Per- and Polyfluoroalkyl Substances (PFAS) in the Irish Environment: Sources, Pathways, and Management Strategies

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Declaration

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Glossary and abbreviations

Abbreviation	Definition
ADONA	Ammonium 4,8-dioxa-3H-perfluorononanoate
AFFF	Aqueous film-forming foams
APFO	Ammonium Perfluorooctanoate
ArcGIS	Chosen geographical information system
BDE	Bond Dissociation Energy
COMAH	Control of Major Accident Hazards involving Dangerous Substances
CFC	Chlorofluorocarbons
diPAP	Polyfluoroalkyl phosphate diester
E-PRTR	European Pollution Release Transfer Register
ECF	Electrochemical fluorination
ECHA	European Chemicals Agency
EPA	Environmental Protection Agency
EU	European Union
F-gas	Fluorinated greenhouse gases
FASAs	Perfluoroalkane sulfonamides
FT	Fluorotelomerisation
FTOH	Fluorotelomer alcohol
FTP	Fluorotelomer-based polymers
FTS	Fluorotelomer sulfonates
FTSA	Fluorotelomer Sulfonic Acid
GenX	Hexafluoropropylene oxide dimer acid
GIS	Geographical Information System
HDPE	High density polyethylene
HFC	Hydrofluorocarbon
HFPO-DA	2,3,3,3,tetrafluoro-2-(heptafluoropropoxy) propanoate
ICT	Information, communications and technology
IED	Industrial Emissions Directive
INVEST p-FASST	An INVESTigation of PFAS from Source to sink - to assess risk and inform a PFAS STrategy in Ireland
ITRC	Interstate Technology Regulatory Council
KEMI	Swedish Chemicals Agency
LEAP	EPA's Licence and Enforcement Access Portal
N-EtFODA	Sulfuramid
N-EtFOSA	N-ethyl perfluorooctane sulfonamide
N-EtFOSAA	N-ethyl perfluorooctane sulfonamido acetic acid
N-EtFOSE	N-ethyl perfluorooctane sulfonamidoethanol
N-MeFOSE	N-Methylperfluorooctanesulfonamidoethanol
OECD	Organisation for Economic Co-Operation and Development
PAP	Polyfluoroalkyl phosphate esters
PASF	Perfluoroalkane sulonyl fluorides
PBT	Persistent, bioaccumulative and/or toxic
PFAA	Perfluoroalkyl acids
PFAS	Per- and polyfluroalkylated substances
PFBA	Perfluorobutanoic acid

PFCA	Perfluoroalkane carboxylates
PFEA	Polyfluoroalkyl ether acids
PFECA	Per- and polyfluoroalkyl ether carboxylates
PFECHS	Perfluoroethylcyclohexane sulphonate
PFHpA	Perfluoroheptanoic Acid
PFHxA	Perfluorohexanoic Acid
PFHxS	Perfluorohexane sulfonic acid
PFNA	Perfluorononoic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
PFOSA or FOSA	Perfluorooctane sulfonamide
PFPE	Perfluoropolyesters
PFSA	Perfluoroalkane sulfonates
PMT	Persistent, mobile and toxic
POP	Persistent Organic Pollutant
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
REACH	Registration, Authorisation and Restriction of Chemicals
vPvM	Very persistent and very mobile
WWTP	Wastewater treatment plant

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Per- and Polyfluoroalkyl Substances (PFAS) in the Irish Environment: Sources, Pathways, and Management Strategies

By Leila Bowe

Abstract

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic chemicals known for their persistence, mobility, and potential toxicity. This thesis investigates the sources, environmental pathways, and risks associated with PFAS contamination in Ireland, with a particular focus on water bodies used for drinking water and ecological purposes. A desk-based study identified major PFAS sources through international literature, regulatory data, and geospatial analysis. Although PFAS are not manufactured in Ireland, 57 compounds are imported annually, several of which are classified as persistent, bio-accumulative, and/or toxic under REACH regulations.

A geospatial database of potential point sources, including industrial facilities, waste management sites, airports, and fire stations, was developed and used to assess environmental risk. These sources were classified and scored based on their likelihood to release PFAS via infrastructure, infiltration, and runoff pathways. A multi-criteria risk assessment methodology was applied to the Lough Corrib catchment, identifying eight drinking water abstractions, two food production sites, and three sensitive ecosystems at risk.

National monitoring data from the EPA and the INVEST p-FASST project confirmed widespread PFAS detections in Irish surface and groundwater, with PFOA more frequently detected than PFOS. PFAS fingerprints were observed near major airports, and linkages were established between positive detections and known point sources such as wastewater treatment plants, refineries, and maintenance yards. However, detections in areas without obvious sources suggest the influence of diffuse contamination and legacy pollution.

This research highlights the complexity of PFAS contamination in Ireland and the need for comprehensive, catchment-wide risk assessment tools to inform future monitoring, mitigation, and policy development. The methodology developed

provides a scalable framework for national application and supports a proactive approach to managing PFAS risks in the Irish environment.

Introduction

Chapter 1 – Sources of PFAS

1.1 Introduction

Per- and polyfluoroalkylated substances (PFAS) are a group of more than 14,000 recorded synthetic compounds[1] with waterproof, oil proof and fireproof properties. The compounds were originally synthesised by 3M company and Dupont in the 1940s in the United States[2], but are now produced and used globally in a multitude of industries including pharmaceutical, chemical, metal and information technology manufacturing. PFAS are highly mobile and can enter the environment during the manufacturing of products that they're used in, during the use of the products themselves and through product disposal. The persistence, bioaccumulation and long-range transportation ability of some PFAS compounds has meant that they have become ubiquitous in the environment and have been detected globally in soil, air, biota, and water[3]. The resistance to degradation has meant that ecological and human receptors can be subject to long-term exposure. Decades of widespread use of these compounds internationally, and in Ireland[4], has raised concerns about potential legacy environmental contamination and their impact on human and ecological health. There is currently little information about the production and use of PFAS sources in Ireland, and similarly there is little research conducted on the extent of contamination in the environment. The INVEST p-FASST project, of which this thesis is an output of, aims to address these data gaps and inform a PFAS strategy in Ireland.

Of the 14,000 PFAS compounds, three (perfluorooctane sulfonate [PFOS], perfluorooctanoic acid [PFOA] and perfluorohexane sulfonic acid [PFHxS]) have been either restricted or regulated under the Stockholm Convention, which is ratified in European Union (EU) Law, and consequently in Ireland. PFAS is also currently regulated and monitored in products and waste material, manufacturing, surface water and drinking water through the Persistent Organic Pollutants (POPs) Regulation (2020)[5], European Registration, Authorisation and Restriction of Chemicals (REACH) Regulation (2021)[6], EU Environmental Objectives (Surface

Waters) (Amendment) Regulations (2019)[7] and the EU (Drinking Water) Regulations (2023)[8]. While there are no current industrial emissions requirements for PFAS compounds in wastewater, there are current proposals to add PFOA and PFHxS to the Industrial Emissions Directive (2010)[9].

With these restrictions and regulations of PFAS compounds and growing public in the topic[10], there is a necessity to better understand the nature and extent of PFAS contamination in the Irish environment. This Chapter examines global and Irish literature to determine the current state of knowledge and trends in PFAS production and potential sources. Chapter 2 examines the relevance the sources in the Irish context and categorises them based on their potential to enter environmental media, such as soil, surface water, groundwater or air. An output of Chapter 2 is a map of major point sources of PFAS in Ireland, based on publicly available data. Chapter 3 consists of a methodology to conduct a spatial risk assessment of the probability for PFAS sources to impact surface and groundwater quality and presents a case study of the Corrib Catchment. Chapter 4 summarises existing PFAS data in Ireland and the preliminary results from the INVEST p-FASST project. Chapter 5 provides recommendations on a strategy for PFAS management, a PFAS Audit methodology for conducting desk-based reviews at licensed facilities and conclusions.

1.2 Aims and objectives

The aim of this thesis is to evaluate PFAS sources and pathways in Ireland, their impacts on water bodies, and to provide evidence-based recommendations for monitoring and management.

The objectives of this thesis are:

- To conduct a desk-based study to determine known and emerging primary and secondary sources of PFAS, including anthropogenic, industrial, civil, agricultural and municipal sources of PFAS sources in Ireland by examining international literature and determine where large volumes of PFAS may exist.
- To review PFAS compounds currently registered as being imported to and used in Ireland under REACH Regulations.

- To develop a geospatially referenced database of potential major PFAS point sources in Ireland and identify data gaps.
- To classify potential point sources in relation to potential risk to the environment.
- To demonstrate the risk model developed to identify and prioritise water bodies that are most at risk from contamination.

1.3 Overview of PFAS Chemistry

Each PFAS compound has unique characteristics and properties, which strongly influence how they are used. As such, it is important to understand the chemical properties of the main classes of PFAS compounds.

There are currently several definitions of PFAS. The INVEST p-FASST project's definition of PFAS is in line with the Organisation for Economic Co-Operation and Development (OECD) definition. This includes aliphatic substances containing the moiety $-C_nF_{2n+1}$ within their structure, where n is at least 1 and substances that contain the moiety $-C_nF_{2n-}$ (n >= 1).[11] Figure 1 - 1 shows examples of per- (fully fluorinated carbon chain) and polyfluorinated (partially fluorinated carbon chain) structures.

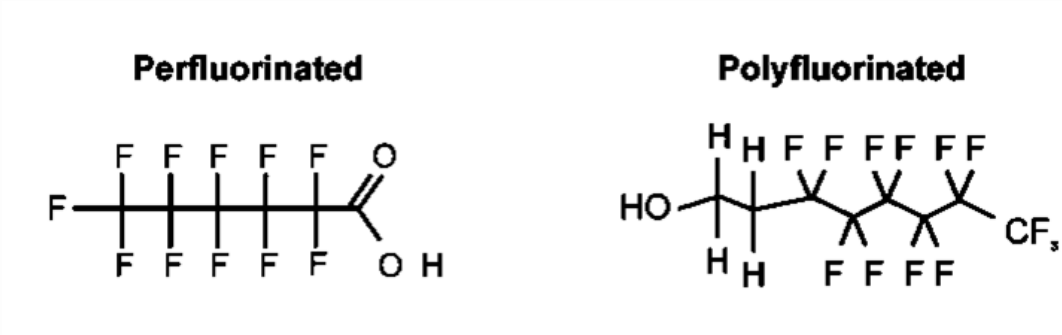


Figure 1 - 1 Perfluorinated and polyfluorinated carbon chain structures (KEMI, 2025)

The carbon-fluorine (C-F) bond is a distinguishing feature of PFAS compounds, ensuring their stability and resistance to degradation. The Bond Dissociation Energy (BDE) of the C-F bond is approximately 488 kJ/mol[12], making t one of the strongest bonds in organic chemistry. Most PFAS compounds are also hydrophobic (contact angle with water greater than 90 degrees) and oleophobic (contact angle with oil greater than 90 degrees) characterisation. PFAS compounds typically consist of a

partially or fully fluorinated hydrophobic carbon chain 'tail' with a hydrophilic 'head'. Most of the defining characteristics of PFAS come from the functional head.

With some PFAS compounds being subject to restrictions, manufacturers are producing new compounds to substitute longer chain compounds. This includes shorter-chained compounds and fluorotelomer compounds, which can be equally as environmentally persistent and concerning for human health as those compounds that they have replaced.

The Interstate Technology Regulatory Council (ITRC)[13] has divided PFAS compounds into two primary classes, non-polymers and polymers, as shown in Figure 1 - 2. Figure 1-2 shows the vast range of PFAS families, classes and groups.[13] Some PFAS are also considered to be precursor compounds which may degrade to terminal products, such as PFOS and PFOA, under certain conditions.[14]

Printed from: Interstate Technology & Regulatory Council (ITRC). 2023. *PFAS Technical and Regulatory Guidance Document and Fact Sheets PFAS-1*. Washington, D.C.: Interstate Technology & Regulatory Council, PFAS Team. https://pfas-1.itrcweb.org/.

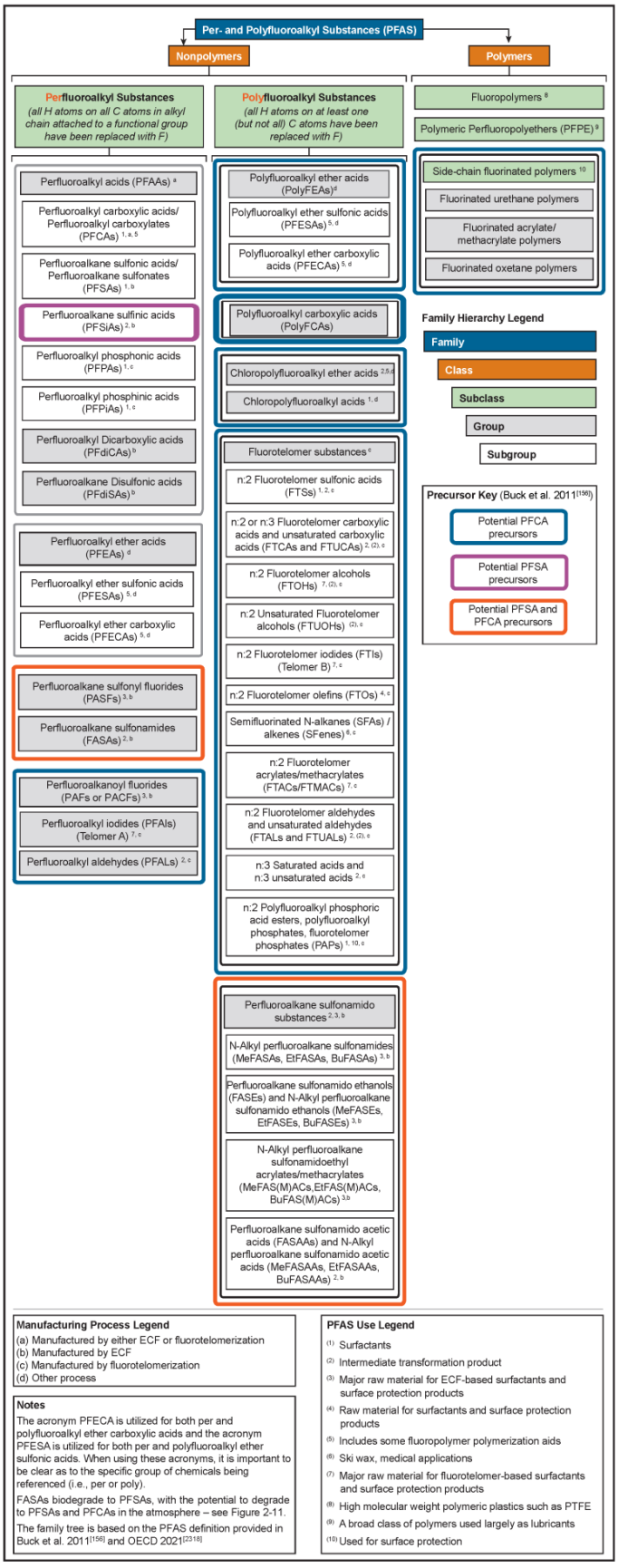


Figure 1 - 2 PFAS Naming Convention (ITRC, 2023)

Globally, polymers such as fluoropolymers (including chlorofluorocarbons [CFCs], hydrofluorocarbons [HFCs] and F-gases) are produced and used in larger quantities than non-polymers. It is currently inferred that polymer PFAS poses less of a risk to human health and the environment as they are less bio-accumulative and persistent that non-polymers, such as PFOA and PFOS[15].

Some PFAS compounds, often referred to as precursors can be transformed or degraded by biotic or abiotic processes into terminal transformation products[16]. Precursors often contain non-fluorinated alkyl carbons and can include perfluoroalkane sulfonamides (FASAs), perfluoroalkane sulonyl fluorides (PASFs) and polyfluoroalkyl ether acids (PFEAs), as shown in Table 1 - 1. Terminal products, such as perfluoroalkyl acids (PFAAs) are some of the least complex PFAS and are unable to breakdown under normal environmental conditions. As such, these make them currently the most tested for in the environment[13]. Differences in PFAS chemistry, such as the proportion of fluorinated carbons, the shape of the compound and functional groups determines the ability of compounds to bond to environmental media. It also determines their ability to transform under environmental conditions[16,17], such as the aerobic soil biotransformation of EtFOSA into PFOS, EtFOSAA, FOSA and FOSAA[18]. The chain length of PFAS compounds also influences the bioaccumulation, persistence and toxicity.[19,20] For example, based on persistence in humans, short chain PFAS, such as PFBA, have a half-life in human blood of days to weeks, whereas longer chain PFAS such as PFOS have a measured half-life of 2-3 years[21].

Table 1 - 1 PFAS classifications (ITRC, 2023)

Classification	Representative compounds	Daughter products	Some known uses
Perfluoroalkyl acids (PFAAs)	Perfluoroalkane carboxylates (PFCAs)	Perfluorooctanoic acid (PFOA) Perfluorobutanoic acid (PFBA)	Teflon/non-stick coatings Aqueous film-forming foams (AFFFs) Street runoff
	Perfluoroalkane sulfonates (PFSAs)	Perfluorooctane sulfonic acid (PFOS) Perfluorobutane sulfonic acid (PFBS)	Textile treatment AFFFs Semi-conductor devices
Perfluoroalkane sulfonamides (FASAs)	Perfluorooctane sulfonamide (PFOSA or FOSA) N-ethyl perfluorooctane sulfonamide (N-EtFOSA)	PFCAs PFSAs	Surfactants and surface protection products Intermediate environmental transformation products
Fluorotelomer substances	8:2 fluorotelomer sulfonate (8:2 FTS) 10:2 fluorotelomer alcohol (FTOH)	PFCAs	Used as major raw materials Environmental transformation products and intermediates
Perfluoroalkane sulfonyl fluorides (PASFs)	Polyfluorinated substances PFAS N-ethyl perfluorooctane sulfonamidoethanol (N-EtFOSE) N-ethyl perfluorooctane sulfonamido acetic acid (N-EtFOSAA)	PFSA	Used as major raw materials Environmental transformation intermediates
Per- and polyfluoroalkyl ether carboxylates (PFECAs)	2,3,3,3,tetrafluoro-2-(heptafluoropropoxy) propanoate (HFPO-DA) Ammonium 4,8-dioxa-3H-perfluorononanoate (ADONA)	Short-chain PFAAs	Replacement as a surfactant and polymerisation aid in production of PTFE

1.3.1 PFAS Detection Methods

PFAS detection methods are widely being developed, but today widely relies on highly sensitive liquid chromatography mass spectrometry (LC-MS) or triple quadrupole. These methodologies have the ability to have a broad analyte coverage and have the ability to quantify PFAS at low detection levels (ng/L)[22].

1.4 Review of Sources of PFAS

Glüge et al (2020)[15], Kissa (2001)[19] and the Environment Agency (2021)[23] have published reviews of PFAS sources on a global scale, however not all these use categories are relevant to the Irish context. This paper will focus on sources that may be associated with Irish industry, agricultural practices, waste management systems and civil use (such as for fire-fighting purposes and military training).

The aim of this mini review is to provide a broad but not exhaustive summary of potential PFAS sources in Ireland and, where possible, any identifying compounds associated with each primary source.

1.4.1 Literature Search Strategy

International literature was reviewed using library catalogues, case studies and public government databases. Searches were performed on key words such as “PFAS uses”, “PFAS sources” and “PFAS contamination”. Additional searches were conducted specifically for suspected or known uses.

1.5 Sources of PFAS in Ireland

Due to their highly desirable properties of being waterproof, oil proof, stain proof and heat resistant, PFAS compounds are ideal for use in a multitude of consumer and industrial applications. These industries include firefighting industries using aqueous film forming foams (AFFFs), chemical manufacturing, building and construction, cabling and wiring, metal finishing and plating, hydraulic fluids, fluoropolymer production, paper products and packaging, semiconductor

manufacturing, textiles and leather production (carpets and furniture), cleaning products (including industrial surfactants), and refrigeration.

PFAS sources can be broken down into primary and secondary categories. Primary sources involve the manufacturing of PFAS compounds (or PFAS synthesis) and the use of PFAS compounds in industrial or commercial applications, such as waterproofing or fire suppression. Secondary sources involve the bioaccumulation and storage of PFAS compounds. The PFAS compounds could be from several primary sources. These include waste management facilities such as landfills and wastewater treatment plants. Literature also refers to environmental receptors such as sediment, soil and groundwater as being secondary sources, as compounds can be stored in this media until they are mobilised by physical or chemical processes[24]. Tertiary sources are reported to be created when PFAS has bioaccumulated in environmental media stores, such as water, sediment, or biota. While environmental media can also constitute receptors of PFAS contamination, they exist as a source to ecological receptors at higher trophic levels, and humans. Environmental media that may become secondary and tertiary sources are also considered to be ecological receptors.

For the purposes of this thesis, sources are defined as anything that can release persistent chemicals into the environment. Pathways are the methods by which these sources can enter the environment, such as discharge and runoff. In this thesis, primary sources of PFAS were broken down into four categories – anthropogenic, industrial, agricultural and civil sources, as shown in Figure 1 -2. The cyclical nature of PFAS sources is also demonstrated.

1. Anthropogenic sources are products that humans interact with daily and can include food and drink packaging, personal care products, textiles and non-stick coatings;
2. Industrial industries that use or process PFAS are chemical manufacturing plants, pharmaceuticals facilities, paper and wood processing plants, information and technology facilities and data centres;
3. Agricultural sources may include pesticides and fertilisers; and

4. Civil sources may involve the use of fire-fighting foams at airports, fire stations, military bases or where flammable liquid fires have been extinguished.

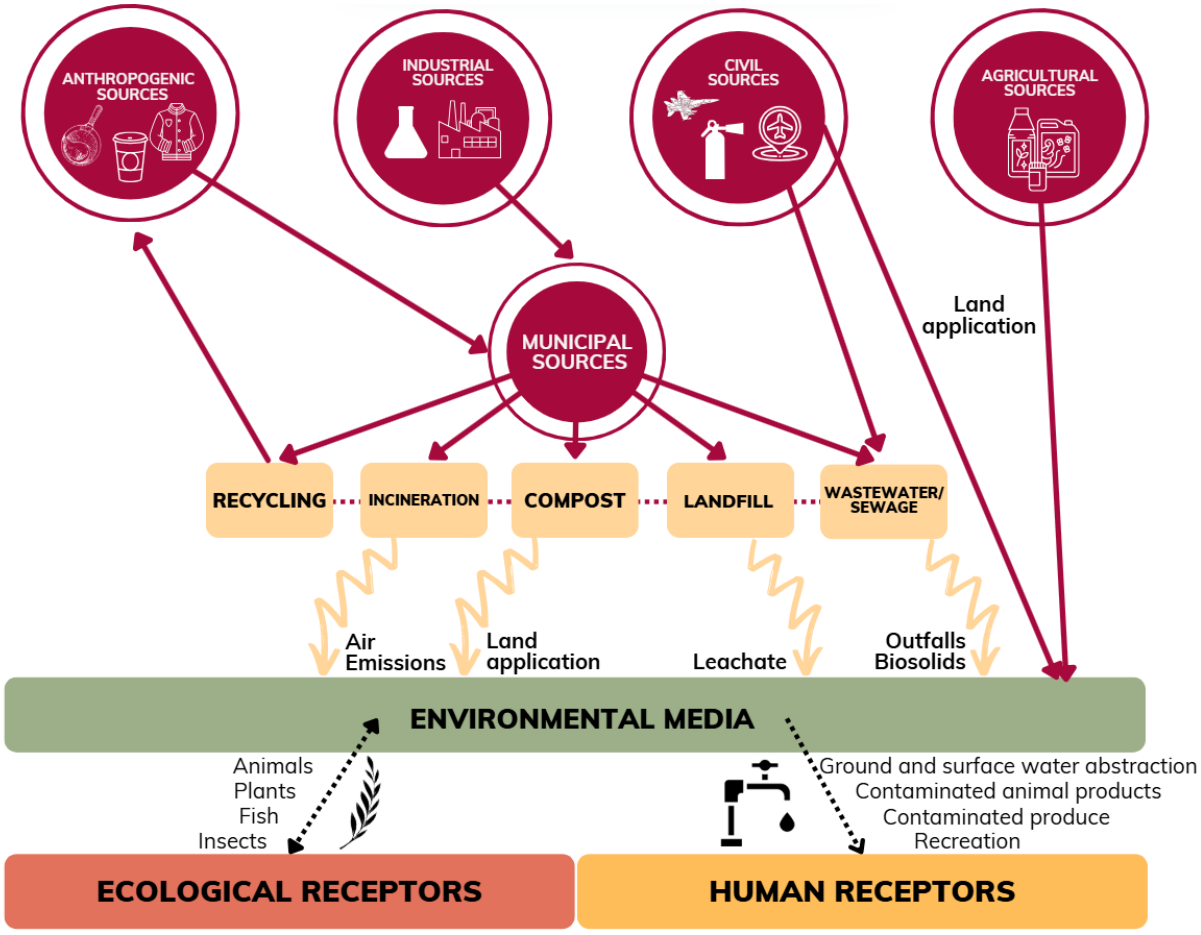


Figure 1 - 3 Movement of PFAS through the waste management (ITRC [2025], Gluge et al [2020] and KEMI [2017])

Apart from the direct land application of PFAS compounds into the environment from agricultural (pesticides and herbicides) and civil sources (AFFF usage), a wide range of PFAS compounds will enter environmental media via the municipal waste management industry. In Ireland, the waste management system consists of recycling, incineration, composting, landfilling and wastewater treatment[25]. PFAS compounds are known to accumulate, degrade and transform within the waste management system before becoming a secondary PFAS source. Air emissions from incineration, biosolid and compost land application, landfill and compost leachate, liquid effluent from wastewater treatment plants are all known sources of PFAS[8].

