.