The following sections provide details on primary and secondary sources of PFAS anticipated to be present in Ireland. Any sources identified in literature that are unlikely to be present in Ireland, such as large-scale fluoropolymer plants, large-scale textile manufacturing and certain anthropogenic sources, such as ski waxes, were not included in the following sections.

1.5.1 Anthropogenic Sources

Anthropogenic sources are items that humans interact with daily and PFAS compounds will predominantly enter the environment via waste streams, including via compost, landfill, incineration or through the wastewater system. These are generally considered point sources of PFAS. The following sections use examples of consumer items known to be used or imported into Ireland.

1.5.1.1 Household products containing PFAS

Household products containing PFAS can cause an additional potential risk to human health via direct contact, consumption or inhalation of dust and indoor air[26]. Known household products that are known to contain PFAS are discussed below and summarised in Table 1 - 2. Table 1 - 2 also contains examples of PFAS compounds associated with the source, and potential pathways for the source to enter environmental media as identified in international literature. The predominant potential pathways for human exposure identified for anthropogenic sources are transdermal contact and direct ingestion and environmental exposure is through household wastewater and solid waste disposal. There is also known exposures

through air emissions. PFAS can aerosol during the use and degradation of household items. These particles can become airborne and settle on surfaces as dust[26] or be inhaled. These exposure routes are further explored in Chapters 2 and 3.

Polytetrafluoroethylene (PTFE) is a fluoropolymer which is widely used non-stick coating in cookware. It has good chemical, thermal and electrical stability and low friction, making it desirable for cooking. PTFE has been referred to as a polymer of "low concern" due to its low bioavailability and stability in the natural environment[26]. While PTFE is considered to be chemically inert for general household purposes, the coating can start to degrade at temperatures higher that 290 degrees Celsius (°C)[27]. At high temperatures, such as in waste incineration or cooking at high temperatures, PTFE can degrade to smaller-chained PFAS compounds, such PFOS and PFOA, which will be released into the air. Schlummer et al. (2014) conducted a study on the emission of PFCA compounds from heated surfaces made of PTFE applied in food contact products. It was found that at 370 °C, up to 12,190ng of total PFCA emissions were released into the gas phase per hour[28], which then presents a risk to humans via consumption or inhalation.

In addition, fluoropolymers, such as PTFE, are made using processing aids that contain other PFAS compounds such as salts of PFOA (Ammonium Perfluorooctanoate [APFO] or Sodium Perfluorooctanoate [NaPFO]), GenX and FTOHs[28]. A study suggests that residual PFOA and FTOHs are not always removed completely during the manufacturing of non-stick coatings. At normal cooking temperatures (179 to 233 °C), the study found that 11-503 picograms per centimeter squared (pg/cm^2) of PFOA[1] , 25-204 pg/ cm^2 of 6:2 FTOH and 42-625 pg/cm^2 of 8:2 FTOH were released into the gas phase[29].

Due to the oleo- and hydrophobic properties of PFAS, they make ideal additives to waterproof cosmetic products such as suncream, insect repellents and mascara and protective hair products such as conditioner. They are often used in these products as emulsifiers and lubricants. Fluorinated surfactants have also been

[1] Different units have been used in this study, relating to the sample matrix that was being analysed.

found in some toothpastes and dental floss as they increase the enamel-fluoride interactions[19] and improve the cleaning properties[30].

The majority of the PFAS that are found in cosmetics and personal care products are polyfluoroalkyl phosphate esters/diesters (PAPs/diPAPs) and PFCAs (including PFOA and shorter chained PFHxA and PFHpA). In one study of 24 cosmetic products, it was found that the concentrations of total PFCA compounds ranged from non-detect to 5.9µg/g for cosmetics and from non-detect to 16 µg/g for sunscreens. Other products, such as mica and talc were found to have been treated with PAPs and were found in concentrations of up to 35 µg/g[31.]

Small amounts of PFAS can be used in hard-surface cleaners, which can enhance the cleaning power. The addition of PFAS can eliminate wiping stripes and improve the reflection of cleaned glass[19]. Fluorinated surfactants can also be very effective at removing scale and cleaning concrete and metal surfaces.

The PFAS that are found in cleaning agents are predominantly FTOHs. 8:2 FTOH was found in concentrations of up to 73,000 µg/kg in a study of PFAS in consumer products.[32]

Paper products and packaging that require water and oil repellent properties have likely been treated with PFAS[33.] In recent years, treated paper products and packaging have been proposed as a compostable substitution of single-use plastic food packaging. A recent study of Canadian food packaging has shown the presence of PFAS compounds in high concentrations in all selected packaging, including baking paper, microwave popcorn bags, coffee cups and other treated paper products[32,34.] PFAS can be either added to the pulp slurry, directly to the paper surface or be included in pigment coatings. They can also be used in photographic materials such as films and papers as wetting agents, emulsion additives stabilisers and antistatic additives. PFAS compounds used in printing inks can improve the properties of aqueous and oil-based inks[19]. The residue of these compounds used in manufacturing can remain on the consumer products.

The coatings of paper products and packaging tend to be blends of mainly side-chained fluoropolymers (including PAPs and diPAPs), FTOHs and FTSAs. In one study, concentrations of FTOHs and several PFCAs were found to be 0.5-6 ng/ cm2)[29]. Other compounds that are associated with paper products and packaging include 6:2 fluorotelomers, PFPE (perfluoropolyesters) and 6:2 FTOH[33]. PFOSA, EtFOSA and EtFOSE are also found in printing inks.

Textiles, upholstery, carpets and leather products that require water and stain resistance, likely have been treated with PFAS products such as Gore-Tex and 3M Scotchguard. They have also been found in aftermarket stain and water repellent sprays and dry-cleaning fluids (such as PureDry®, which has been used as a replacement for perchloroethylene)[13.] The compounds typically used in textile production and surface coatings are fluorotelomer-based polymers (FTPs) such as 8:2 FTOH, 6:2 FTOH and PASF. Carboxylic compounds (such as PFOA and PFHxA) have also been used in surface treatments but are starting to be phased out due to regulatory restrictions [35]. These compounds will degrade to terminal PFAAs. PTFE is also used in highly porous fabrics, including waterproof linings in rain jackets and other outdoor gear. Some studies have shown that N-Methylperfluorooctanesulfonamidoethanol (N-MeFOSE) may be present in textiles and carpets, as well as in furniture paints and varnishes.

Releases of PFAS to the environment can occur during the manufacturing phase of textiles, through leaching of PFAS from fabric, from commercial laundering activities[36] and in the dry cleaning of textiles. In Europe, it is estimated that approximately 0.7 tonnes of 6:2 FTOH are emitted per year from outdoor rain jackets treated with fluorotelomer-based side chain fluorinated polymers [37].

PFAS are also used in leather production, in processes such as hydrating, bating, pickling, degreasing and tanning as well as in the water and stain repellent treatments of tanned leather[19]. In a 2012 article that analysed PFAS in Norwegian consumer products, two furniture leather samples and one shoe leather sample were found to contain PFOS levels that exceeded the EU regulation of 1µg/m^2 [38,39]. In a supervised machine learning paper about PFAS source allocation, Kibbey et. Al. identified a number of PFAS compounds, predominantly perfluorinated sulfonates,

surrounding two tanneries[40]. These findings indicate the potential for leather production facilities to be a significant source of PFAS contamination.

PFAS has been used widely as an additive in paints, coatings and surface treatments used in construction. Almost 20% of paints in the global decorative coatings market contain PFAS, and it can increase to 50% for industrial paints[41]. The properties of PFAS are advantageous in ensuring levelling and smooth application of paints and consistent pigment dispersion[19]. They're also highly effective at repelling water and oil stains and are resistant to weathering which makes the useful in architectural paints, industrial coatings and protective finishings for buildings, vehicles and furniture. The compounds usually found in paints and coatings are FTPs, ammonium salts of PFHxA and diPAPs[42].

Similar to textiles and leather production, many sports products are treated with PFAS compounds to ensure that they are waterproof[33]. Examples of products include climbing ropes, tents, hiking boots, tennis rackets, fishing rods and astroturf[43]. In astroturf, PFAS is used in the production of the synthetic grass, rather than the tyre crumb[44]. Some surf waxes also contain PFAS compounds, called fluorowaxes, which contain high concentrations of PFCAs and PFSAs (up to 159.8 µg/kg in one study[32]). Some guitar strings are also known to contain PFAS compounds.

Table 1 - 2 Household products containing PFAS, examples of known PFAS compounds and potential exposure pathways for human and ecological receptors

Source	Examples of PFAS compounds	Potential environmental pathway
Non-stick coatings [20–23]	PTFE PFOA (and associated salts) GenX 6:2 FTOH 8:2 FTOH	Gas emissions Direct ingestion Household wastewater Solid waste disposal
Cosmetics and personal care products[30,31]	PAPs diPAPs PFCAs (eg. PFOA)	Transdermal contact Direct ingestion Household wastewater Solid waste disposal
Cleaning agents [19,32]	PFAAs PFSAs (eg. PFOS, PFBS) PASF FTOHs PFOS	Transdermal contact Household wastewater Solid waste disposal
Paper products and packaging [19,29,32–34]	PAPs diPAPs PFCAs PFPE FOSA EtFOSA EtFOSE	Food absorption Direct ingestion Transdermal contact Solid waste disposal
Small-scale textiles, leather production (eg. GORE-tex, Scotchguard) and commercial laundering [13,19,35–37,45]	FTPs FTOH (eg. 6:2, 8:2, 10:2) PTFE PFCAs (eg. PFOA, PFBA) PFSAs (eg. PFBS) N-MeFOSE PASF	Transdermal contact Household wastewater Commercial wastewater (Dry cleaners) Solid waste disposal
Coatings (building and construction industry)[19]	FTPs PFHxA diPAPs	Transdermal contact Surface run-off
Sports and leisure (astroturf, surf waxes, climbing ropes, guitar strings etc.) [32]	PTFE PFCA (eg. PFOA) PFSA (eg. PFOS)	Transdermal contact Solid waste disposal

1.5.1.1 Urban Surface Water Runoff

Urban surface water runoff is a known source of PFAS contamination, particularly longer chained PFCA contamination[46]. This is linked to the sorption of longer-chained compounds to sediment particles that are found in urban surface water runoff.

Where stormwater drains discharge into surface water bodies, elevated levels of PFAS concentrations have been identified[46–48]. These compounds can be linked to a vast number of sources, but in towns and cities, these elevated concentrations can be linked to wear and tear of vehicles, dust and leaks from general road usage. Kali et al. (2025) found that PFAS concentrations increased in streams with stormwater inputs following wet weather events[48]. Long-chain PFAS and FTS compounds were more prevalent in the stream during wet weather events, which would indicate that runoff is a significant source. The highest PFAS concentrations were found downstream of urban areas and point sources, like airports and wastewater treatment plants.

Windscreen wash and automotive waxes contain PFAS to improve the spread and resistance to water and oil[33]. Interiors shampoos and conditioners for fabrics and vinyl surfaces contain PFAS compounds[49]. The compounds found in these products are like the cleaning agents outlined in Section 1.5.1.1. Hydraulic fluid additives contain PFAS compounds, such as PFSA salts, to prevent evaporation, fires and corrosion of the metals they are used within[50]. Hydraulic fluids are further discussed in Section 1.5.2.3. Commercial car washes also use PFAS in several products and processes, such as sprays, waxes and rinses to prevent the build-up of water, oil and dirt[51].

1.5.2 Industrial sources

Industrial sources reflect a significant input of PFAS into the environment[23,52]. Like anthropogenic sources, PFAS compounds will predominantly enter the environment via waste streams (point sources), including through waste-water effluent, air emissions and industrial solid waste. Some additional pathways may include dust, leaking of underground pipes and firewater retention tanks and systems into the

groundwater and surface run-off. However, large concentrations of fluorinated substances used in the industrial environment are generally contained in a controlled environment, such as in coolant systems[53].

In an industrial setting, PFAS can be involved in three different categories[54]. The production of PFAS itself involves ECF and FT processes[13,55]. PFAS can also be used in manufacturing processes such as the production of chemicals and products that may contain PFAS, such as pharmaceuticals products and metal manufacturing[56]. It can also be stored or handled, often in the case of AFFFs or other fire-fighting materials. AFFFs are often stored at facilities where there is bulk liquid fuel storage, such as petrol stations, or facilities with back up energy generators[57].

The following section provides details on some major industries that are found in Ireland, commonly used PFAS compounds and potential pathways into the environment. This review is limited to a general understanding of production processes and is not comprehensive. A summary of the sources, potential compounds and exposure pathways are summarised in Table 1 - 3.

1.5.2.1 Metals manufacturing

PFAS can be used in the manufacturing of metals, in several finishing processes, including electroplating, coating, etching, cleaning and anodizing. They can be used to prevent corrosion, reduce mechanical wear on the materials or enhance the aesthetic appearance[19,33,56,58].

Salts of PFOS have been used as primary surfactants in electroplating solutions, particularly in chromium, zinc, nickel, copper, and tin plating. The properties of PFAS promote the flow of coatings and surface treatments and prevent cracking once hardened. They are also used as wetting agents and mist-suppressing agents in decorative plating and non-decorative hard plating[59].

Common compounds found in metals manufacturing and chrome plating include PFOS, PFBS, PFHxS, FTSAs, PASFs, PFCAs and PFPE and would likely be found in the wastewater of facilities[33]. It is reported by the European Commission that 6500 kg of PFOS is used in the hard chrome plating industry per year in Europe[60].

1.5.2.2 Information, Communications and Technology (ICT) and Electronics

PFAS are highly desirable in the electronics industry and in the manufacturing of semi-conductors due to their low surface tension and high dielectric and breakdown strength[61,62]. They have been used in the production of printed circuit boards, loudspeakers, transductors and other products[33]. PFAS compounds are predominantly used as solutions and reagents in the photolithography process to apply antireflective coatings, etchants, barrier layers, photoresists and cleaning solutions. Due to their low heat conductivity properties, PFAS can be used as a heat transfer fluid in the cooling of electrical equipment.

The semiconductor manufacturing sector uses closed-system manufacturing equipment to limit the amount of PFAS being released into the environment via wastewater, exhaust air and waste. However, there are still small amounts being emitted via wastewater, which is also the case in the electronics manufacturing industry.[61,62] In a study conducted by Jacob et al. (2021), concentrations of PFAS discharged in fab wastewater can be in the orders of 1000s of ng/L[63]. Fab wastewater is the effluent directly after the manufacturing process.

Common compounds that are associated with ICT manufacturing are FTSAs (6:2 FTSA), PFOS and PFBA, which have all been positively identified in printed circuit boards[38]. Polyvinylidene fluoride (PVDF) is used in various applications, including electrical insulation for wires and cables and chemical processing. It is reported by the European Commission that 9.3 kg of PFOS is used in the semiconductor manufacturing industry per year in Europe[60].

1.5.2.3 Chemical and Pharmaceuticals Industry

As mentioned Section 1.5.1.1, PFAS has been used widely as an additive in paints, coatings and surface treatments used in construction[41,42]. They are also used in adhesives and sealants[15,56].

PVDF is used as architectural coatings to prevent rusting and the wearing of facades. Similarly, when PFAS are used in cement tiles, they are more weather resistant[19].

Surfactants, specifically FTOHs and fluorotelomer ethoxylates (FTEOs), can also be used as an antifogging film on some glass lenses and anti-fogging spray[64], mirrors, car windshields[19].

Non-polymer PFAS, such as PFAAs and PFCAs, can be used as processing aids in the manufacturing of certain ingredients and additives for pharmaceutical products. They can be used as dispersants in self-propelling aerosol pharmaceuticals[15,19,33,65]. Furthermore, PFAS can be used as solvents and emulsifiers in pharmaceuticals. Can also be used in intravascular oxygen carriers and blood substitutes[15].

Fluoropolymers such as PTFE are used in the manufacturing of medical devices such as endoscopes, mechanical heart valves, artery tubes and the equipment for implanting them[66].

PFAS, mostly fluoropolymers, are used in the manufacturing phase of different rubber articles such as the moulding of plastics and rubber, and also as mould release and anti-blocking agents and lubricants[15,33]. The use in manufacturing gives the finished products desirable properties, such as avoiding surface corrosion[67].

Hydraulic and brake fluids used in both cars and in aircrafts are both manufactured using PFAS compounds, such as PFECHS,[68] and also have PFAS compounds as additives. They are ideal additives because they prevent fire, corrosion and evaporation in the hydraulic system[49].

Historically, PFOS is the predominant compound used in hydraulic fluids, however this is currently being phased out and being replaced by other highly fluorinated substances[33]. It is reported by the European Commission that 600-730 kg of PFOS is used in the hydraulic fluids for the aviation industry per year in Europe[60].

1.5.2.4 Mineral Industry and Mining

Fluorinated surfactants, such as PFOS historically, are used to increase the amount of metal recovery from ore by accelerating the wetting of the ore and removing the oxide layer. This method is predominantly used in copper and gold mines.[15] There

are other uses for PFAS in mining such as facilitating the leaching of certain metals (vanadium and uranium), by dispersing leaching agents and enhancing the metal recovery[69]. However, there are no historical or operational vanadium or uranium mines in Ireland[70].

There are a couple of historical and current oil and gas operations in Ireland[70]. During these sorts of operations PFAS can be used in the drilling fluid to reduce surface tension and as an oil-well stimulation agent. Compounds may include, PFOA, PTFE and FTOH[15,33].

1.5.2.5 Paper and Wood Processing

PFAS have been used for the manufacturing of wood and products of wood and cork[35]. Polymer PFAS fabric is used during the bleaching of wood.[13,71] Non-polymer compounds, such as PFOA, PFHxA and PAPs, can be used in the coating of the wood substrate and chipboards to reduce swelling if wet. They can also be used as an additive or coating to impart certain surfactant qualities to finished paper products[52].

Mofokeng et al. (2024) conducted a study analysing the presence of PFAS in paper grades used for the manufacture of recycled paperboard. It was found that the majority of PFAS was associated with additives and cross-contamination. It was found that post-consumer paper products had the highest sum of 22 PFAS concentration of 213 ng/g, when compared with pre-consumer and retail products, indicating that PFAS can bioaccumulate in recycling processes[72].

1.5.2.6 F-Gases

The OECD definition of PFAS includes some F-gases which are used in refrigerants[53]. Some of these are referred to as hydrofluorocarbons (HFCs), and they are produced in much larger quantities than non-polymer PFAS compounds. However, they are less bio-accumulative, can breakdown to less toxic compounds in natural environmental conditions and are less critical from a toxicological viewpoint[15].

These refrigerants may be used as a health transfer liquid in the cooling of data centres[73], in the testing of electronic devices and switchboards, fire suppression systems and in air conditioning units.

1.5.2.7 AFFFs storage

Fire-fighting foams containing PFAS are predominantly used for the extinguishment of liquid fires. They are stored, tested and used as fire suppression at industrial sites where there may be a risk associated with flammable liquids, such as solvents, hydrocarbons, alcohols and other specialty chemicals[57]. There is also evidence that certain dry powder fire-fighting foams historically contained PFAS.[74]

Table 1 - 3 Industrial sources of PFAS, examples of known PFAS compounds and potential exposure pathways for human and ecological receptors

Source	Examples of PFAS compounds	Potential environmental pathway
Metals Manufacturing[19,59,60]	PFCAs PFSAs (eg. PFOS, PFHxS, PFBS) FTSAs PASFs PFPE	Industrial effluent Gaseous emissions
ICT and electronics[33,38,59,60]	FTSA PFOS PFBA PVDF PFCAs	Industrial effluent Gaseous emissions
Chemical and pharmaceuticals[15,19,33,60,66,68,75–77] *Chemical industry* *Fluoropolymer manufacturing* *Paints and adhesives* *Pharmaceuticals* *Plastics and rubber* *Hydraulic fluids*	PFBS PFOA GenX ADONA PTFE FTPs PFHxA diPAPs PVDF	Industrial effluent Gaseous emissions Surface run-off
Mineral industry and mining [15,33]	PFOS PFOA PFTE FTOH	Industrial effluent Injection of fluids into ground Dewatering
Paper and wood processing[13,35]	FTOH PTFE PVDF PFCAs PFSAs	Industrial effluent
F-Gases[15]	HFCs 1H-pentafluoroethane	Gaseous emissions Leaking of coolant pipes
AFFF storage (bulk fuel storage)[57,74]	PFOA PFOS 6:2 FTS PFHxA PFPeA PFHpA PFNA	Land application Leaking of pipes Surface run-off Industrial effluent

1.5.3 Civil sources

The storage, handling and use of PFAS in civil and military settings is a significant source of PFAS in the environment. This use can include the storage, handling and use of AFFFs at bulk fuel storage sites such as petrol stations, or airports, fire-fighting stations and associated training grounds and military training grounds.

AFFFs are the most prominent method of widespread environmental dispersal and most critical environmental risk, as it is often released directly to an environmental receptor in high volumes[78]. Sites where AFFFs have been used during fire training practices, equipment testing, accidental discharge and incident responses are diffuse sources of PFAS. They can also be dispersed during the storage and transfer of foam concentrate. There are two main classes of firefighting foams (Class A and Class B). Class B firefighting foams contain fluorosurfactants and have been used to extinguish flammable liquids since 1962[79]. Class A foams are used for wood, paper, rubber and textile fires and generally do not contain PFAS. These foams are generally released using high expansion foam generators.

As mentioned in Section 1.5.2.7, Class B firefighting foams are stored and used at sites where there is a risk of liquid fires, including hydrocarbons, alcohols, solvents and specialty chemicals. They are commonly found at chemical, petrochemical and pharmaceutical plants, oil refineries, military sites, civil fire stations and civil airports[80]. Class B firefighting foams containing PFAS are usually stored in the form of a foam concentrate, which is diluted with water before being released via a sprinkler system. Some may contain a pre-mixed foam, which is activated by gas when released.

In addition to the globally recognised risk environmental risk of AFFFs being used at airport, military and fire-fighting training sites, major sources of AFFF environmental contamination can be linked to facilities that have a prior history of large liquid hydrocarbon fires. Fluorinated surfactants are also used in dry fire-extinguishing agents to make the powder non-wettable by hydrocarbons[19]. Commonly found compounds in AFFFs include PFOS, PFOA, precursor compounds to PFHxS, PFHxA, and precursors to FTS. A full list of compounds is included in Table 1 - 4.

Table 1 - 4 Civil sources of PFAS, examples of known PFAS compounds and potential exposure pathways for human and ecological receptors

Source	Examples of PFAS compounds	Potential exposure pathway
AFFFs at civilian airports, military training grounds, fire-fighting stations and petrol stations [19,78–80]	PFOA PFOS 6:2 FTS PFHxA PFPeA PFHpA PFNA FTOH	Land application/infiltration Surface run-off

1.5.4 Agricultural sources

Agricultural sources are predominantly diffuse sources rather than point sources, such as pesticides and biosolids, and they can contribute to minor background concentrations of PFAS[24] in the environment from their extensive use across Ireland. They are generally applied directly to soil or vegetation and can leach into underlying water-bearing units and runoff into nearby receiving water bodies. The compounds associated with each source are summarised in Table 1 - 5.

1.5.4.1 Pesticides and fertilisers

PFAS has been used as both the active ingredient and as an additive to plant protection agents, or insecticides. These include sulfuramid (N-EtFODA), flursulamid and lithium perflurooctane sulfonate or 'Super-Arinosu-Korori' and Novaluron, and pesticides[15]. PFAS compounds are also used as anti-foaming agents and dispersants in various pesticides as they are a powerful wetting agent for leaves. They are also used as a wetting agent for insecticides for aiding in suffocation. In the United States in the last 10 years 30% of conventional pesticide active ingredients were PFAS[50]. PFAS compounds can also be used as inert additives to pesticides, which are not required to be publicly disclosed on the label[81]. In the US, PFPAs and PFPiAs are no longer permitted as pesticide additives.[82] However, in their 2024 industry survey report, Fidra found that there are 25 known PFAS active substances still in use in United Kingdom pesticides, six of which have been identified as Highly Hazardous Pesticides[83]. These compounds include Diflufenican and Picolinafen, herbicides reported to be used on 2,488,059 ha and 624,957 ha, respectively in the UK arable sector in 2022.

PFBA, PFPeA, PFHxA, PFHpA, PFuDA, PFOA, PFNA and PFDA have also been found in HDPE packaging used for a variety of uses, including pesticide packaging[84,85]. These PFAS can also be used in the creation of high-density polyethylene (HDPE) packaging, and they can remain as a contaminant on the walls of the containers. The US EPA reported the leaching potential of PFAS from the walls into the liquids that they contained.

1.5.4.2 Recycled compost and biosolids

Compost created from recycled municipal waste contains PFCAs and PFSAs associated with composted items, such as fruit, vegetables, compostable bags and readily biodegradable packaging[86]. In one study of US municipal organic solid waste composts, concentrations of total PFAAs ranged from 28.7 to 75.9 µg/kg. PFOS and PFOA were detected in all nine samples.

Urban wastewater treated sewage sludge is commonly referred to as 'biosolids'. Following treatment, it is still used as an agricultural fertiliser in Ireland. There are well-documented examples of significantly elevated concentrations of PFOS and PFOA in biosolids, especially when they have come from wastewater treatment plants with industrial inputs as well as municipal. Following land application, compounds have been detected in underlying and surrounding soils, groundwater, livestock, crops and surface water receptors[87].

Table 1 - 5 Agricultural sources of PFAS, examples of known PFAS compounds and potential exposure pathways for human and ecological receptors

Source	Examples of PFAS compounds	Potential exposure pathway
Pesticides and fertilisers[15,82,84]	PFOS EtFOSA PFuDA	Land application/infiltration Surface run-off
Recycled fertilisers and biosolids [86,87]	PFOA PFOS 6:2 FTS diPAPs	Land application/infiltration Surface run-off

1.5.5 Waste Management

Secondary sources of PFAS involve the bioaccumulation and storage of PFAS compounds from several primary sources. Waste management facilities can be considered point sources, in the case of wastewater treatment plants (WWTP), incineration and lined landfills and diffuse sources in the case of unlined landfills.

PFAS are widely used in both industrial and consumer products that will then present and bioaccumulate and bio magnify within solid waste streams, wastewater streams and organic waste[16]. Industrial and municipal waste streams act as a secondary source of PFAS, by which compounds from these products can enter the environment if not removed appropriately.

In Ireland, the major avenues by which solid waste is processed is by landfilling and incineration, however solid recovered fuel, organics composting and recycling are more sustainable management avenues used for smaller quantities of waste. Industrial liquid wastes are predominantly processed by either on-site wastewater treatment plants or diverted to larger municipal WWTP that also treat household and commercial liquid wastes[88].

1.5.5.1 Landfilling

The treatment of landfill leachate for PFAS is currently not common practice[78,89]. Once treated for other contaminants, landfill leachate is often discharged directly to a surface water body or is passed through a WWTP before being discharged. There is a distinct disparity in PFAS composition of the input solid waste and the landfill leachate. While input solid waste may enter in the form of diPAPs and FTOH, it is predominantly detected in the leachate as FTCA and PFCAs. This indicates the potential for PFAS compounds to bio-transform in landfills and also release semi-volatile PFAS to the atmosphere[89].

In 2020, Harrad et al. investigated the presence and behaviour of PFAS in 40 Irish landfills by assessing leachate, air, soil and groundwater samples[78]. PFAS was detected in leachate in all 40 landfills and there were higher concentrations in lined landfills than unlined. However, groundwater near unlined landfills had significantly

higher concentrations of PFOA (average 69ng/L) compared to lined sites (4.1ng/L), which is likely due to the uncontrolled nature of the leachate.

1.5.5.2 Incineration

Recent research suggests that the incineration of solid waste materials >650°C will break PFAS bonds[90], however this is a subject of considerable study at present and has only been completed in laboratory trials. In 2023, the United States Department of Defence (USDoD) had an Incineration Moratorium (or a ban) for PFAS until guidance is issued on destruction methods[91]. As such, while it is likely that the majority of PFAS is destroyed, there remains potential for solid waste that is incinerated to release PFAS compounds into the atmosphere through gaseous emissions.

1.5.5.3 Solid Recovered Fuel

Solid recovered fuel is made from dry, non-hazardous waste such as paper, wood and textiles, that can be transferred into generating heat or to operate high-capacity industrial plants such as cement factories. Some of the fuel may contain PFAS compounds, such as in the manufacturing, bleaching and coating of wood in the water- and oil proofing of paper and packaging products and the treatment of textiles, upholstery, carpets and leather products that require water and stain resistance. Cement kilns operate at extremely high temperatures (>1000°C), so like incineration methods, it is likely that the majority of PFAS compounds are destroyed but there is still potential for solid recovered fuel to release PFAS compounds into the atmosphere through gaseous emissions[92].

1.5.5.4 Organics Composting

Organics composting is considered in Section 1.5.3.2 as an agricultural source of PFAS.

1.5.5.5 Recycling

PFAS compounds found in recyclable products such as textiles, paper, cardboard, wood, metals and plastics may bioaccumulate when recycled and transformed into new products[93,94,58].

1.5.5.6 Wastewater treatment

Wastewater treatment plants are a known location for the bioaccumulation and transformation of PFAS compounds[16,93]. Due to the range of solubilities, PFAS will pass through the WWTPs in both the solid and liquid phase[95].

Major point sources of PFAS include PFAS producing or PFAS using industrial sites such as papermaking, textile mills, and electroplating. Non-industrial sources may include environmental degradation of polyfluorinated microfibres released by water-resistant clothing during laundry[37], human excretion after ingestion, and also likely PFAS compounds in municipal drinking water[96].

Several WWTPs in the US have reported an increase in total PFAS in the effluent, when compared to the influent, particularly PFOA, which increased by an average of 6ng/L. It was found in the same study that concentrations of PFOS did not change between the influent and effluent, which indicates that longer chained PFAS will preferentially adsorb to the biosolids and because polyfluorinated precursor compounds will transform into terminal products throughout the treatment processes[97]. Kali et al. (2025) found that there was a consistent contribution of PFAS compounds into streams during both dry and wet weather[48].

1.6 Conclusions

It is recognised that the major point sources of PFAS to the environment globally[13,23,57] are from a range of sources.

Waste management facilities, such as landfills, compost facilities, incinerators and wastewater treatment plants are a significant source of PFAS into the environment. These facilities aid in the bioaccumulation and transformation of PFAS compounds from anthropogenic and industrial waste before either leaching into the groundwater, being released into the air or being discharged into surface water bodies respectively. Industrial effluent from facilities that either produce or process PFAS and facilities that use PFAS in chemicals or manufacturing metals, ICT and electronics, AFFFs, chemicals, pharmaceuticals, treated paper and wood products, textiles and air conditioning units. Effluent can be discharged into surface water bodies and leaks from pipework, tanks or spills of PFAS containing chemicals may

leach into the groundwater. Gaseous emissions from some industries may also contain PFAS.

Locations where AFFFs may be stored, used or released, such as fire-fighting stations, training areas, military bases and airports are also a major source. AFFFs may be present at locations where bulk fuels, oil or solvents are stored such as industrial facilities, petrol stations and refineries and power plants.

Stormwater overflows in Ireland are conduits for urban surface water runoff and sewage system overflows, which are both known sources of PFAS[98]. As such, they are point sources of PFAS. Where there are misconnections or cracks, the stormwater drains could leak into the underlying groundwater.

Major diffuse sources are:

- Agricultural use of pesticides, herbicides and bio-solids application from wastewater treatment plants. Major pathways would include runoff and infiltration to groundwater, depending on underlying soil type.
- Runoff from urban areas, where there are no stormwater overflows or drains.
- Historic use of PFAS that has led to legacy contamination.

Table 1 - 6 summaries the major sources of PFAS that may be found in Ireland. A detailed exploration of the chemicals associated with each source is included in the supplementary information of Glüge et al (2020)[15]. The locations and environmental pathways of potential PFAS sources in the Republic of Ireland are further discussed in Chapter 2.

Table 1 - 6 Summary of potential PFAS sources in Ireland from international literature

Type of source	PFAS source category	PFAS source	Potential environmental exposure pathways
Point sources	Waste management facilities (landfills, compost, incinerators and wastewater treatment plants)[16,36,58,88–97]	• Non-stick coatings[20–23] • Cosmetics and personal care products[30,31] • Cleaning agents [19,32] • Paper products and packaging[19,29,32–34] • Textiles, leather and commercial laundering[13,19,35–37,45] • Coatings and paints[19] • Sports and leisure products [32]	• Leaching to groundwater • Volatilisation and air emissions • Effluent discharge
	Industrial effluent	• Chemical manufacturing (fluoropolymer production, paints and adhesives, pharmaceuticals, plastics and rubber, hydraulic fluids) [15,19,33,60,66,68,75–77] • Metals manufacturing[19,59,60] • Mining and minerals industry[15,33] • Electronics and semi-conductor manufacturing [33,38,59,60] • Paper and wood product manufacturing[13,35] • Textiles manufacturing and treatment[13,19,35–37,45] • Air conditioning unit production (F-gases) [15]	• Effluent discharge • Leaching into groundwater from pipework, tanks or spills of PFAS containing chemicals • Gaseous emissions
	AFFF use, storage or released [19,78–80]	• Fire-fighting stations • Fire training areas • Military bases • Airports • Bulk fuel storage[57,74]	• Runoff • Effluent discharge • Leaching into groundwater

Type of source	PFAS source category	PFAS source	Potential environmental exposure pathways
	Stormwater overflows and drains	• Urban runoff [46] • Sewage overflows	• Effluent discharge • Leaching into groundwater where there are misconnections
Diffuse sources	Agricultural sources	• Pesticides and herbicides[15,82,84] • Bio-solids from wastewater treatment plants[86,87]	• Runoff • Leaching into groundwater
	Urban runoff[46]	• Car maintenance products • Hydraulic fluids • Car washes	• Runoff • Leaching into groundwater
	Legacy contamination [99]	• Historical use, production and storage of AFFFs and PFAS chemicals	• Runoff • Leaching into groundwater

Chapter 2 - PFAS Sources in Ireland

2.1 Introduction

Chapter 1 reviewed global studies and international literature to determine sources of PFAS. Although PFAS is now produced and used globally in a multitude of industries, not all sources will directly pose a risk to environmental or human receptors. Similarly, not all PFAS discussed carry equal risk, based on the compound's characteristics. Chapter 2 identifies potential PFAS sources in Ireland and reviews their level of risk to entering the environment. The PFAS compounds predominantly considered in this thesis are those that are the most toxicologically studied[100,101] and regulated and those that are the most frequently detected PFAS globally. These compounds include perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkane sulfonic acids (PFSAs), fluorotelomer sulfonates (FTSs), Perfluoroalkyl Sulfonamides & Sulfonamide Derivatives (eg. FOSA), Chlorinated Polyfluoroalkyl Ether Sulfonates (Cl-PFESAs), Perfluoroalkyl Ether Carboxylic Acids (eg. PFECHs) and Polyfluoroalkyl Phosphate Esters (PAPs).

2.1.1 Aim

The aim of this Chapter is to review the findings of Chapter 1 to identify relevant PFAS sources in the Irish context, based on Ireland's industrial profile, land use and infrastructure. Using the information, sources will be classified in relation to their potential risk to the environment to inform the risk assessment.

2.1.2 Objectives

The objectives of this Chapter are to:

- Conduct a desk-based study to determine which PFAS sources are relevant to the Irish context, and where large volumes of PFAS may exist within the county.
- Conduct a review of PFAS compounds currently registered in Ireland under the REACH Database.

- Create a geospatially referenced database of potential major PFAS point sources in Ireland and export using a Geographical Information System (GIS) package.
- Identify potential knowledge gaps or data deficiencies in Ireland with regards to PFAS source identification.
- Consider the potential pathways for each potential point source.

2.2 PFAS in Ireland

Chapter 1 reviewed international literature to infer the potential major point and diffuse sources of PFAS in Ireland. These include waste management facilities, industrial effluent from facilities that may use or store PFAS, sites where AFFFs have been used, stored or released, stormwater overflows and urban runoff, agricultural sources and legacy contamination.

As PFAS has never been manufactured in Ireland, all PFAS sources are predominantly secondary sources. Pollutants enter water environments from two main types of sources:

- Point sources, which are single identifiable sources of pollution, such as a pipe or a drain; and
- Non-point sources of pollution, which are termed as 'diffuse' sources[24]

The following sections summarise current knowledge on point sources of PFAS in Ireland and PFAS compounds that are registered to be imported into Ireland on the REACH database.

2.2.1 Known PFAS sources in Ireland

There have been a number of case studies conducted in Ireland to investigate sites where there is known PFAS contamination[26,78,95]. The case studies have indicated that there is a range of PFAS compounds present in indoor air and dust, drinking water, outdoor air, soil, landfill leachate, biosolids and groundwater.

2.2.1.1 Waste management facilities

The Irish EPA-funded FUEL project revealed that PFAS concentrations in leachate collected from 40 Irish landfills were comparable to concentrations elsewhere in North America, Europe and Asia.[78] Under the EU Landfill Directive (1999/31/EC), all landfills in Ireland are required to be lined since 1999. However, some landfills established pre-1990s are now managed as legacy landfills or historic dump sites. It was found that groundwater from unlined landfills had higher PFOA concentrations (mean of 69ng/L) than groundwater sourced from lined landfills (mean of 4.1ng/L). It

was estimated that 3.5kg of target PFAS compounds are emitted from landfills in Ireland every year. This indicates that both lined and unlined landfills are significant sources of PFAS in Ireland.

PFAS compounds were also detected in all 21 samples of wastewater treatment plant derived biosolids in Ireland[95]. The study showed that the concentrations of the 39 target PFAS generally fell into the lower range of reported international studies. However, there is still potential for biosolids to be a large contributor to PFAS loads in the environment as a diffuse source and as a result, they will be considered in this study.

Despite there not being specific investigations, it is fair to assume, based on the presence of PFAS compounds in the solid phase, that Irish wastewater treatment plant effluent will also be a major source of PFAS into surface water bodies.

2.2.1.2 AFFF usage

The EPA commissioned an engineering consultancy AECOM to conduct the sampling of soil, sediment, vegetation and surface water at five sites to investigate the presence of PFAS compounds. Four of the sites were selected to be potential PFAS 'hot spots' associated with the historical or recent use of PFAS containing AFFFs and one sample was taken in a background site. The presence of PFAS in each media type is summarised in Table 2- 1. The results indicate that sites where AFFFs have historically or currently been used or stored can be significant sources of PFAS in Ireland.

Table 2- 1 Summary of the occurrence of PFAS at sites potentially impacted by AFFFs and a background site (AECOM, 2017)

Site	Sample Type	PFAS compounds detected	Highest frequency of compounds detected (out of 17)
Site 1 – Dublin Fire Brigade Training Area	Soil	Yes	13
	Vegetation	Yes	5
	Surface water	Yes	9
Site 2 – Bunclody Fire Station	Soil	Yes	11
	Sediment	Yes	2
	Vegetation	Yes	4
	Surface water	Yes	2
Site 3 – Shannon Airport	Soil	Yes	10
	Vegetation	No	-
	Surface water	Yes	7
Site 4 – Wolftrap Mountain (background)	Soil	Yes	3
	Vegetation	No	-
	Surface water	Yes	1
Site 5 – Irving Oil Whitegate	Soil	Yes	13
	Vegetation	Yes	1
	Surface water	Yes	6
	Groundwater	Yes	12

2.2.1.3 Facilities with PFOA Stockpiles

The Persistent Organic Pollutants Regulation is enacted in Ireland through the EU (POPs) Regulations 2020 - S.I. No. 1 46/2020[102]. In addition to other requirements, the POPs Regulation requires that industrial facilities with stockpiles containing PFOA or related substances present on site that are greater than 50 kg and above the threshold concentrations of >0.025 mg/kg for PFOA and its salts and >1 mg/kg for any individual PFOA-related compounds or combination of PFOA-related compounds) need to be reported to the EPA and the PFOA disposed of as a waste in

a facility licenses to accept POPs waste. Currently, there are no facilities licensed to accept PFAS waste. At the time of writing this thesis, this waste is required to be shipped off shore.

The EPA provided the INVEST p-FASST team with a list of the facilities that have registered PFOA stockpiles greater than 50kg. There are 107 registered stockpiles at 39 locations. The distribution across the counties is shown in Figure 2 - 1 and the locations are shown in Figure 2 - 2. While there may not necessarily be a pathway for the PFOA stockpiles to impact the environment (ie. If they are stored in an impermeable tank), they are still considered to be a potential major source of PFAS in Ireland and hence the facilities that they are stored at are considered in this study.

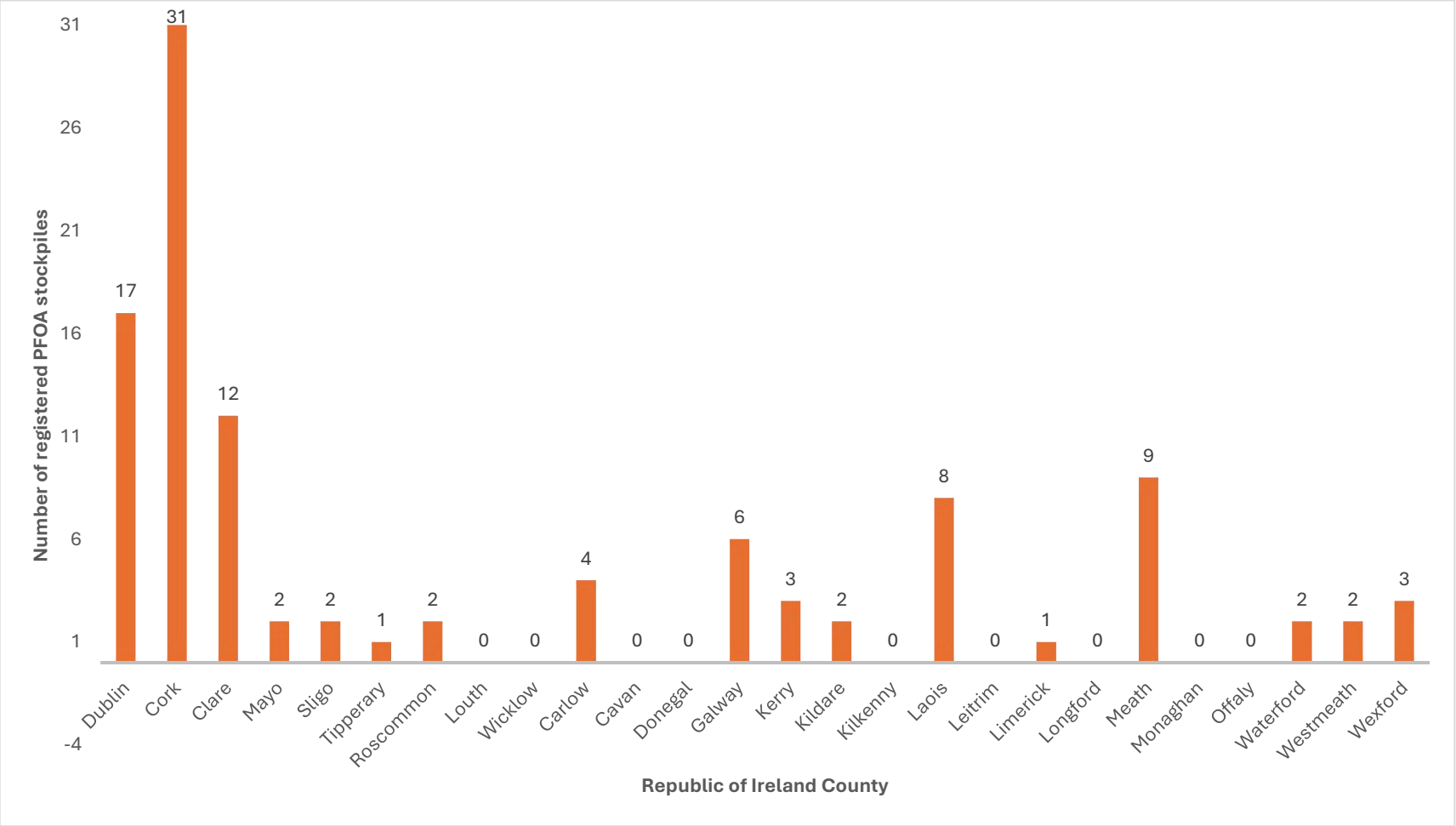


Figure 2 - 1 PFOA Stockpiles registered in each Irish county (EPA, 2025)



Figure 2 - 2 PFOA Stockpiles registered under POPs Regulation (EPA, 2025)

2.2.2 ECHA PFAS Import details

As PFAS is not manufactured in Ireland, some compounds have been imported for use in a variety of industries. Other compounds may be imported via articles (such as on clothing, or in personal care products). It is important understand what type of chemicals are being imported in Ireland as it can indicate what compounds may be found in the environment.

The European Chemicals Agency (ECHA) manages the REACH database to regulate the importation and production of chemicals in the European Union, including Ireland. Their database includes all public data submitted in REACH registration dossiers by substance manufacturers, importers, or their representatives[54]. A total of 26,865 chemicals has been registered in REACH and can be placed on the European Economic Area (EEA) market by companies with a valid registration. Chemicals that are either produced or imported in quantities of above 100 tonnes per year are required to supply information on long-term toxicity and environmental fate, as outlined in Annex IX of the REACH Regulations[103].

A methodology to obtain PFAS-related chemical data that is reported under the United States Toxic Substances Control Act (2016) and the Substances in Preparations in Nordic Countries (SPIN) database of Denmark, Finland, Norway and Sweden is outlined in Glüge et al (2020)[15]. A similar approach was used with the REACH database to determine the types of PFAS chemicals that are being imported into Ireland. The methodology and results are included in the following sections.

2.2.2.1 Methodology

REACH registration dossiers are created for substances which have been registered and can be placed on the European market by companies with valid registrations. The dossiers are stored on the ECHA CHEM Database[54]. The database was filtered based on ‘Substance name’ including ‘fluoro’ or ‘fluro’ and ‘Administrative data in which registered’ for ‘Ireland’. The two searches were reconciled. Substances that did not conform to the OECD definition of PFAS were removed (ie. non-polymeric substances that did not contain the –CF2CF2– moiety and polymeric substances that did not contain the –CF2– moiety[104]). A total of 69 PFAS compounds were

reported to have been imported into Ireland more than 100 tonnes per year. Table 2 -2 summarises the exports from the REACH database.

Table 2- 2 Exports from REACH Database

Category	Total Compounds
Exported – 'fluoro' or 'fluro' and registered in Ireland	200
Filtered – has 'fluoro' or 'fluro' in name	178
Known PFAS (as per OECD definition)	57
Known non-PFAS	42
Unknown	79
Ceased manufacture	19
Registration no longer valid	3

Figure 2 - 3 shows the total registered importers with active registrations in the Republic of Ireland and how their registration location is distributed across all 26 counties. Dublin is the county with the most registered importers. It is to be noted that even though a company is registered in a particular county, the chemicals may be distributed further to other counties.



Figure 2 - 3 Diagram showing the number of PFAS importers for different counties. According to this figure, Dublin has the highest number of PFAS importers registered in Ireland (ECHA, 2025).

Tonnage bands are included in the database where the compound is not used for intermediate use only or the tonnage data isn't confidential. The minimum quantity of PFAS compounds entering Ireland yearly is 161,146 tonnes and the maximum is 1,610,170 tonnes.

This methodology is unable to give a full picture of the types and quantities of PFAS compounds entering Ireland. This is due to several reasons including the lack of information available and some dossiers being classified as being for 'confidential uses'. Some compounds are imported by consultants and hence the final use is unknown or confidential. Many substances also enter the EU through the imports of articles such as in clothing or personal care products, rather than specific compounds so these quantities of compounds are unknown.

In a large number of uses, PFAS compounds are only required in low quantities to achieve the desired effect[33] because they are very effective. In REACH, there are only register requirements for importers of substances from 100 tonne/year[6]. Therefore, registered chemicals being imported in low quantities (<100 tonnes/year), such as some PFAS are not required to submit any information, including hazard or risk assessments.

2.2.2.2 Chemical properties

The dossiers of each PFAS were reviewed to determine whether the chemicals were persistent, bio accumulative and/or toxic (PBT) and the German Environment Agency REACH Guidance and Methods for the Identification and Assessment of PMT/vPvM Substances was reviewed to identify whether the chemicals were persistent, mobile and toxic (PMT) or very persistent and very mobile (vPvM). 15 compounds were classified as either P, B or T, or a combination of the three criteria and 2 were classified as vPvM. Table 2 -3 shows a summary of the PBT, PMT and vPvM status of the chemicals exported from the REACH database.

Table 2- 3 Persistent (P), Bioaccumulative (B) and Toxic (T), Persistent (P), Mobile (M) and Toxic (T) and Very Persistent and Very Mobile (vPvM) status of chemicals from REACH database (ECHA, 2025)

Category	Total Compounds
P, B and/or T	15
Not PBT/vPvB	35
vPvM	2
"No information" on PBT status	101
Not applicable	5

2.2.2.3 Potential use categories, environmental use and sector end of use

Each dossier was examined of the compounds that were classified as PFAS compounds. Where available, Section 3 of the dossiers provides information on the manufacture, use and exposure, which includes the formulation or repacking, use at an industrial site, widespread use by professional workers, consumer uses and service life. Not all dossiers container this information, as such a non-exhaustive list of product categories has been summarised in Table 2 -4. The product categories (PC) are used to classify chemicals based on their intended use and there may be multiple categories for each compound. These do not include articles that are imported in a fully manufactured state.

Table 2- 4 ECHA database summary of product categories of imported PFAS compounds ("PC" refers to "Product Category") (ECHA, 2025)

Product category number	Description	Total compounds included in category
PC0	Other – Fire suppression agent or extinguishing medium	4
PC0	Other – Foaming/blowing agent	2
PC1	Adhesives and sealants	1
PC9a	Coatings and paints	2
PC9b	Fillers, putties, plasters and modelling clay	1
PC15	Non-metal surface treatment products	1
PC16	Heat transfer liquids	8
PC19	Intermediate	8
PC21	Laboratory chemicals	5
PC27	Plant protection products	1
PC29	Pharmaceuticals	6
PC32	Polymer preparations and compounds	6
PC33	Semi-conductors	2
PC34	Textile dyes and impregnating products	1
PC35	Washing and cleaning products	4
PC39	Cosmetics and personal care products	2
Not specified		19

The sector end of use (SU) categorisation describes in which sector of the economy the substance is used. There may be multiple for each compound, and these have been summarised in Table 2-5.

Table 2- 5 ECHA database summary of the sector of use of imported PFAS compounds ("SU" refers to "Sector Use") (ECHA, 2025)

Sector end of use number	Description	Total compounds included in category
SU0	Other – Transportation	1
SU0	Other – Electronics industry	1
SU0	Other - Production of active pharmaceutical ingredients	2
SU0	Other - Pharmaceutical manufacturing	1
SU0	Other - Industrial, professional and private use of room air conditioning (RAC)/ mobile air conditioning (MAC)	1
SU3	Industrial uses	2
SU5	Manufacture of textiles, leather, fur	1
SU8	Manufacture of bulk large scale chemicals (including petroleum products)	6
SU9	Manufacture of fine chemicals	27
SU11	Manufacture of rubber products	3
SU12	Manufacture of plastics products, including compounding and conversion	3
SU16	Manufacture of computer, electronic and optical products, electrical equipment	3
SU17	General manufacturing	8
SU19	Building and construction work	1
SU20	Health services	1
SU22	Professional uses, public domain	2
SU23	Electricity, steam, gas water supply and sewage treatment	1
SU24	Scientific research and development	3
Not specified		6

The environmental release category (ERC) describes the release factors of a chemical substance in a specific use exposure scenario. There may be multiple for each compound and has been summarised in Table 2-6.

Table 2- 6 ECHA database summary of the environmental release category of imported PFAS compounds ("ERC" refers to "Environmental Release Category") (ECHA, 2025)

Environmental Release Category number	Description	Total compounds included in category
ERC1	Manufacture of the substance	10
ERC2	Formulation into mixture	14
ERC3	Formulation into solid matrix	3
ERC4	Use of a non-reactive processing aid at industrial site	4
ERC5	Use at an industrial site leading to inclusion into/onto article	3
ERC6a	Use of monomer in polymerisation process at industrial site	20
ERC6b	Use of reactive processing aid at industrial sites	1
ERC6c	Use of monomer in polymerisation processes at industrial site	1
ERC6d	Use of reactive process regulators in polymerisation process at industrial site	2
ERC7	Use of functional fluid at industrial site	9
ERC8a	Wide dispersive indoor use of processing aids in open systems	3
ERC8b	Wide dispersive indoor use of reactive substances in open systems	3
ERC8c	Wide dispersive outdoor use of processing aids in open systems	1
ERC8d	Wide dispersive outdoor use of reactive substances in open systems	1
ERC9a	Widespread use of functional fluid - indoor	4
ERC9b	Widespread use of functional fluid - outdoor	2
ERC10a	Widespread use of articles	2
ERC11a	Widespread use of articles	1
Not specified		13
No release of gas from closed equipment		1

2.3 Data Collection

An output of the INVEST p-FASST project is to conduct a desk-based study building on the literature review, recent work and other sources to understand where large volumes of PFAS may exist within the country. Building on the known PFAS sources in Ireland identified in Section 2, Section 3 identifies additional potential sources based on their reported operations in publicly available databases.

2.3.1 European Pollution Release Transfer Register (E-PRTR)

Industries in Ireland that may produce, use or emit PFAS compounds were determined using the E-PRTR[105]. The publicly accessible and searchable database is maintained by the Environmental Protection Agency (EPA) and identifies over 400 facilities that engage in environmentally hazardous activities, as defined in the E-PRTR Regulation, (EC) No 166/2006[106]. The PRTR categories are as follows:

- Animal and vegetable products from the food and beverage sector
- Chemical industry
- Energy sector
- Intensive livestock production and aquaculture
- Mineral industry
- Paper and wood production and processing
- Production and processing of metals
- Waste and wastewater management
- Other activities

Each facility is classified under one of 65 E-PRTR economic activities. They are required to report on the quantities of identified pollutants that they released to air, water and wastewater, as well as the quantities of waste transferred off their facilities.

PFAS are currently not included in the identified list of contaminants, however it is anticipated that some compounds will be included in the future, as identified in the 2022 Industrial Emissions Directive (IED) and E-PRTR Implementation Appraisal conducted by the European Parliamentary Research Service[107]. Following the review of international literature, certain economic activities were flagged as having the

potential to produce, use or emit PFAS compounds into the environment. Some of these economic activities include the production of pharmaceutical products (PRTR Activity 4e), industrial plants for the preservation of wood and wood products with chemicals (PRTR Activity 6c) and surface treatment of products using organic solvents for waterproofing and other applications (PRTR Activity 9c). A full list of economic activities that were flagged as potential sources are included in Table 2-7. The PRTR facilities were downloaded from the EPA Geoportal[108] and visually displayed on Figure 2 - 4. It is to be noted that this list may not be comprehensive but is an indication of potential major PFAS sources.

Where the main activities of a licensed site was not obvious from the E-PRTR classification, the EPA's Licence and Enforcement Access Portal (LEAP)[109] was used to further investigate whether the site was a potential source of PFAS.

Table 2- 7 E-PRTR economic activity categories that may involve the production, use or storage of PFAS compounds (EPA, 2025)

E-PRTR Main Sector	E-PRTR Activity Category	E-PRTR Activity	Number of facilities registered in Ireland
Energy sector	1a	Mineral oil and gas refineries	2
	1c	Thermal power stations and other combustion installations	17
Production and processing of metals	2c(iii)	Installations for the processing of ferrous metals: application of protective fused metal coats	5
	2e(ii)	Installations for the smelting, including the alloying, of non-ferrous metals, including recovered products	3
	2f	Installations for the surface treatment of metals and plastic materials using an electrolytic or chemical process	12
Mineral industry	3a	Underground mining and related operations	3
	3b	Open cast mining and quarrying	14
	3c(i)	Cement clinker in rotary kilns	4
	3c(iii)	Production of cement clinker or lime in other furnaces	1
Chemical industry	4a - Chemical installations for the production on an industrial scale of basic organic chemicals such as:	i) Simple hydrocarbons	4
		ii) oxygen-containing hydrocarbons	2
		iv) Nitrogenous hydrocarbons	2
		vii) Organometallic compounds	2
		viii) Basic plastic materials (polymers and synthetic fibres)	6
		x) Production of dyes and pigments	1
		xi) Surface -active agents and surfactants	1
	4b – Chemical installations for the production on an industrial scale of basic inorganic chemicals such as:	i) Gases	2
		ii) Acids	1
		iv) Salts	1
		v) Non-metals	2
	4d	Chemical installations for the production on an industrial scale of basic plant health products and of biocides	1

E-PRTR Main Sector	E-PRTR Activity Category	E-PRTR Activity	Number of facilities registered in Ireland
	4e	Installations using a chemical or biological process for the production on an industrial scale of basic pharmaceutical products	41
Waste and wastewater management	5	a) Recovery or disposal of hazardous waste b) Incineration of non-hazardous waste c) Disposal of non-hazardous waste d) Landfills f) Urban waste-water treatment plants g) Independent industrial waste-water treatment plants	143
Paper and wood production and processing	6b	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	3
	6c	Industrial plants for the preservation of wood and wood products with chemicals	3
Other activities	9c	Installations for the surface treatment of substances, objects or products using organic solvents, in particular for dressing, printing, coating, degreasing, waterproofing, sizing, painting, cleaning or impregnating	21

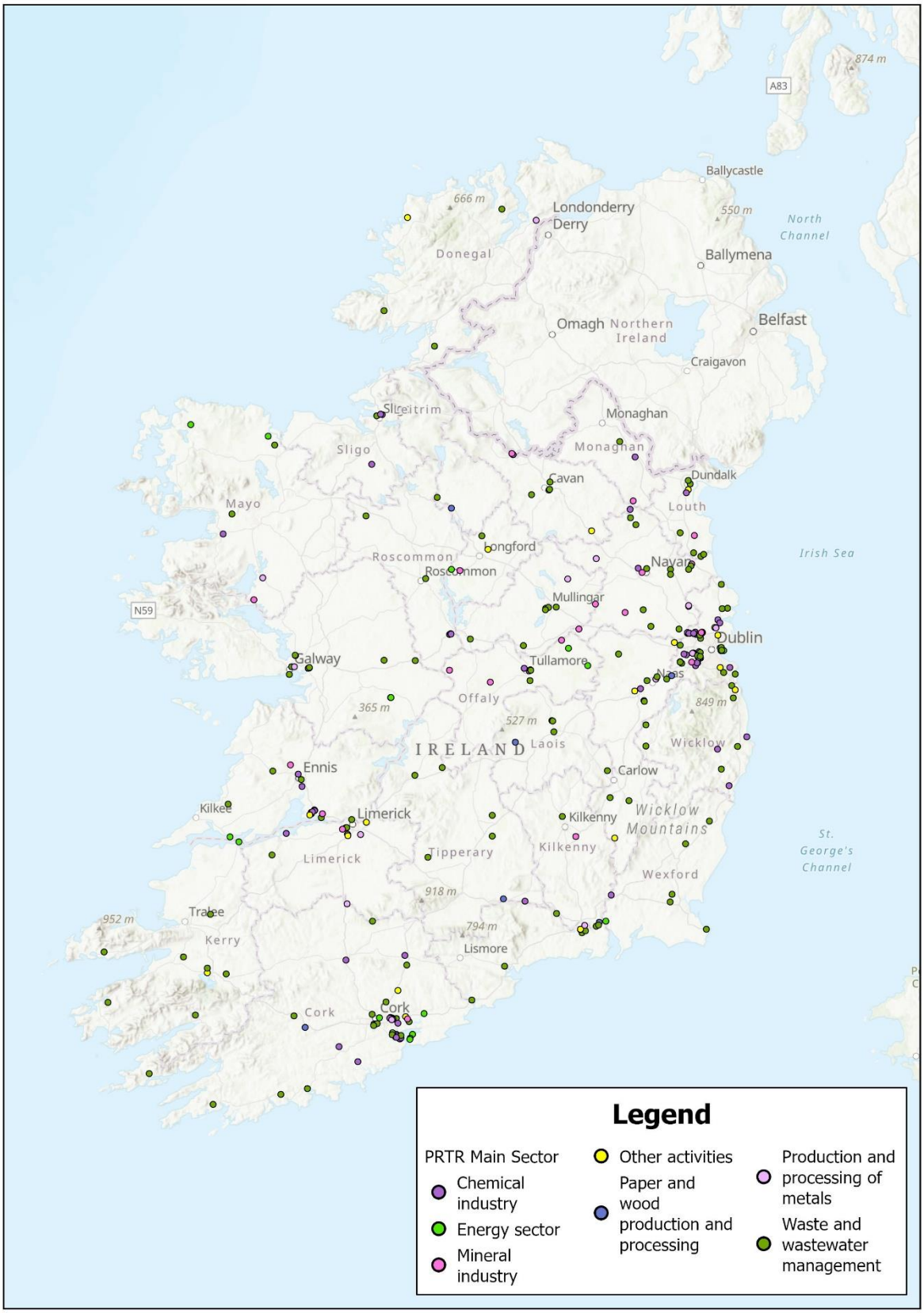


Figure 2 - 4 Potential PFAS Sources - PRTR Main Sector (EPA, 2025)

2.3.2 EPA Databases and ArcGIS Online Maps

EPA Databases and ArcGIS Online Maps were used to locate other secondary sources of PFAS where several primary sources can bioaccumulate or transform[16,89,97] before being emitted into the environment, such as waste management facilities, historical landfill boundaries, other industrial emissions licensed facilities, airports and firefighting stations.

Street runoff is considered a point source of PFAS when it is channelled into stormwater drains following rainfall and discharged into surface water bodies[46]. Combined sewers are where storm and wastewater are collected in one pipe and are operational in storm conditions when the downstream system is overloaded[110]. Stormwater discharge locations, such as stormwater drains and combined drains were obtained from the EPA Geoportal. It is also important to consider street runoff as a diffuse source where it is not collected in drains and should be considered in risk assessments and source attribution.

A summary of the potential sources is shown in Table 2- 8 and the locations are visually displayed on Figure 2 - 5. As there are many stormwater discharge locations, they are visually displayed in Figure 2 - 6 on the Tolka and Dodder sub-catchments as an example.

Table 2- 8 Sources from EPA Databases and ArcGIS Online that that may involve the production, use or storage of PFAS compounds

Potential source	Number of facilities registered in Ireland	Reference
Fire-fighting stations	209	ArcGIS Online[111]
Wastewater treatment plants	751	EPA Geoportal[108]
Historic landfills	68	EPA Maps[112]
Current and historical airports	23	ArcGIS Online
Current and historical military bases (post 1940s)	25	Irish Defence Forces[113]
Stormwater discharge locations	-	EPA Geoportal

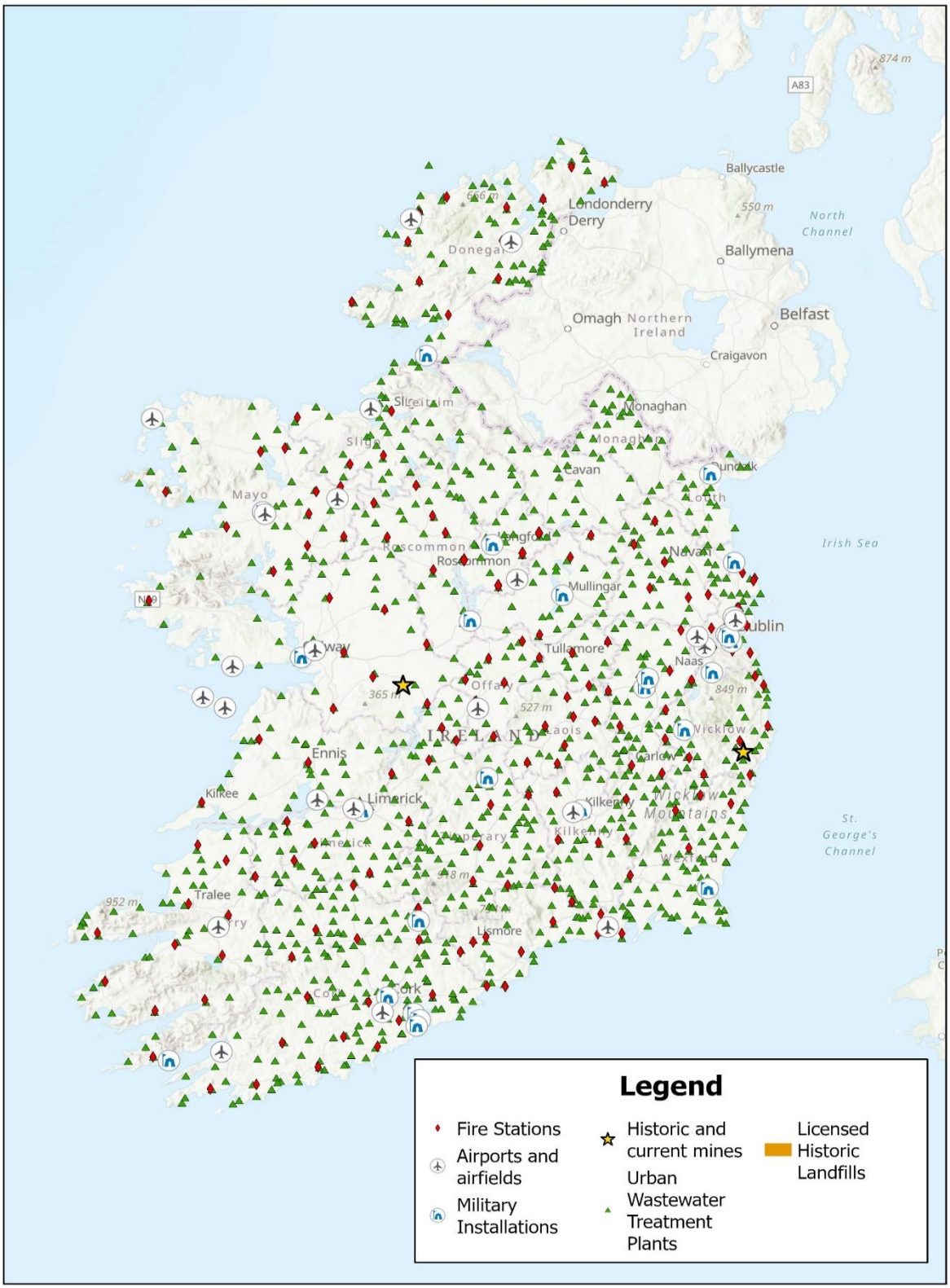


Figure 2 - 5 Potential PFAS Sources - EPA Maps (2025) and ArcGIS Online (2025)



Figure 2 - 6 Discharge Locations in the Tolka and Dodder Sub-catchments (EPA, 2025)

2.3.3 Control of Major Accident Hazards involving Dangerous Substances (COMAH) Regulations (2015)

The purpose of the COMAH Regulations is to prevent major accidents involving dangerous substances. Sites that are required to take tiered measures under these Regulations have a certain level of dangerous substances present[114]. Upper Tier sites are facilities that store, handle, or process significant quantities of hazardous substances, such as oil refiners, and Lower Tier sites can have smaller quantities of hazardous substances, or conduct logistics and distribution operations, such as smaller oil terminals or power stations. Other sites can include chemical manufacturing and storage, oil and gas production and storage, petrochemical plants, explosives manufacturing and large-scale storage of hazardous or dangerous substances.

COMAH sites are likely to either historically or currently store AFFF in fire suppression systems. There is potential for PFAS to be released to ground or water

via accidental loss, training, demonstration of emergency systems and in incident response[115]. PFAS may also be used in some industrial processes.

Both minor and major incidents at these sites can lead to significant contamination. During an incident at the Buncefield Oil Storage Depot in the UK, over 250,000 litres of firefighting foam was used to extinguish the flames[116], which lead to widespread PFAS contamination in the surrounding watercourses and consequently in the local drinking water supply[117].

There are a total of 49 upper tiered sites[118] and 55 lower tiered sites[119] registered in Ireland and they are shown in Figure 2 - 7.

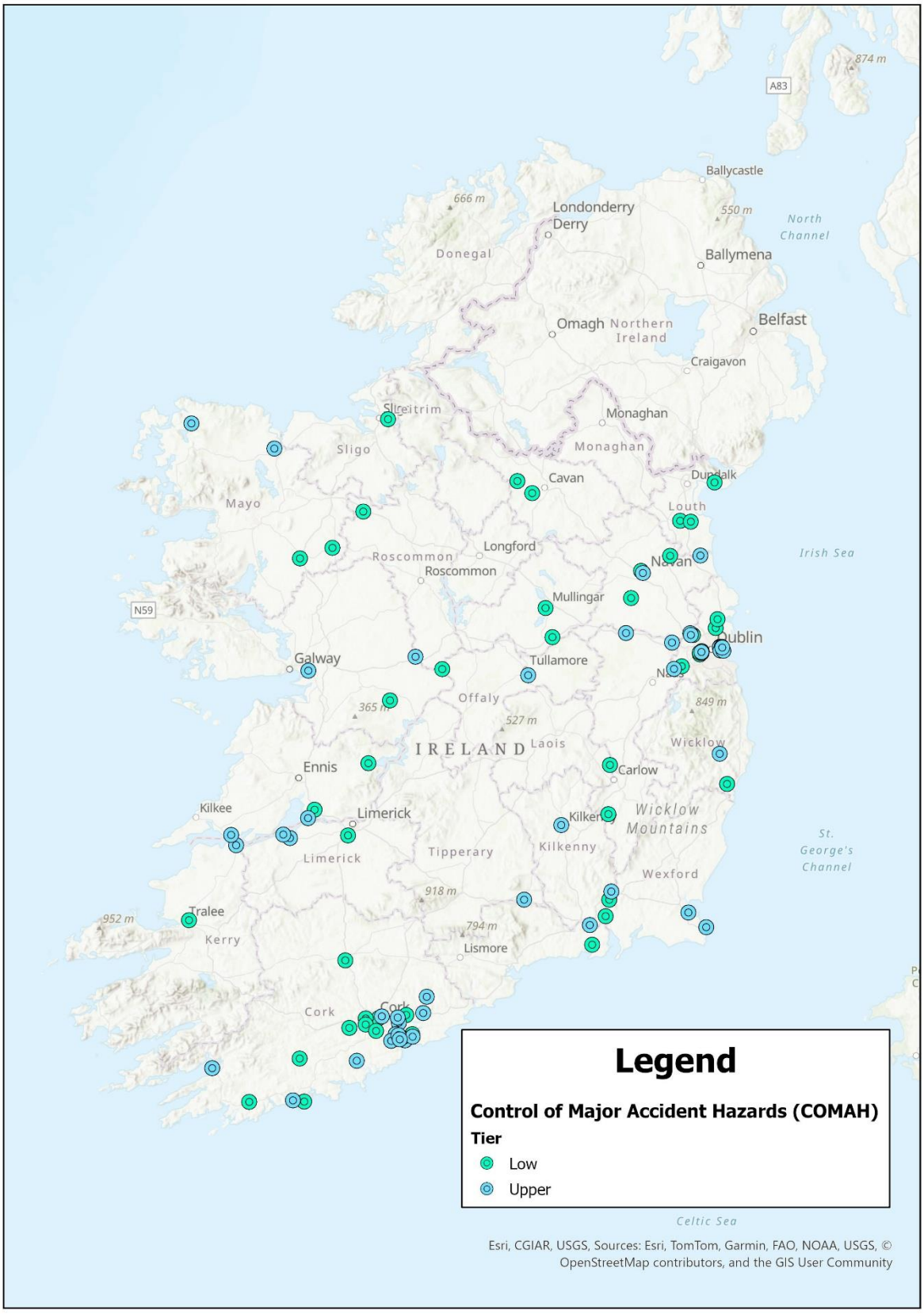


Figure 2 - 7 Control of Major Accident Hazards Tiered sites in Ireland (Health and Safety Authority, 2025)

2.3.4 Limitations

In identifying potential PFAS sources using publicly available data, there were several limitations identified.

Some sites that may process, use or store PFAS might not fit within the Scope of the PRTR Regulation[105]. For example, there is no PRTR economic activity directly associated with the manufacturing of semi-conductors, electronics and ICT equipment, however there are known facilities operating in Ireland conducting these activities[120]. The electronics and semi-conductor industries were identified in Chapter 1 as being potential sources of PFAS as it can be used in anti-reflective coatings or for wafer thinning[15]. Other potential sources, such as the additional releases including greywater reuse, residential compost use, septic systems and historical fire locations (emergency reuse) are also not readily available in public databases.

Under the Fire Services Act[121], it is a requirement for all buildings to have fire extinguishers installed. Not all buildings will have a requirement for Class B fire extinguishers (usually PFAS-containing), hence it is unrealistic to identify all locations that would potentially store them. Additionally, unless the site had tested the extinguishers or used them on a historical fire, extinguishers are considered to be of low risk to enter the environment as there are limited pathways[122]. In 2020, the EPA commissioned Sweco to conduct a study on determining the current and historical levels of PFAS in AFFFs used in the Republic of Ireland. It was found that facilities with tank farms and/or significant quantities of stored solvents, fuels and other chemicals have the largest quantities of AFFFs. Other facilities include power generation plants, chemical facilities, fuel storage facilities and aviation hangars. A total of 1,112,797L of PFAS containing AFFFs was reported from the respondent sites and the median value of foams held at the above-mentioned facilities is 1000L. Due to the lack of responses from the surveyed respondents, it only provides a snapshot of the current situation regarding the use of PFAS AFFFs in Ireland.

Historic use of PFAS that has led to legacy contamination on industrial and civil sites and historical fires is also important to consider when conducting a risk assessment and source attribution[23]. A recent investigation in the Blue Mountains, Australia

found that three potential sources of PFAS contamination - two separate motor vehicle accidents in the catchment and the Rural Fire Brigade Station[123] - had contributed to elevated concentrations in the Medlow and Greaves Creek Dams which are used for drinking water supply. The first two sources were not initially picked up in investigations due to assumptions regarding known sources in the catchment. Due to the lack of publicly available data regarding historical fires, it hasn't been included in this investigation.

Pesticides and herbicides are considered to be diffuse sources of PFAS[84] and are widely used in agriculture.[85] Although assumptions can be made using the Corine Land Use Map[124], on where pesticides are used, anecdotal evidence would need to be collected and chemical safety data sheets would need to be reviewed to confirm whether the environment or human health is at risk from pesticide use.

Land-spreading of biosolids and composts are also considered to be a diffuse source of PFAS[125]. Approximately 98% of biosolids produced in Ireland are reused on agricultural land as a fertiliser[126]. With multiple applications, PFAS can build up in the soil and may enter the food chain[127]. Similar to pesticides, assumptions can be made on where biosolids may be spread, using the Corine Land Use Map[124] or where they are restricted from being spread[128], however anecdotal information would be required to confirm.

Atmospheric or aerial deposition is an indirect source of PFAS that has led to environmentally relevant groundwater impacts and should be considered in environmental assessments[129,130]. In an environmental fate and transport model of PFOA emissions which were released from the stacks of the Washington Works Plant, it was determined that PFOA would then be deposited and infiltrated with rainfall recharge and eventually reaching the groundwater table[130]. Due to the high-level nature of this project, atmospheric deposition was not included as a source but should be considered when conducting smaller-scale investigations.

The above-mentioned potential sources have not been included in the PFAS sources maps, but will be considered throughout the project, including in the risk assessment, results analysis and source attribution. If conducting a sub-catchment

or catchment wide investigation, it is important to conduct a PFAS audit on individual premises to understand both the point and diffuse source contributions to the environmental load.

2.4 Spatial Distribution and Analysis of PFAS Sources

2.4.1 Data collection and processing

During the desk-based study, each potential PFAS source was geospatially referenced and compiled into a Microsoft Excel database to ensure that it was suitable to be used by ArcGIS Pro. The database was converted to a comma separated value (csv) file and subsequently imported into ArcGIS Pro.

2.4.2 Geographical trends

To better understand the distribution of potential sources across Ireland, they were divided into use categories and plotted on a stacked column graph, as shown in Figure 2 - 8. The total number of potential PFAS sources was processed on ArcGIS Pro using publicly accessible shape files from GeoHive[131], as shown in Figure 2 - 9. Cork is an outlier with the highest number of potential PFAS major point sources (206). Approximately 48% of these sources are urban wastewater treatment plants and 8% are chemical or pharmaceuticals facilities, a large proportion of these are in the Ringaskiddy area. Cork is followed by Dublin and Tipperary with 113 and 85 potential major point sources, respectively. Leitrim and Longford have the least number of sources, but this could be attributed to the size of the counties.

The total number of potential PFAS sources were then standardised using the areas of the counties[132]. The results showed that Dublin was an outlier with the highest density of potential PFAS point sources (123 sources/1000km^2). This was followed by Louth and Waterford (39 and 34 sources/1000km^2, respectively). Galway, Mayo and Kerry had the lowest densities (9, 10 and 11 sources/1000km^2, respectively). The densities are shown on Figure 2 - 10.

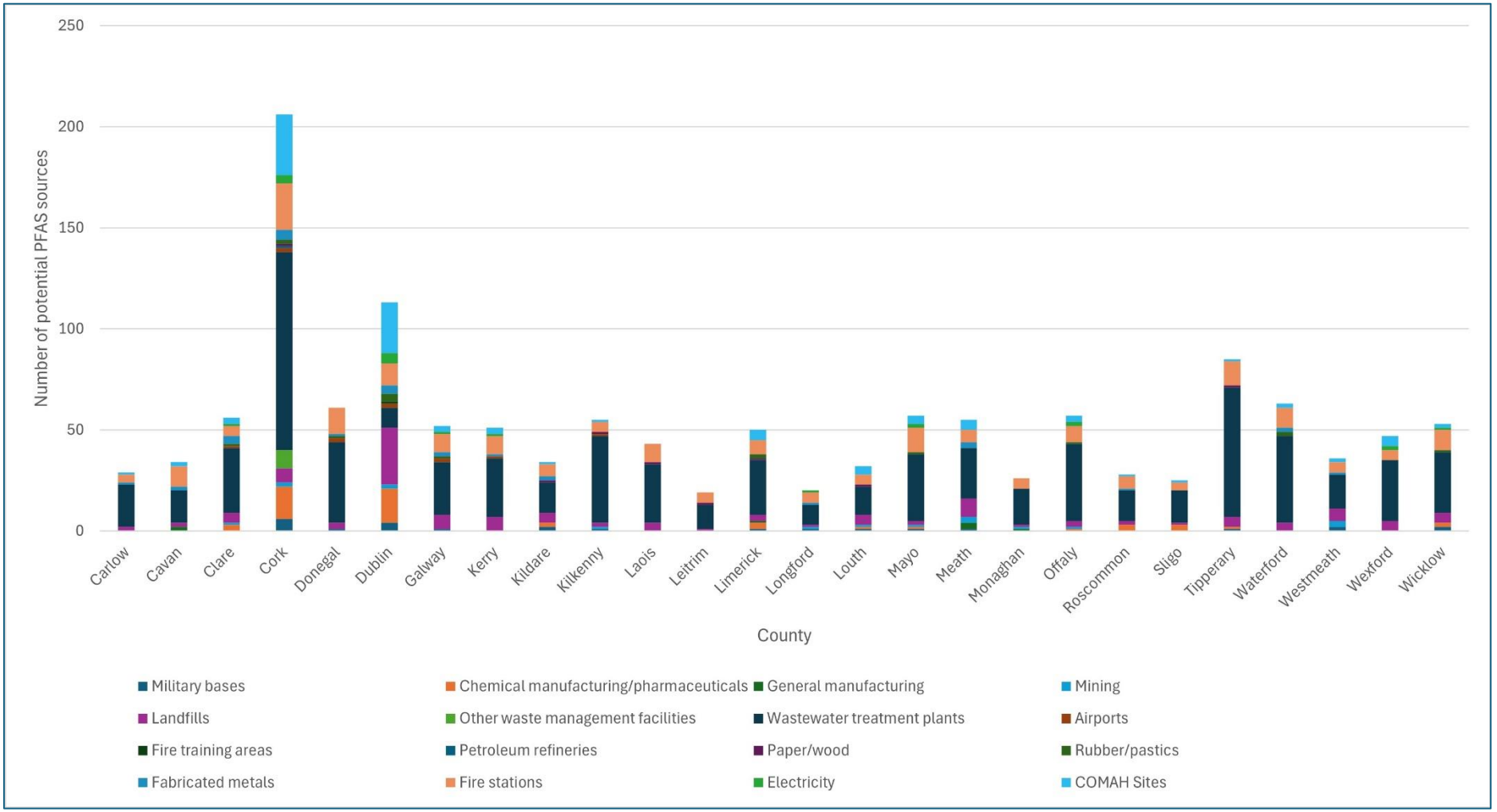


Figure 2 - 8 Potential PFAS point sources as distributed in each county from publicly available data (EPA Maps [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

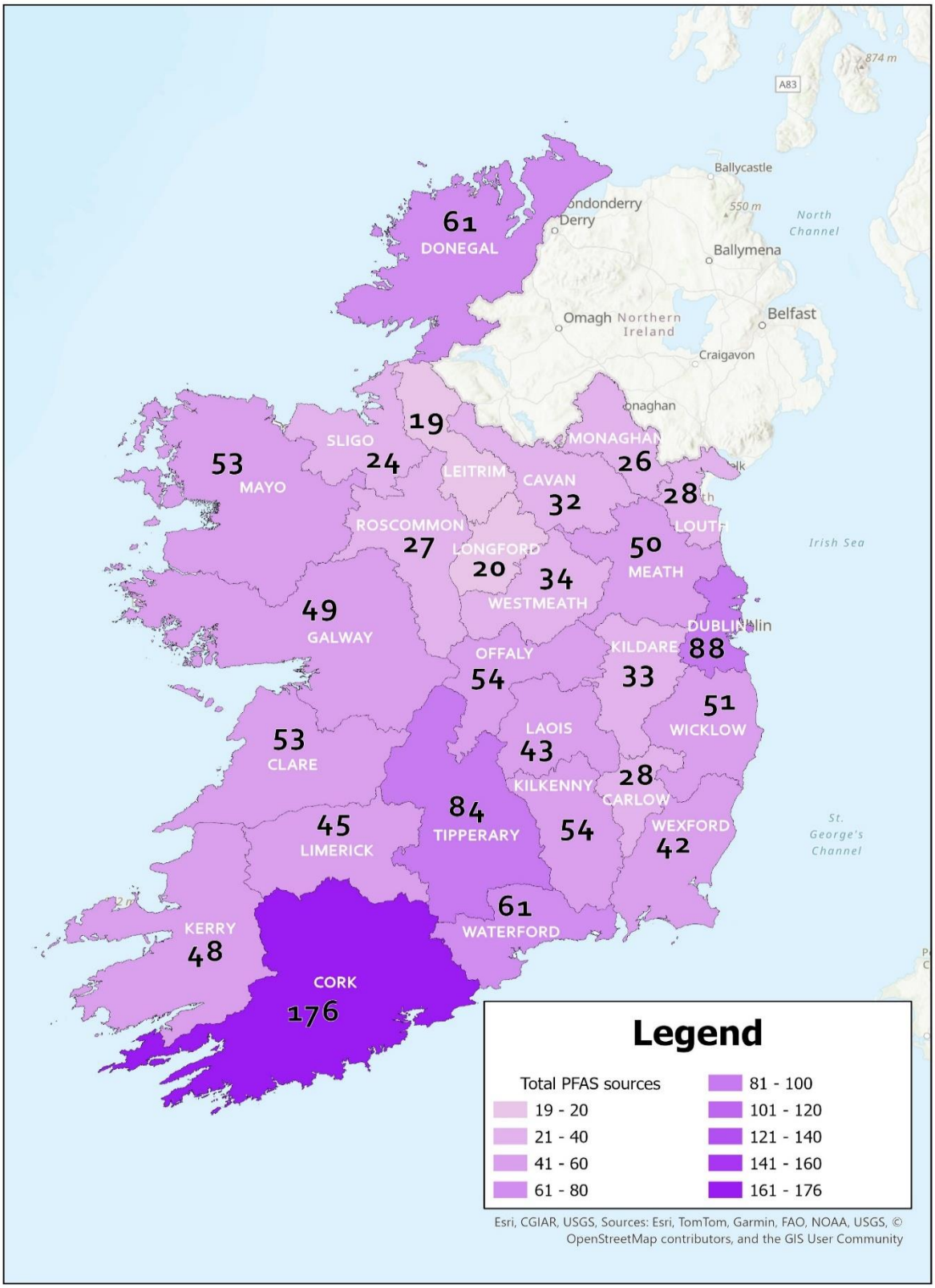


Figure 2 - 9 Total number of PFAS point sources per county (EPA Maps [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

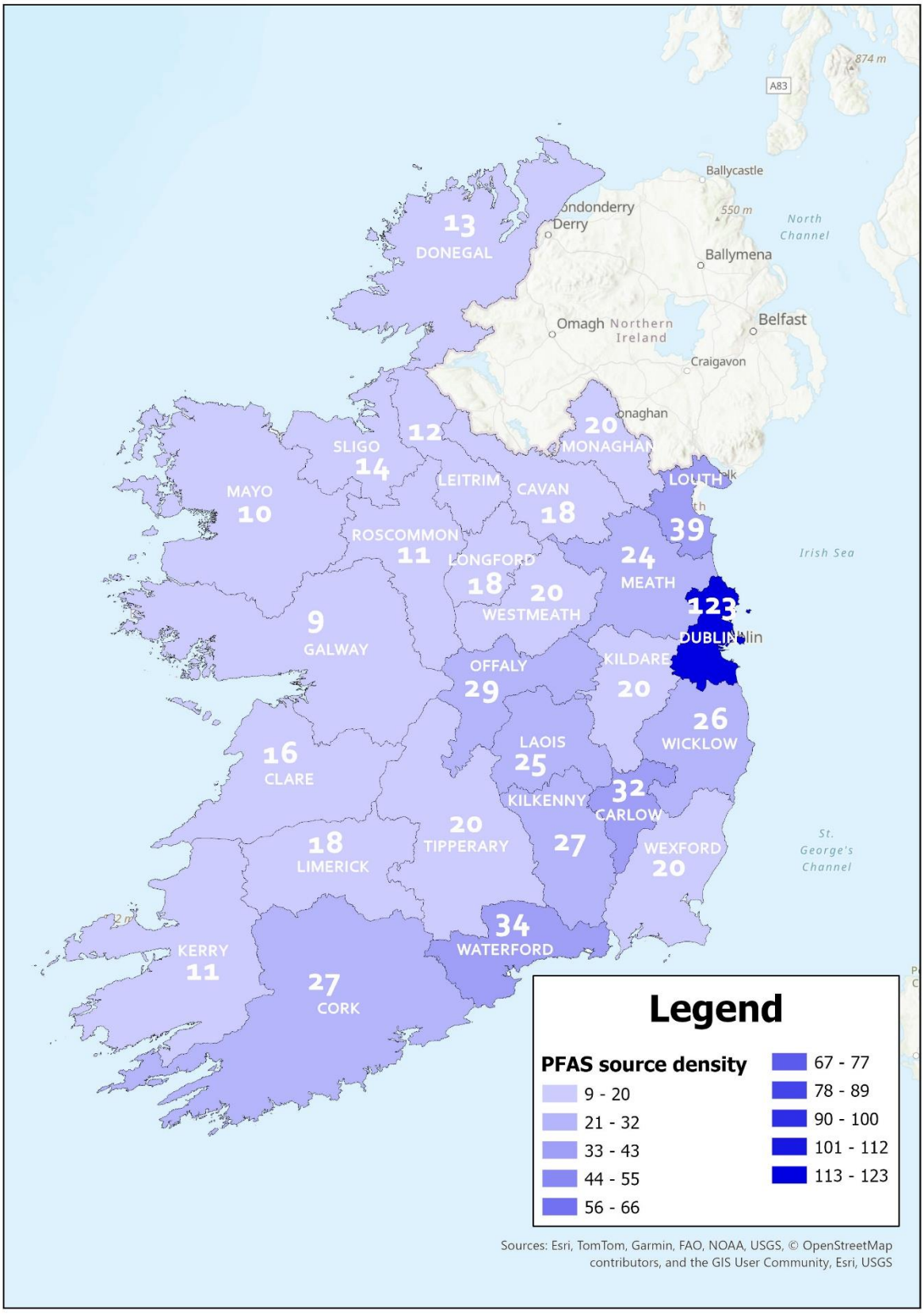


Figure 2 - 10 Density of potential PFAS point sources (Number of sources/1000km^2) (EPA Maps [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

2.4 Conclusions

Based on Ireland's industrial profile, land use and infrastructure, there are a large variety of potential PFAS sources. A desk-based study was conducted of existing case studies pf PFAS sources in Ireland. These include waste management facilities, including lined and unlined landfills, fire-training facilities, fire stations, airports, petroleum refineries and sites with PFOA stockpiles >50kg. In the 2020 EPA survey conducted by Sweco, it was determined that the largest volumes of PFAS containing AFFFs were in facilities with tank farms and/or significant quantities of solvents, fuels or other chemicals[122].

As PFAS is not manufactured in Ireland, most compounds are imported for use in a variety of industries. To determine where and how these compounds are being used, a review of the ECHA REACH database was conducted. It was found that 57 known PFAS compounds are currently being imported into Ireland. The minimum quantity of PFAS compounds entering Ireland yearly is 161,146 tonnes and the maximum is 1,610,170 tonnes.

Most importers are registered in Dublin and Cork, but they may be transported to be used elsewhere in the country. A total of 15 of these compounds were classified as either P, B, or T or a combination of the three criteria and 2 were classified as vPvM. The most frequently identified product use categories were heat transfer liquids (PC16) and intermediate compounds (PC19). The most prevalent sector end of use categories was the manufacture of fine chemicals (SU9) and bulk large-scale chemicals (SU8). The most common environmental release categories were "use of monomer in polymerisation process at industrial site" (ERC6a) and "formulation into mixture" (ERC2). This could indicate that most imported PFAS is used in closed manufacturing processes, particularly for chemicals manufacturing.

To create a geospatially referenced database of potentially major PFAS point sources in Ireland, potential primary and secondary sources were identified using publicly available databases. These included the E-PRTR database, EPA Maps, COMAH Regulations and ArcGIS Online. The largest category of potential point sources was urban wastewater treatment plants followed by fire-fighting stations

and solid waste management facilities. Discharge locations from stormwater drains and sewage overflows also have a high frequency across the country. Spatial analysis showed that Cork had the most potential point sources when compared to other counties and Dublin had the highest density of potential point sources. Some point sources may not have been identified in the used methodology, including those that may not fit within the Scope of the PRTR Regulation and legacy contamination sites, such as historical fires. Other data gaps were identified including the use of PFAS-containing pesticides and land-spreading of biosolids in the Irish context,

Potential pathways to the environment were determined for each potential point source and then they were classified in relation to their potential risk to the environment. The risk scores will be used to inform PFAS risk maps in Chapter 3.

Chapter 3 - Risk Assessment Methodologies

3.1 Introduction

In Chapter 2, known and potential PFAS sources in Ireland were identified, including where large volumes of PFAS exist. Some sources of PFAS are higher risks than others due to the form of product that they're in, the types of PFAS present or the concentrations that they're in. In this Chapter a relative level of risk is allocated to each potential PFAS source is, based on international literature.

If PFAS is released into the environment, certain environmental factors, such as groundwater vulnerability and proximity to surface water bodies, impacts the fate and transportation of contamination and the potential for receptors to be impacted. This Chapter uses this information, as well as the allocated source risks, as inputs into PFAS Groundwater and Surface Water Risk Maps for the Lough Corrib Catchment in County Galway. The Lough Corrib Catchment was selected as it is the catchment with the lowest number of potential sources. The methodology can be refined in this catchment and then repeated for counties with a higher number of sources. The PFAS Risk Maps highlight areas that may be at the highest risk of PFAS contamination from the identified sources. The maps will be used to enable the prioritisation of in-depth local assessments of areas that may present a risk to water supplies and the wider environment. The methodology can then be used in other catchments across Ireland.

3.1.1 Aim

The aim of this Chapter is to develop and apply a spatially informed risk assessment methodology to determine the potential for the identified PFAS sources may impact water bodies used for drinking water supply in Ireland. The assessment integrates the source characteristics with Irish environmental factors to identify areas that may be at risk of PFAS contamination.

It is also to assess how well empirical observations align with the spatial risk assessment developed. Using the Lough Corrib Catchment, the predicted risk is

compared with observed data to identify inconsistencies and data gaps in the assessment.

3.1.2 Objectives

The objectives of this Chapter are to:

- Review the characteristics of PFAS compounds to understand the risks that they may pose to the environment and/or human health;
- Examine existing methodologies for assessing PFAS environmental risk;
- To spatially map and overlay risk-ranked PFAS sources across Ireland using geographical information system (GIS) tools to visualise their distribution;
- Incorporate Irish hydrogeological and hydrological data into the spatial analysis to identify zones of higher susceptibility to PFAS contamination;
- Develop a multi-criteria GIS based risk tool that evaluates the potential for PFAS migration from identified sources to impact vulnerable water bodies, based on source risk ranking, environmental pathways and receptors sensitivity;
- Assess the proximity of PFAS sources and potentially impacted water bodies to drinking water abstraction points, both surface and groundwater; and
- To identify and prioritise water bodies and catchments in Ireland that are most at risk from PFAS contamination, providing a scientific basis for targeted monitoring and management.
- Overlay the risk assessment outputs from the Lough Corrib Catchment in Chapter 3 and compare to observed data;
- Validate and refine the risk assessment approach; and
- Recommend targeted monitoring actions based on potentially high-risk areas with little to no data.

3.2 Environmental mobility and toxicity

Due to their persistence, bioaccumulation and long-range transportation, PFAS has been globally detected in soil, air[26], biota[133] and water[40,82,134]. Further, their widespread use, potential transformation of precursors into PFAS of regulatory concern[40] and many potential contamination pathways, has meant that it is difficult to identify a specific point source of PFAS contamination[135]. However, identifying the presence of certain PFAS compound groups and particular characteristics may assist in refining a potential source or number of sources. The type of PFAS also determines the relative environmental significance[136].

3.2.1 Degradation and transformation

PFAS manufacturing processes, such as fluoro-telomerisation (FT) and electrochemical fluorination (ECF), can create different isomers. The compounds created from these processes are called precursors, which then can degrade into intermediates and subsequently terminal products[13], as shown in Figure 3- 1.

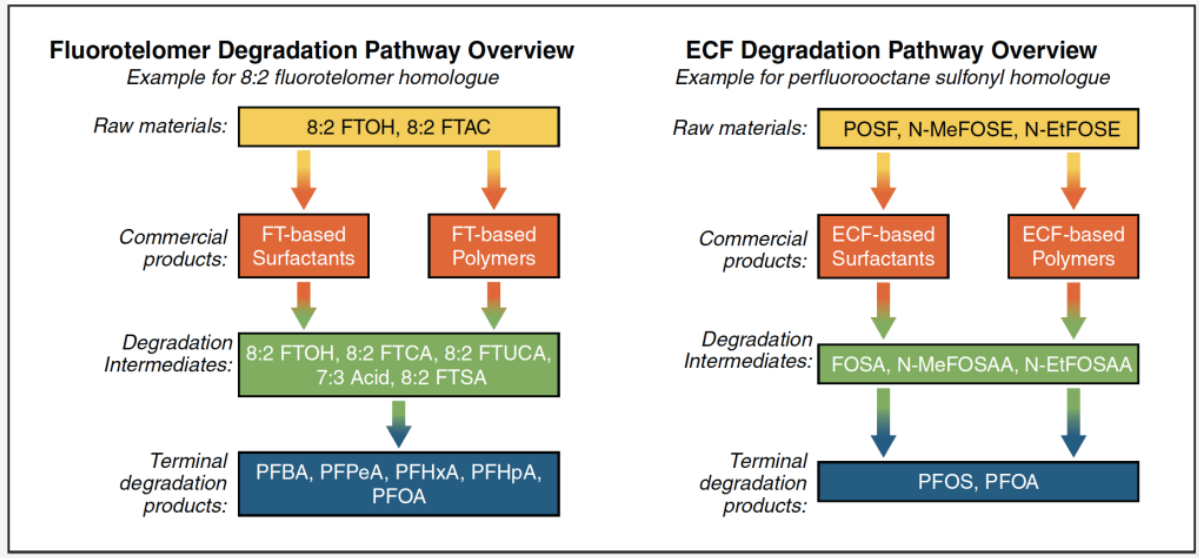


Figure 3- 1 PFAS degradation pathways (ITRC, 2020)

FT produces commonly found fluorotelomers including fluorotelomer sulfonic acid (FTSA), fluorotelomer carboxylic acid (FTCA) and FTOH. These can then degrade into terminal degradation products which are primarily linear PFCAs, such as PFBA, PFPeA, PFHpA and PFOA[13], as shown in Figure 3- 2.

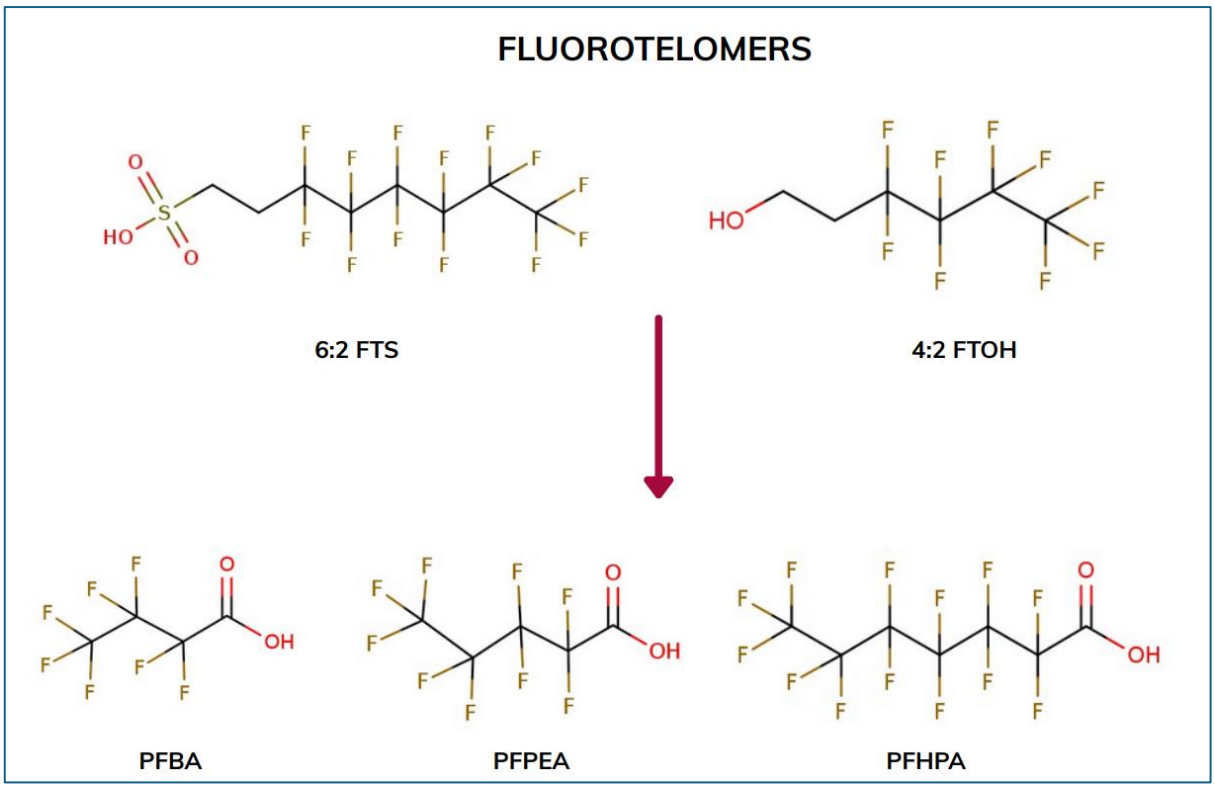


Figure 3- 2 Fluorotelomer (associated with FT) degradation into terminal products (ITRC, 2020 and ECHA CHEM, 2025)

ECF produces perfluoroalkane sulfonamide ethanol (FASE), FASA and N-MeFOSAA, which can degrade into a mixture of branched and linear PFCAs and PFSAs, including terminal degradation products PFOS and PFOA, as shown in Figure 3- 3[13].

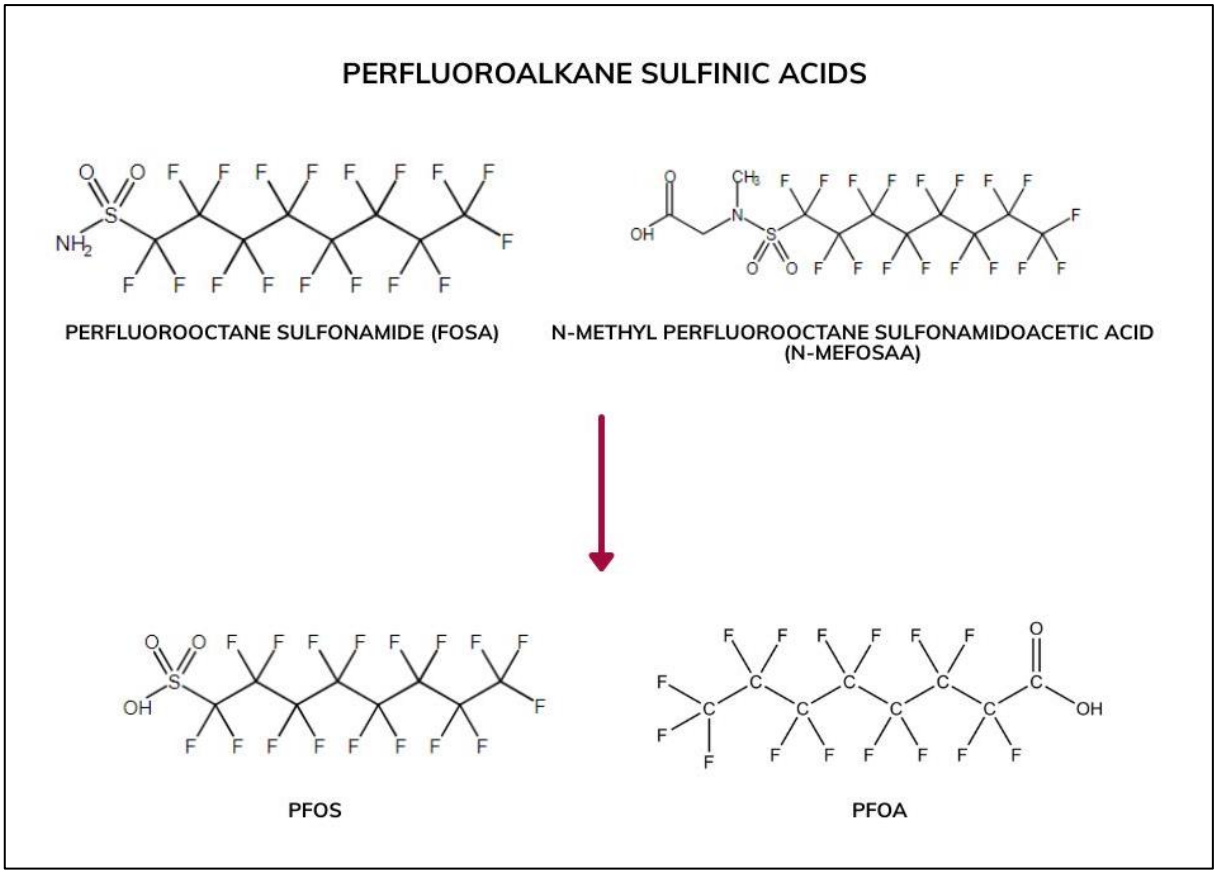


Figure 3- 3 Perfluoroalkane sulfunic acids (associated with ECF) degradation into terminal products (ITRC, 2020 and ECHA CHEM, 2025)

3.2.2 Solubility and mobility

The structural properties of individual PFAS influence their transport in the environment. For example, PFAS compounds with shorter alkyl chain lengths, C4-C6, are reported to be more soluble in water than those with longer lengths[13]. The longer chain PFAS, generally those with six or more carbons, more readily sorb to soils and sediment, have a lower polarity and have a higher Log Kow (often >4)[137]. Once sorbed onto sediment, PFAS can associate with dissolved organic carbon and be remobilised along with the sediment during heavy rainfall, flooding or organic rich runoff. While shorter chain PFAS are mobile in the aquatic environment, due to their high solubility in water[138,139], higher polarity and lower Log Kow (often <2)[137]. Solubility is also linked to the functional group of the compound. For example, perfluoroalkyl carboxylic acids (PFCAs) have a higher solubility than perfluoroalkane sulfonic acids (PFSAs)[139,140] because the carboxylic acid group is more polar and forms stronger bonds with water. This makes PFSAs more likely to adsorb to surfaces.

Fluoropolymers, such as PTFE may pose little environmental risk once it's in a product as it's insoluble. However when manufacturing the product, there may be potentially significant environmental releases of other more mobile compounds[136].

Some PFAS, such as fluorotelomer alcohols (FTOHs), are volatile and display low solubility, and when in dissolved from, they tend to adsorb to solid material[139].

3.2.3 Bioavailability and biomagnification

Once soluble PFAS are in the aqueous phase, they are highly bioavailable to organisms and plants[24]. Studies have found concentrations of PFAS in a plethora of animals and biota including bottle-nosed dolphins, seals, squid, alligators and polar bears[133].

Due to their inability to break down, PFAS can also biomagnify in the food chain. It has been found that in animals with lungs that PFOS is more concentrated in the predator than in the prey[24]. In a review of published literature on trophic magnification of different PFAS by Miranda et al. (2022), it was found that PFOS consistently biomagnified in multiple food webs whereas other long-chain carboxylates varied in biomagnification[141].

3.2.4 Toxicity and Health Impacts

Due to the reported toxicity of PFAS compounds, most studies have been focused on risk to human life and function, while risk to non-human biota is not as well researched[133]. Ecological receptors are more sensitive to human receptors in terms of risk characterisation as they reside entirely within an impacted environment and their diet will comprise of PFAS impacted media obtained within their habitat, whereas humans have a diversity in their diet rather than from one source. Their body weight is also often lower than humans and thus will have a higher estimated body burden[142].

The nature of impacts is specific to the species and nature of contamination, but impacts have been studied in both laboratory and field assessments. Embryo and larval studies have observed developmental reproductive effects and reduced

fecundity in fish, reduced cell density, respiration and growth rate in phytoplankton and increased time to metamorphosis in frogs[133].

In addition to environmental impacts, recent studies have shown that exposure to some PFAS more than the tolerable weekly intake (TWI) guidelines have been linked to adverse health outcomes in humans, including increased cholesterol levels, reduced immune response and reproductive effects[143,144]. In a review conducted by Dehghani et al, it is suggested that the main pathways to humans are through the ingestion of PFAS contaminated food and drinking water[145]. An Irish study by Abdallah et al. confirmed the presence of PFAS compounds in breastmilk[146] and quantifiable presence of PFAS in food from other western European countries[143], which suggests that the Irish population is exposed to PFAS via diet.

Current research has suggested that prolonged exposure in excessive concentrations to certain PFAS compounds, such as PFOA, PFHxS and PFOS could lead to adverse health effects in both humans and ecological receptors, such as neurotoxicity, endocrine disruption and carcinogenicity[147]. The toxicity of PFOA and PFOS have been evaluated in many humans and laboratory animals, but there is less available data for other compounds. In available epidemiological studies, there are suggestions that their associations between perfluoroalkyl exposure and several health outcomes including pregnancy induced pre-eclampsia (PFOA, PFOS), increases in total cholesterol (PFOA, PFOS, PFNA and PFDA), decreased antibody response to vaccines (PFOA, PFOS, PFHxS, PFDA) and small decreases in birth weight (PFOA, PFOS). Increases in testicular and kidney cancers have also been observed in highly exposed humans[148].

3.3 Risk Assessment Conceptual Framework

When characterising potential risks of PFAS compounds to the environment it is important to consider both the properties of the PFAS used and where and how they may be released into the environment. Risk depends on a number of factors including the source of PFAS, the compounds present, leachability of the PFAS and concentration, potential for bioaccumulation, degree of exposure, types of receptors exposed, land use, environmental values, level of environmental protection and the environmental media[24]. For example, PTFE is a stable, insoluble fluoropolymer which may not be released into the environment once it's part of a product, such as a non-stick frying pan, unless the chemical bonds are put under stress at high temperatures or a scratched surface that may be washed down the drain[13]. While other PFAS compounds that are used in manufacturing processes and are soluble (such as PFAAs and GenX) can be released into the environment via effluent[24]. The first step to conducting a risk assessment is to determine whether a source has a valid pathway to enter the environment.

In line with Irish EPA best practice[149], to assess the risk of known or suspected contamination, a staged approach should be taken to address key elements in succession. A critical part of the assessment is developing a Conceptual Site Model (CSM). It is established in "Stage 1: Site Characterisation and Assessment" and reviewed as additional information and data is acquired throughout the assessment process. The CSM identified the potential sources of contamination at a site, the migration pathways and the receptors the contamination could impact upon. If a valid source, pathway and receptor (SPR) linkage exists, then the pollutant linkage will need to be characterised and assessed.

This approach has been taken to develop the conceptual framework for the nation-wide multi-criteria GIS risk-based tool and is shown in Figure 3- 4. The purpose of this tool is to help identify potential high-risk PFAS source areas and enable the prioritisation of local assessments. To achieve this, some generalisations and assumptions are made throughout the development process, and these will be detailed throughout.

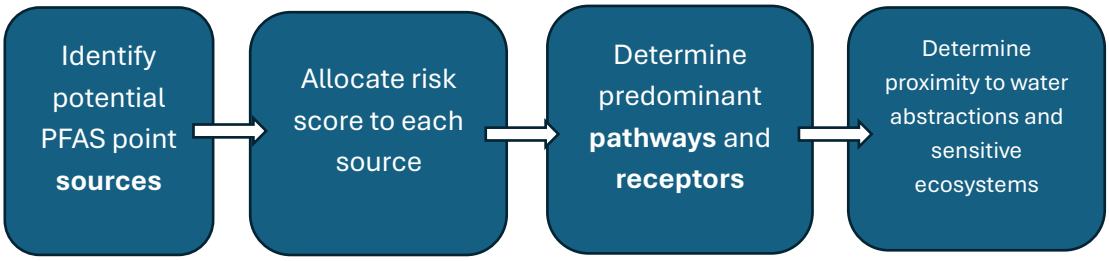


Figure 3- 4 Conceptual framework for risk-based tool

3.3.1 Sources

Chapter 2 identified where large volumes of PFAS exist in Ireland, known and potential sources of PFAS. In order to understand the level of risk associated with each potential source, a methodology established by Guelfo et al (2018)[129] was followed to allocate arbitrary risk score to Irish sources. Each risk score is relative to each other and is based on a literature review of published literature and regulatory data on potential PFAS source types, associated characteristics and the concentrations and types of PFAS found in the surrounding environment of potential release sites. Each source type was assigned a risk score of 25, 50, 75 or 100, with the maximum being sites with the highest groundwater PFAS concentrations and number of different PFAS compounds. The risk scores of 25, 50, 75 and 100 were selected to standardise comparisons across different source types and allow for multiplication with other risk factors in the GIS model. The approach allows for a semi-quantitative assessment that supports prioritisation of sites for further investigation or remediation, especially when comprehensive data is not available. The suggested risk scores for each potential PFAS source in Ireland is presented in Table 3- 1.

Table 3- 1 Risk scores used in calculating risk index (Guelfo et al, 2018)

PFAS source	Upper magnitude (µg/L)	No. PFASs	Risk Score	Source type
Military facilities[150–152]	10,000	28	100	AFFF use
Chemical manufacturing[153–155]	1,000	13	100	Intermediate use
Landfills[156,157]	1,000	11	100	Waste streams (landfills)
Airports[134,158]	100	28	75	AFFF use
Fire training areas[159]	100	28	75	AFFF use
Petroleum refineries and COMAH sites[159]	10	28	75	AFFF use
Paper[160,161]	10	13	50	FP coatings
Rubber/plastics	10	13	50	FP coatings
Fire stations	N/A	28	25	N/A
Fabricated metal	N/A	11	25	N/A

Ojha et al (2022)[162] used the same risk scores for surface water bodies. Urban WWTPs replaced "Landfills" the risk rankings for surface water bodies, being given a risk score of 100.

3.3.2 Pathways

To determine the predominant pathways for PFAS compounds to enter the environment, two visual conceptual site models were developed. Figure 3- 5 shows the potential PFAS sources and pathways associated with industrial sites and Figure 3- 6 shows the potential pathways associated with the municipal waste system. It is to be recognised that there may be other pathways associated with individual sites but generalisations, based on major pathways identified in other nation-wide assessments[23,24], were made to conduct an Irish specific assessment.

As discussed in Chapter 2, the predominant pathways identified for this assessment are Pathway A – 'infrastructure', Pathway B1 – 'infiltration' and Pathway B2 – 'runoff'.

To determine the fate of chemicals transported through each pathway, the physical, hydro-chemical and ecological characteristics of the surrounding environment need to be considered[163].

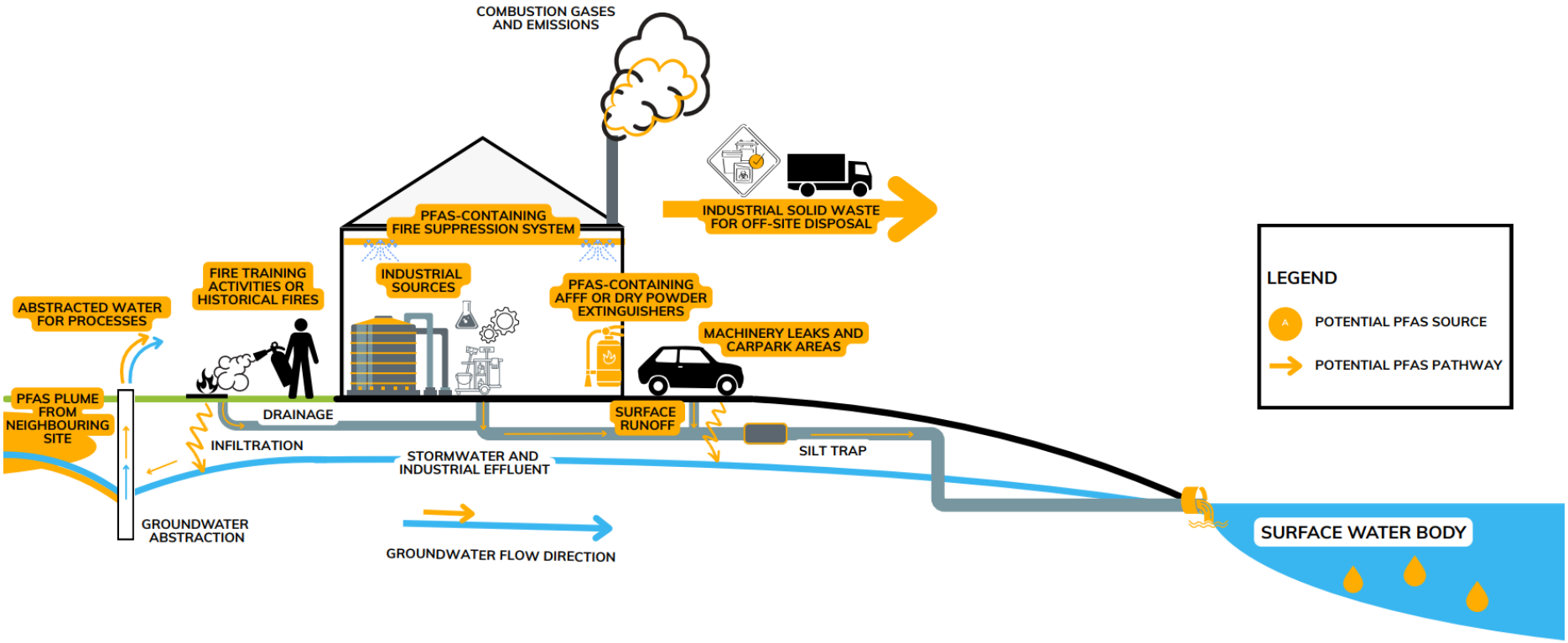


Figure 3- 5 Potential PFAS sources and pathways associated with industrial sites

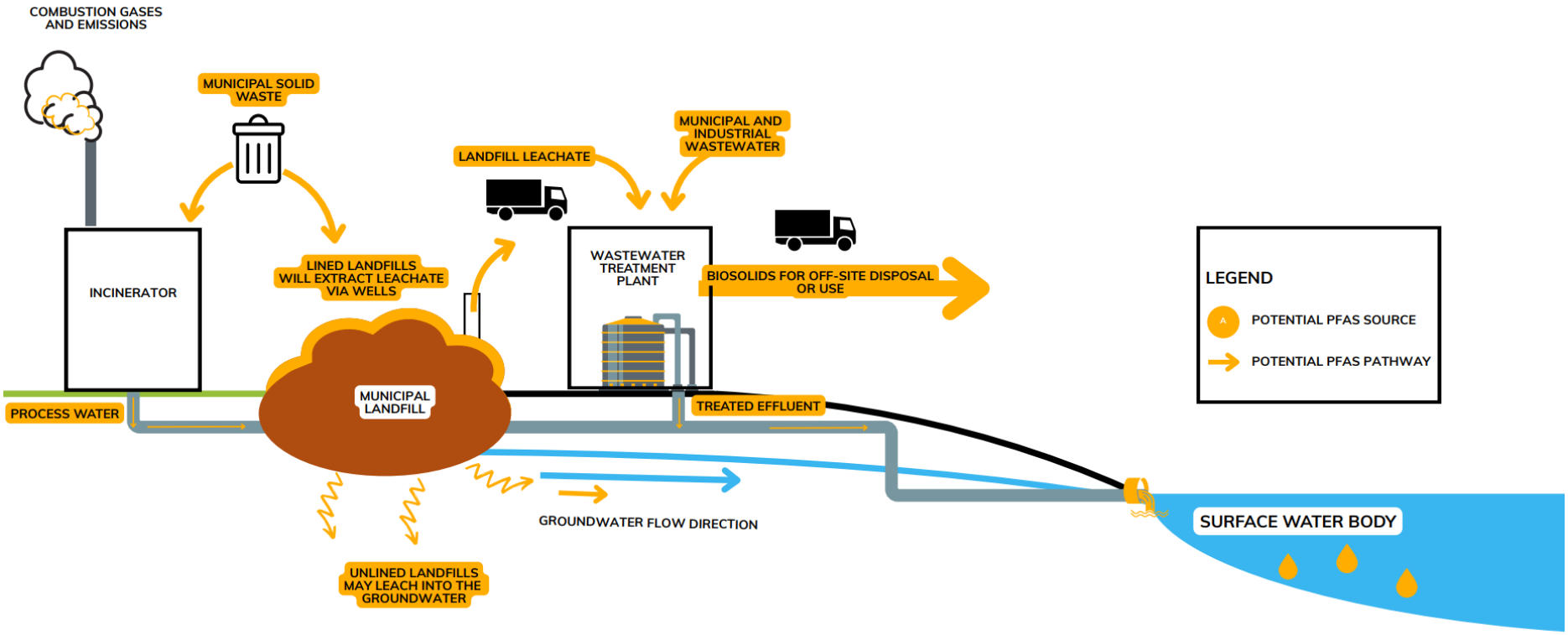


Figure 3- 6 Potential PFAS sources and pathways associated with municipal waste

Each potential PFAS source type identified in Chapter 2 was then classified based on their predominant pathways to enter the environment. Sources where it was unlikely for PFAS compounds to enter the environment, such as office buildings with hand-held fire extinguishers, were a “low risk use” and were not considered further in the high-level classification. Other predominant pathways were determined to be Pathway A - ‘infrastructure’, Pathway B1 - ‘infiltration’, Pathway B2 – ‘runoff’ or ‘multi-pathway’, which is a mixture of both Pathway A and Pathway Bs.

3.3.2.1 Pathway A – Infrastructure

Pathway A - ‘infrastructure’ pathway is associated with point sources where PFAS may be discharged through industrial effluent (such as from pharmaceuticals sites, metal manufacturing facilities and chemical plants), process water, sewage, stormwater drains or wastewater treatment plants, as shown in Figure 3- 7.

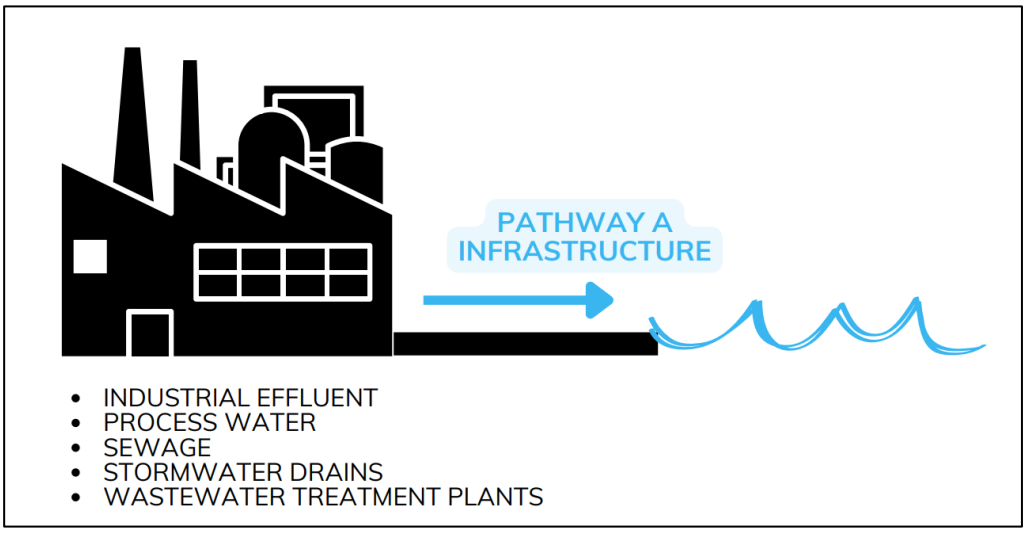


Figure 3- 7 Pathway A infrastructure sources

Industrial effluent sites are shown in red and wastewater treatment plants are shown in green in the Liffey Dublin Bay Catchment in Figure 3-8. A single catchment was chosen to display the results of this methodology due to the large number of potential sources across the country. The Liffey Bay Dublin Catchment was used as an example because it has the highest density of potential point sources. Lined landfills and fire stations are also considered to have Pathway A as a potential pathway as their drainage systems may feed into the sewage system. These sites are included in yellow in **Error! Reference source not found.**. The point sources have

been overlayed on the Coordination of Information on the Environment (CORINE) land-use map[164], the legend of which is included in Figure 3-9.

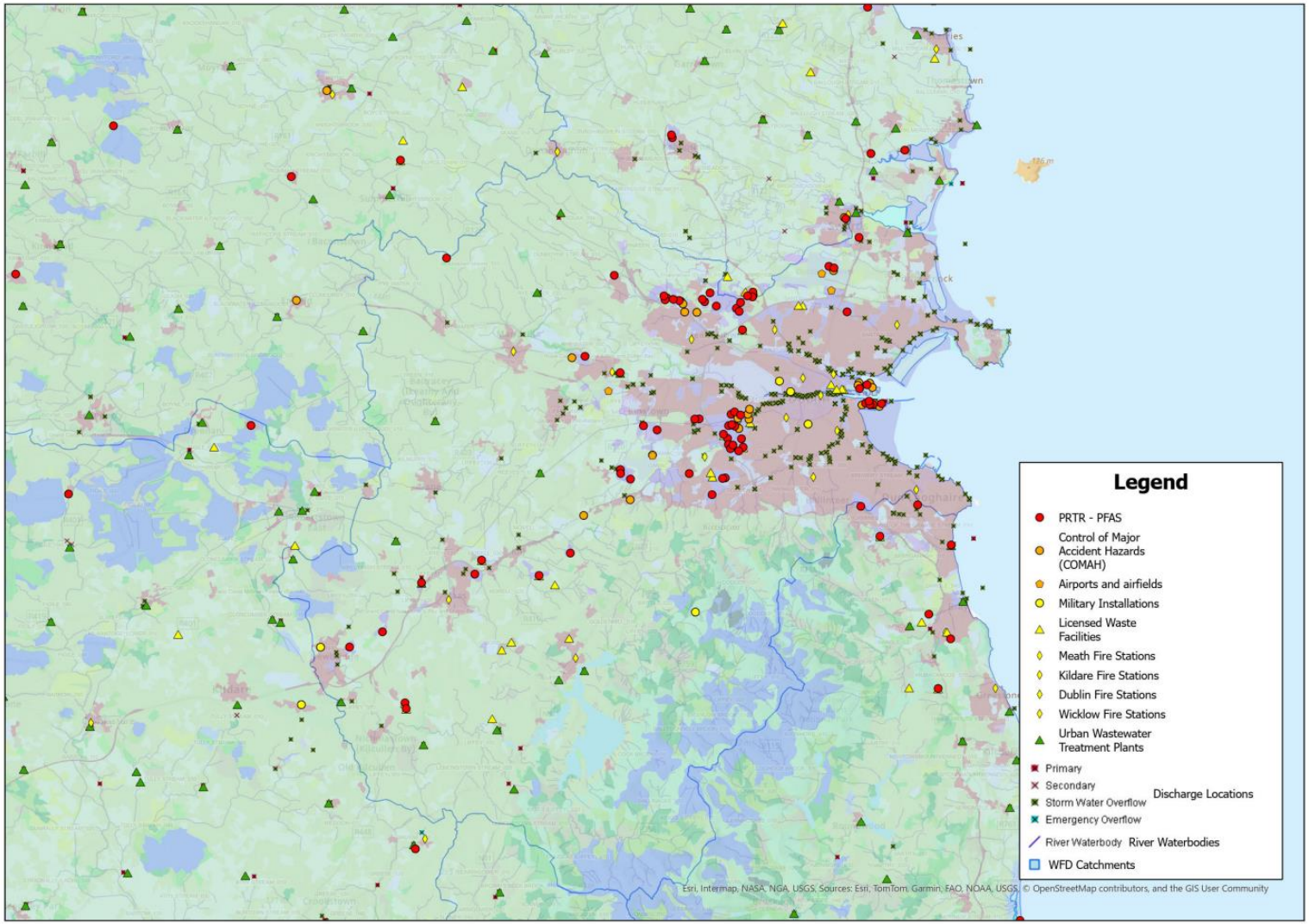


Figure 3- 8 Sites with Pathway A - 'infrastructure' as a potential pathway (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])



Figure 3- 9 Corine (2018) Legend for Figure 3-8

PFAS are commonly detected in effluent and drainage from sites where it has been used in manufacturing processes or used for firefighting purposes at sites such as chemical manufacturing facilities[76,130], WWTPs[23] and airports[3]. Concentrations are likely to be variable and dependent on whether the effluent has been treated or whether treatment is secondary, tertiary or quarternary[165]. Some types of PFAS are difficult to remove using conventional treatment processes and currently, very few water treatment plants are designed to remove PFAS from their effluent.[166] As such, it is broadly assumed that if PFAS is used on site, it will make its way into the effluent that is then discharged either directly into a surface water body, possibly following on-site treatment or it is diverted through to an urban WWTP before being discharged to a surface water body. It is difficult to determine which sites would discharge their effluent directly as opposed to diverting through a WWTP, so it has been assumed that all sites discharge directly to their closest surface water body. As it is likely that PFAS hasn't been removed from the effluent, Pathway A is considered to be a high risk pathway[3].

Once having entered the surface water body such as rivers, lakes or transitional water bodies, the fate and transport of the contamination is dependent on the flow rate, velocity and dilution potential[163]. Simple hydrologic models can be used to assess the risk posed to a receptor.

3.3.2.2 Pathway B1 – Infiltration and Pathway B2 – Runoff

The 'infiltration' and 'runoff' pathways are associated with both point and diffuse sources, such as those presented in Figure 3- 10. These sources predominantly interact with the ground, such as fire-fighting activities, military bases, landfills and agricultural use of pesticides and biosolids. Point sources are shown in Figure 3- 12 and Figure 3- 14 and diffuse sources, such as agricultural sources, can be inferred using the CORINE map[164] (uses 211, 222, 231, 242 and 243).

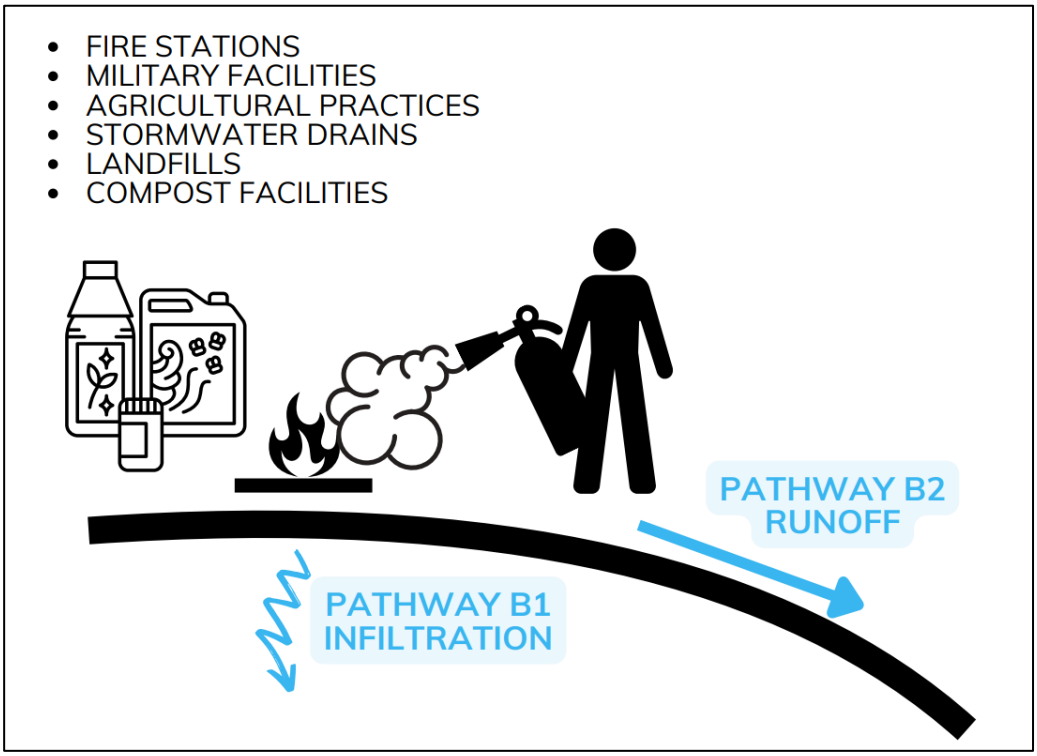


Figure 3- 10 Pathway B1 and B2 infiltration and runoff sources

The Pathways Project was an EPA funded investigation to characterise pathways of contaminant transport in Irish catchments[167]. A four-pathway working CSM was identified, which included overland flow, interflow, shallow groundwater flow and deep groundwater flow. This CSM is shown in Figure 3- 11. Additional pathways were identified to also be important for contaminant transfer pathways in poorly productive aquifers. These included artificial drainage and the transition zone (weathered zone at the top of the bedrock). Infiltration and runoff are driven by a number of factors, including land-use, groundwater vulnerability, depth to bedrock,

soil type and the underlying aquifer productivity, which can be found on the Geological Survey Ireland (GSI) Spatial Resources[168].

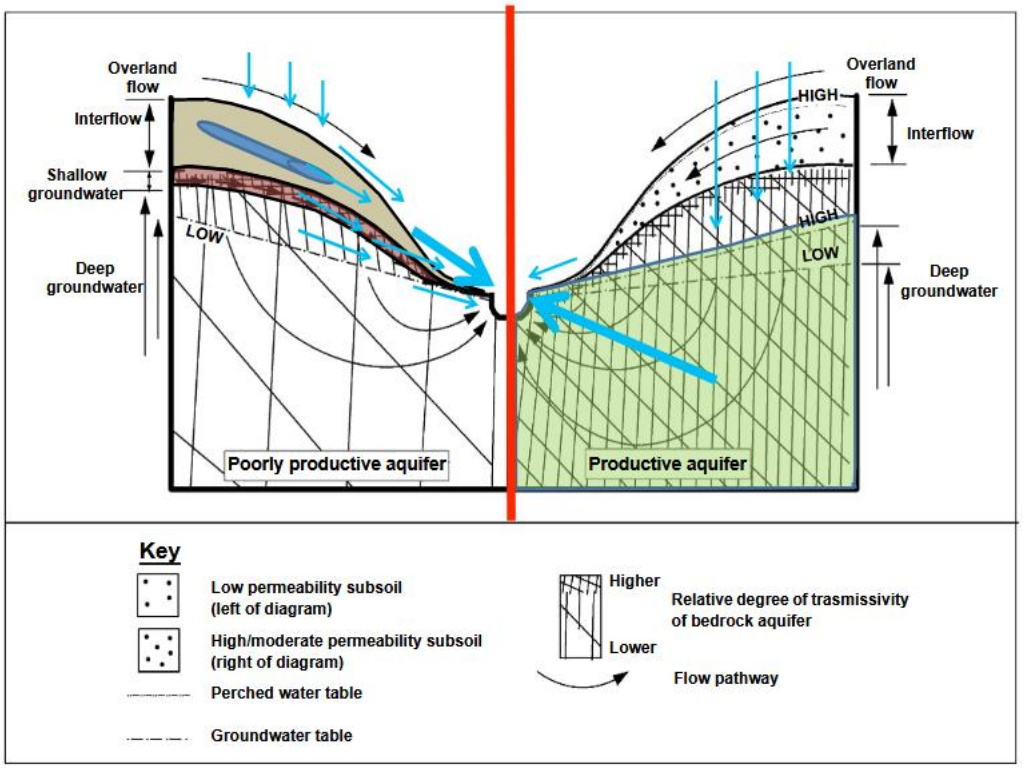


Figure 3- 11 Pathways present in poorly productive aquifers (left) and productive aquifers (right) (adapted from RPS, 2008). Archbold et al (2016)

The nature of underlying bedrock combined with groundwater vulnerability are indicators of contamination likelihood and transport.

Groundwater vulnerability is an indicator of the likelihood for an aquifer to be contaminated if a contamination event occurs[169]. The classification encompasses intrinsic geological and hydrogeological characteristics, including the type and thickness of subsoils (sands, gravels, glacial tills/boulder clays, peat, lake and alluvial silts and clays), and the presence of karst features. Groundwater is at the highest vulnerability where subsoils are either absent or very thin or where surface streams sink underground at swallow holes. The categories are rock near surface or karst (X), Extreme (E), High (H), Moderate (M) or Low (L). The point sources identified as having Pathway B1 – infiltration as a predominant pathway have been overlain the groundwater vulnerability map in Figure 3- 12. For example, using fire-fighting foams in an area of extreme vulnerability is considered to be a high-risk use, as the

underlying aquifer may be covered only by a thin layer of sand, when compared to using it in an area of low vulnerability, as the underlying aquifer may be protected by a thick layer of clay[170].

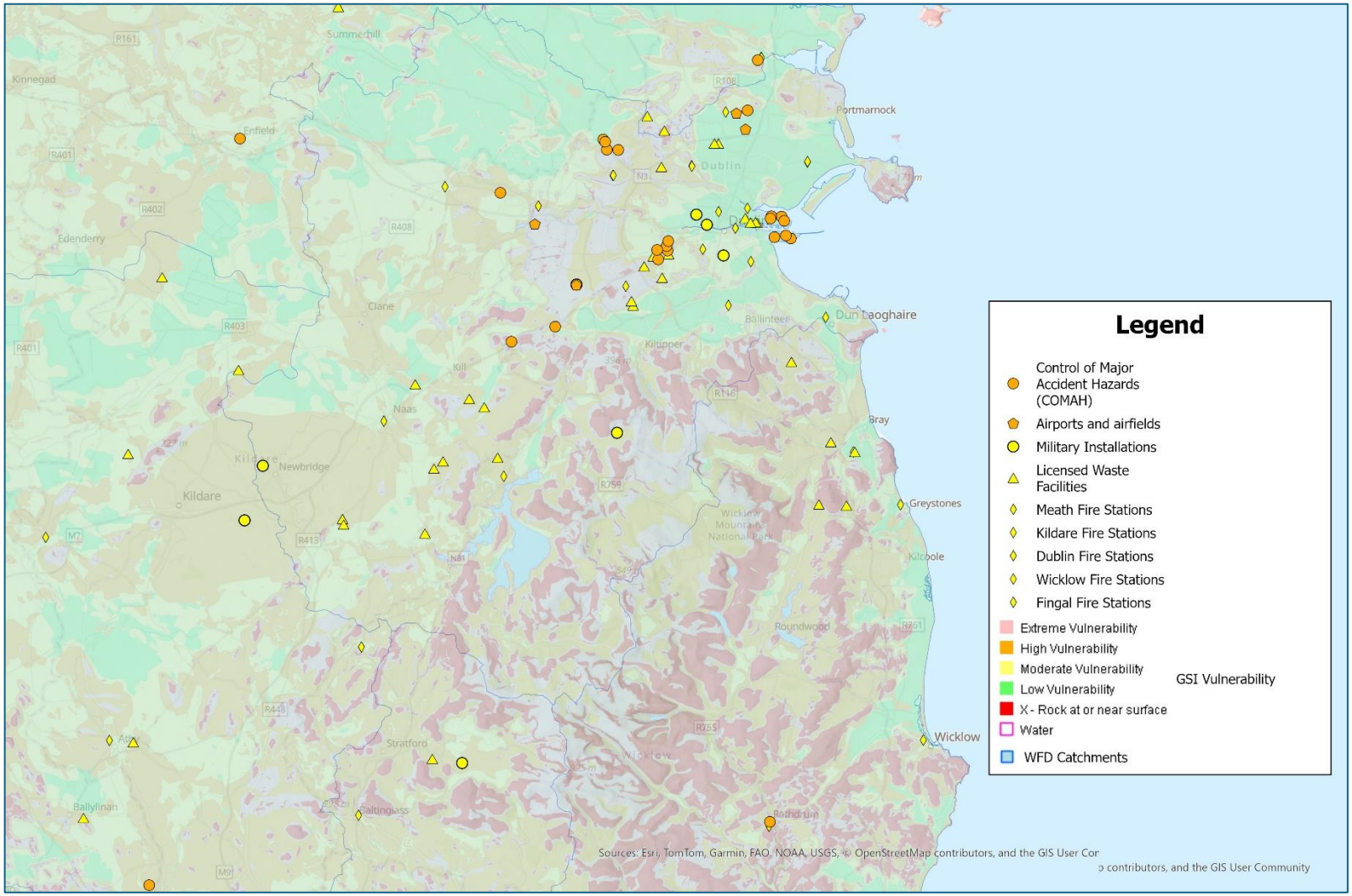


Figure 3- 12 Pathway B1 sources overlaying groundwater vulnerability map (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

Aquifer classification is also an important indication of whether contamination can use groundwater as a valid pathway. Based on the hydrogeological characteristics and the value of the groundwater resource, Irish land surface is divided into nine aquifer classifications. The following eight aquifer categories were defined in the Groundwater Protection Schemes (1999):

- Regionally Important (R) Aquifers
    - Karstified bedrock (Rk)
    - Fissured bedrock (Rf)
    - Extensive sand and gravel (Rg)
- Locally Important (L) Aquifers
    - Sand and gravel (Lg)
    - Bedrock which is Generally Moderately Productive (Lm)
    - Bedrock, which is Moderately Productive, only in Local Zones (Ll)
- Poor (P) Aquifers
    - Bedrock which is Generally Unproductive except for Local Zones (Pl)
    - Bedrock which is Generally Unproductive (Pu)

A ninth aquifer classification was established during the delineation for the Water Framework Directive, which was Locally Important Karstified Bedrock (Lk). The point sources identified as having Pathway B1 – infiltration as a predominant pathway have been overlain the aquifer classification map in Figure 3- 13.

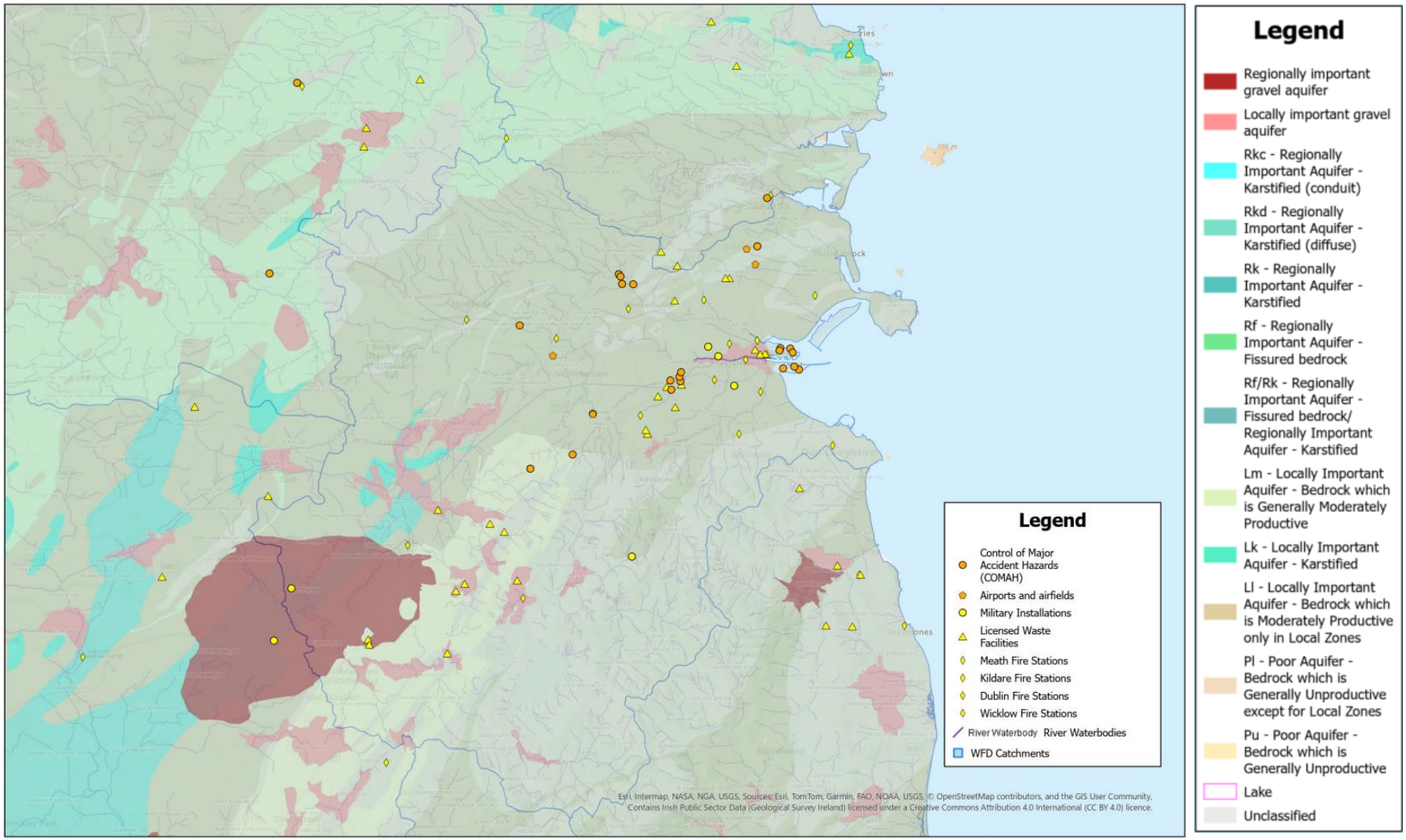


Figure 3- 13 Pathway B1 sources overlaying aquifer classifications (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

In areas where there are poor aquifer classifications, runoff or overland flow may become the predominant transport pathway as the contamination may preferentially choose to travel through artificial drainage channels or the transition zone above the bedrock. Land-use or surface type as determined by the CORINE map[164], can also indicate whether main driver of overland flow or runoff is the predominant pathway[163]. The point sources identified as having Pathway B1 or B2 have been overlain the CORINE map in Figure 3- 14. Discharge locations have also been included as runoff is collected in stormwater drains prior to being discharged to surface water bodies via outfalls.

It is important to note that while there may be other local factors influencing how contamination may enter the groundwater such as drainage network density and topography. However, for the purpose of this thesis, focus was placed on regional classification to prioritise sites for further investigation.

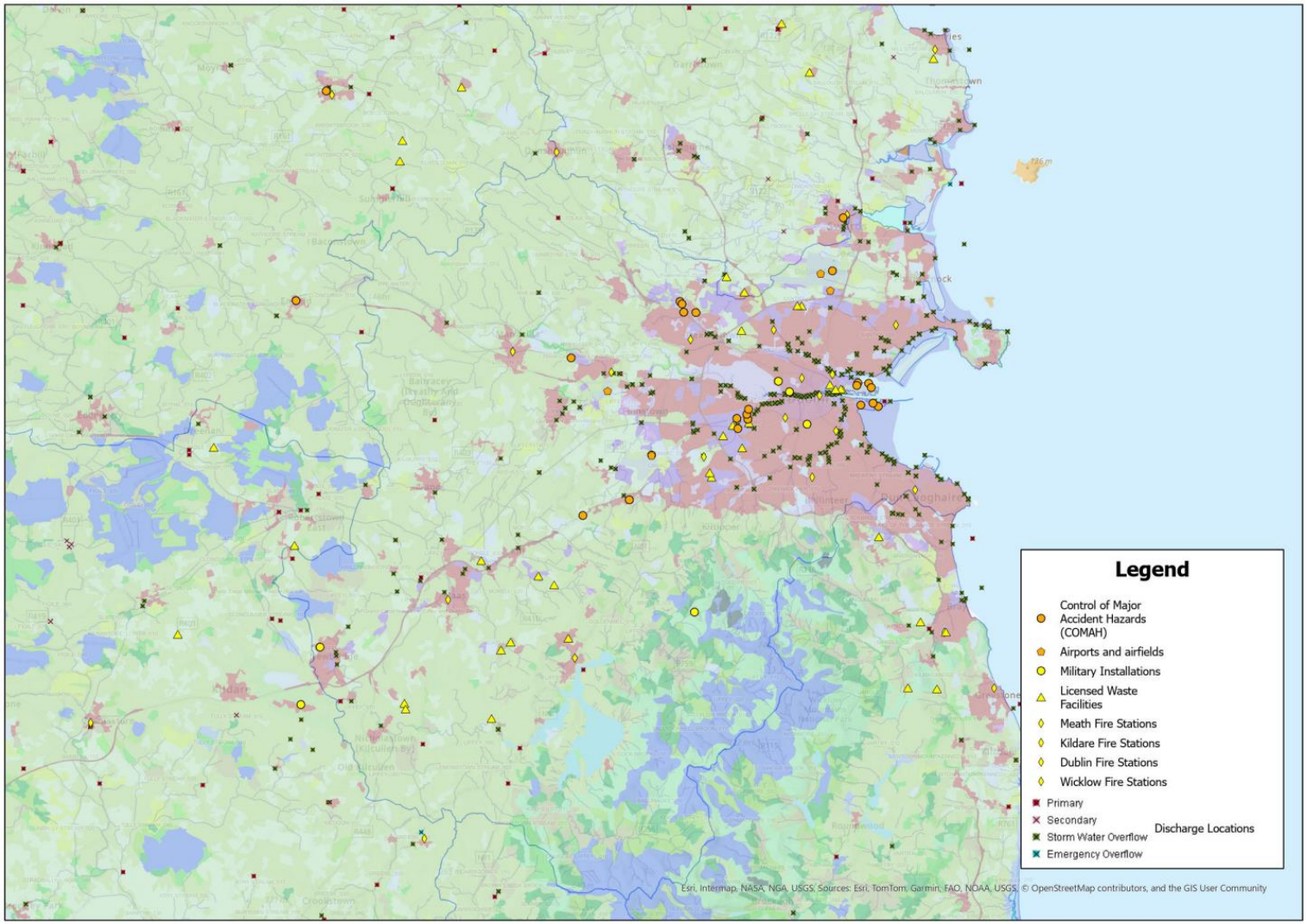


Figure 3- 14 Pathway B2 sources overlaying CORINE land use map (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])



Figure 3- 15 Corine (2018) Land use Legend for 3-14

There are several other potential pathways in the Irish environment, such as dewatering operations in quarries or mining and water abstraction for agricultural purposes. Dewatering and abstraction may create a cone of depression surrounding the wells, drawing in any potential contamination in the vicinity. Due to the ubiquitous nature of PFAS contamination, it is possible that dewatering operations may mobilise dissolved phase plumes from legacy contamination by introducing a cone of depression and distribute them through their licensed discharge locations. Even if dewatering is not a direct source of PFAS, it can activate or accelerate existing SPR linkages[171]. For the purposes of this high-level risk assessment, these pathways are considered as secondary mobilisation pathways and will be used in catchment specific assessments rather than the nation-wide assessment.

Atmospheric transport and deposition to soils and water bodies are pathway that also have not been considered in this investigation and is a data gap[129,130,171].

3.3.3 Receptors

Risk assessment is often done with respect to the receptor[23,129]. For the INVEST p-FASST project, the purpose of the risk assessment is to visually highlight which water bodies that are used for drinking water supply will be at highest risk of PFAS contamination. In Ireland, water resources are dominated by surface waters (81.5%), followed by groundwater (11.5%) and then springs (7%)[172]. Once a valid linkage is determined between a PFAS source and a pathway, the consequence of harm from PFAS can be determined by assessing the potential for the linkage to interact with sensitive receptors. Table 3- 2 summarises the sensitive receptors for human and ecological health in Ireland and they are visually presented for the Liffey Dublin Bay Catchment in Figure 3- 16 and Figure 3- 17.

Table 3- 2 Human and ecological health receptors in Ireland (EPA Maps [2025] and ArcGIS Online [2025])

Human Health	
Sensitive Receptors	**Data source**
Residential areas, including home-grown produce	CORINE Map[164]
Schools and early childhood centres where an unacceptable risk has been identified	ArcGIS Online[111]
Aged care facilities and hospitals where an unacceptable risk has been identified	ArcGIS Online[111]
Agricultural areas	CORINE Map[164]
Aquaculture (eg. Shellfish Protected Areas)	EPA Maps[112]
Drinking water supply sources, including Public Water Supply Source Areas (PWSSA) and Group Water Scheme Zones of Contribution (GWSZOC) rivers designated for drinking water and stock and private groundwater wells	EPA Maps[112,173]
Irrigation bores	EPA LEAP Portal[173]
Water used for recreation and/or fishing (eg. Salmonid Waters)	EPA Maps[112,173]
Ecological	
Special Areas of Conservation (SAC)	EPA Maps[112]
Special Protection Areas (SPA)	EPA Maps[112]
Natural Heritage Areas (NHA)	EPA Maps[112]

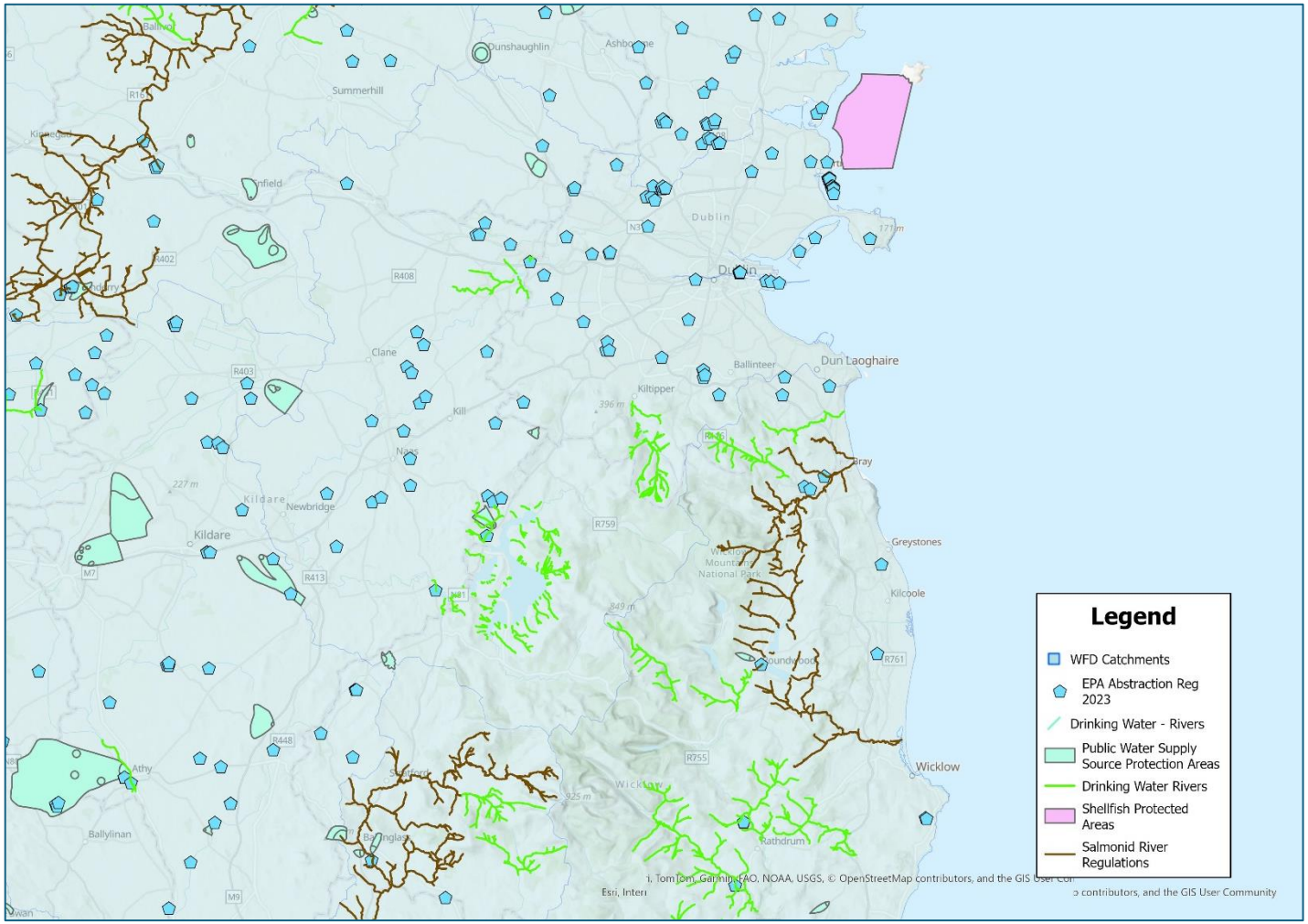


Figure 3- 16 Sensitive Human health Receptors in the Liffey Dublin Bay Catchment (EPA Maps [2025] and EPA [2025])

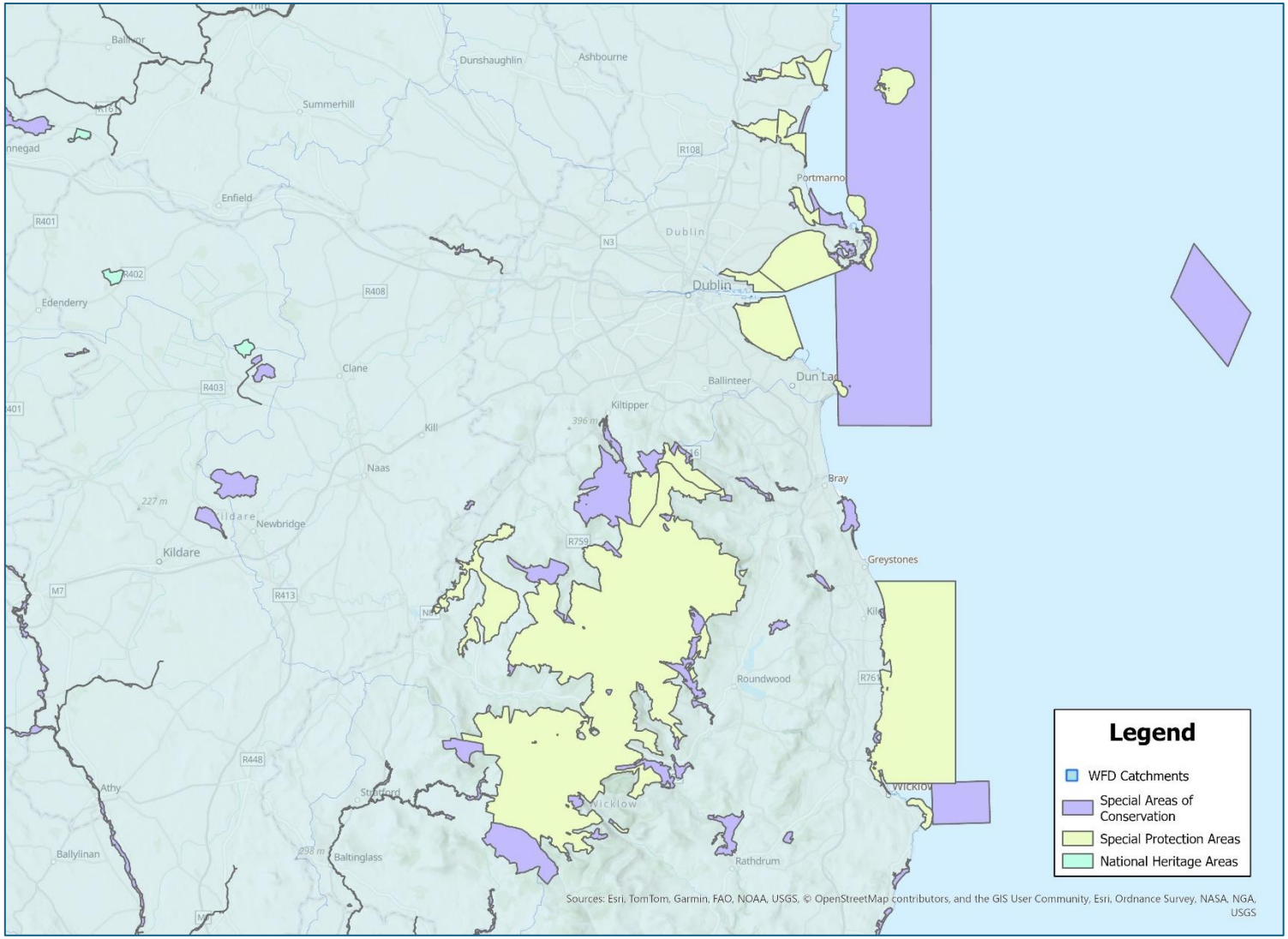


Figure 3- 17 Sensitive Ecological Receptors in the Liffey Dublin Bay Catchment (EPA Maps [2025])

3.4 Data sources and preparation

All potential PFAS point sources identified in Chapter 2, pathway and receptor maps, have been compiled and stored in a national Microsoft Excel and GIS database by standardising coordinate systems. To prepare the data for the investigation of a singular catchment, a mask was created of the catchment from EPA Geoportal[174] downloaded data. This mask was then used to clip databases (Analysis – tools – pairwise clip) to ensure that only source, pathway and receptors data relevant for that catchment were included in the investigation.

3.5 Risk Assessment Methodology

To establish a multi-criteria GIS risk-based tool, it was decided that it would be the most feasible to test it on a singular catchment before using it in other catchments and eventually upscaling to a nation-wide investigation, as was done in Guelfo et al [129] for Rhode Island. Lough Corrib catchment was selected as the target catchment because County Galway has the lowest density of potential PFAS sources and the catchment has a number of sensitive human health and ecological receptors, including drinking water abstractions, SACs and SPAs[175]. Once the methodology has been tested and refined, it could be used in other catchments such as the Liffey Dublin Bay catchment reviewed earlier.

To assess the risk associated with the major pathways, it was determined that creating two risk maps was going to be required. One map considers sources identified in Section 3.2.1 and the Pathway A – Infrastructure. As the infrastructure pathway involves conduits, such as rivers, drains and outfalls, the map uses linear layers and identifies risk based on intersections with sensitive receptors. Figure 3-18 shows the workflow for creating the surface water risk map.

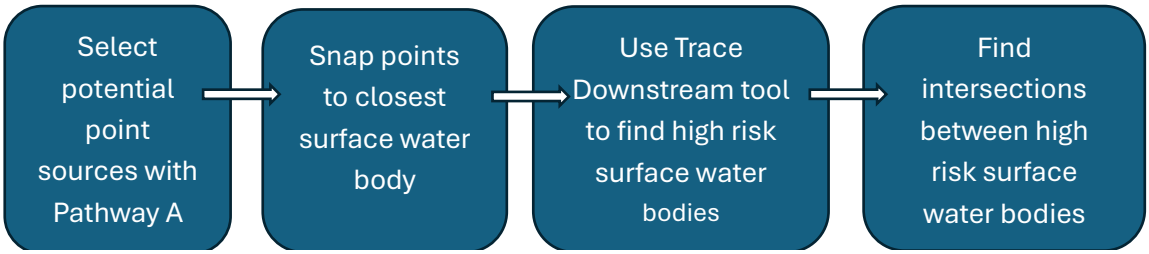


Figure 3- 18 Workflow for creating surface water risk map

The second map for groundwater risk considers sources identified in Section 3.2.2 and Pathway B1 – Infiltration and Pathway B2 – Runoff. As these pathways involve several spatial factors, including groundwater vulnerability and aquifer classification, the map overlays raster files and polygon layers to estimate risks posed to sensitive receptors. A raster is a type of digital image that represents an image as a grid of pixels with its own colour value.

The GIS tool 'Suitability Modeller' was selected to create the risk-based tool as it has the ability to identify areas vulnerable to contamination by weighing and combining different criteria, such as the source risk scores, pathways and receptor sensitivity[176]. The user can standardise the categories and values in each layer by giving them a score from 1-10, with 1 being the category least susceptible to contamination, or the least 'risky', and 10 being the most. The user can then emphasise the relative importance of each layer by weighting them against each other in the analysis. Figure 3- 19 shows the workflow for creating the groundwater risk map.

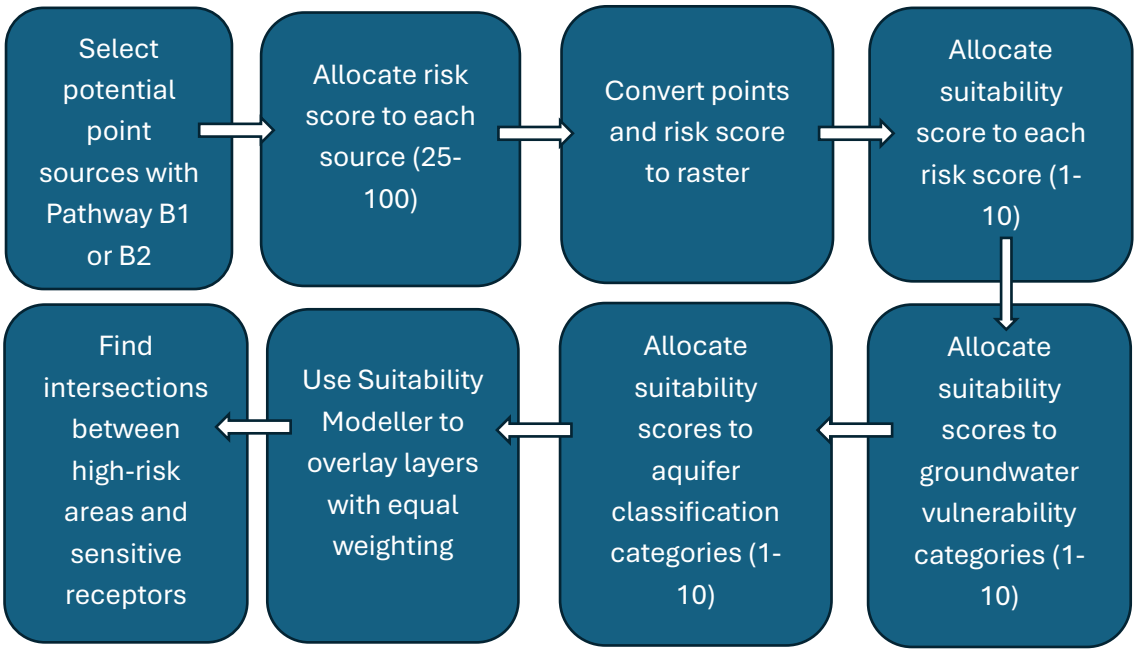


Figure 3- 19 Workflow of groundwater risk map

As mentioned previously, there are multiple other local conditions that may impact the risk classification, such as drainage networks, topography and other geological features. However, the purpose of this high-level model is to provide an indication of

areas that may be at higher risk and could warrant further site-specific investigations.

The following sections outline the methodology established, while using the Lough Corrib investigation as a case study.

3.5.1 Source characterisation

The potential PFAS sources in the Lough Corrib were extracted from the national database using the Pairwise Clipping tool. The risk scores were then allocated to each potential source, as presented in Section 3.1[129]. The environmental setting of each potential PFAS source was then reviewed to determine the potential pathways for the source to enter the environment. The potential PFAS sources in the Lough Corrib Area, potential pathways and associated risk scores are shown in Table 3- 3.

Table 3- 3 Potential PFAS sources and associated risk scores in Lough Corrib Catchment (EPA Maps [2025], HSA [2025] and ArcGIS Online [2025])

Type	Potential pathway	Name	Risk Score
Waste management facilities	Pathway A, B1 and B2	Carrowbrowne Landfill Site Bruscar Bhearna Teoranta (Carrowbrowne) Galway Corporation Depot	100
Urban wastewater treatment plants	Pathway A	Oughterard WWTP Headford WWTP Ballindine WWTP Tuam WWTP Clonbur WWTP Glenamaddy WWTP Ballyhaunis WWTP Ballinrobe Town WWTP Claremorris WWTP Irishtown WWTP Hollymount WWTP Moycullen WWTP Shrule WWTP Kilmaine WWTP Dunmore WWTP Cong WWTP Roundfort WWTP Toormakeady WWTP Cloonfad and Environs Wastewater Treatment Works WWTP Milltown (Galway) WWTP Claregalway WWTP Clonbur WWTP Milltown (Galway) WWTP	100
Lower tier COMAH Sites (AFFF storage)	Pathway A, B1 and B2	Calor Teoranta Claremorris Bulk Station Flogas Ireland Ltd., Hazelhill	75

Type	Potential pathway	Name	Risk Score
Production and processing of metals	Pathway A, B1 and B2	McHale Engineering Unlimited Company	50
Mineral industry	Pathway A, B1 and B2	Cregaree Quarry	50
Fire stations	Pathway A, B1 and B2	Ballinrobe Fire Station Ballyhaunis Fire Station Claremorris Fire Station Tuam Fire Station	25

To develop the groundwater risk map only potential sources with the Pathways B1 or B2 were selected, and the points were converted into a raster file with the risk score as the value field. An output cell size of 1000 m was selected, as an assumption was made that immediate contamination from a source would only spread a maximum of 1km from the source.

While the point source cells had risk scores allocated to them, the rest of the raster file was allocated a risk score of zero. A risk score of zero indicates that there is no PFAS contamination risk in those areas. This is unlikely due to the ubiquitous nature of PFAS contamination and potential impacts from biosolids, pesticides and urban runoff, but as this map is for point sources only, this assumption was appropriate. The Reclassify geoprocessing tool was used to specify that the absence of data (or NoData) was equal to a risk score of 0 within the Lough Corrib Catchment. The source risk raster file shown in Figure 3- 20.

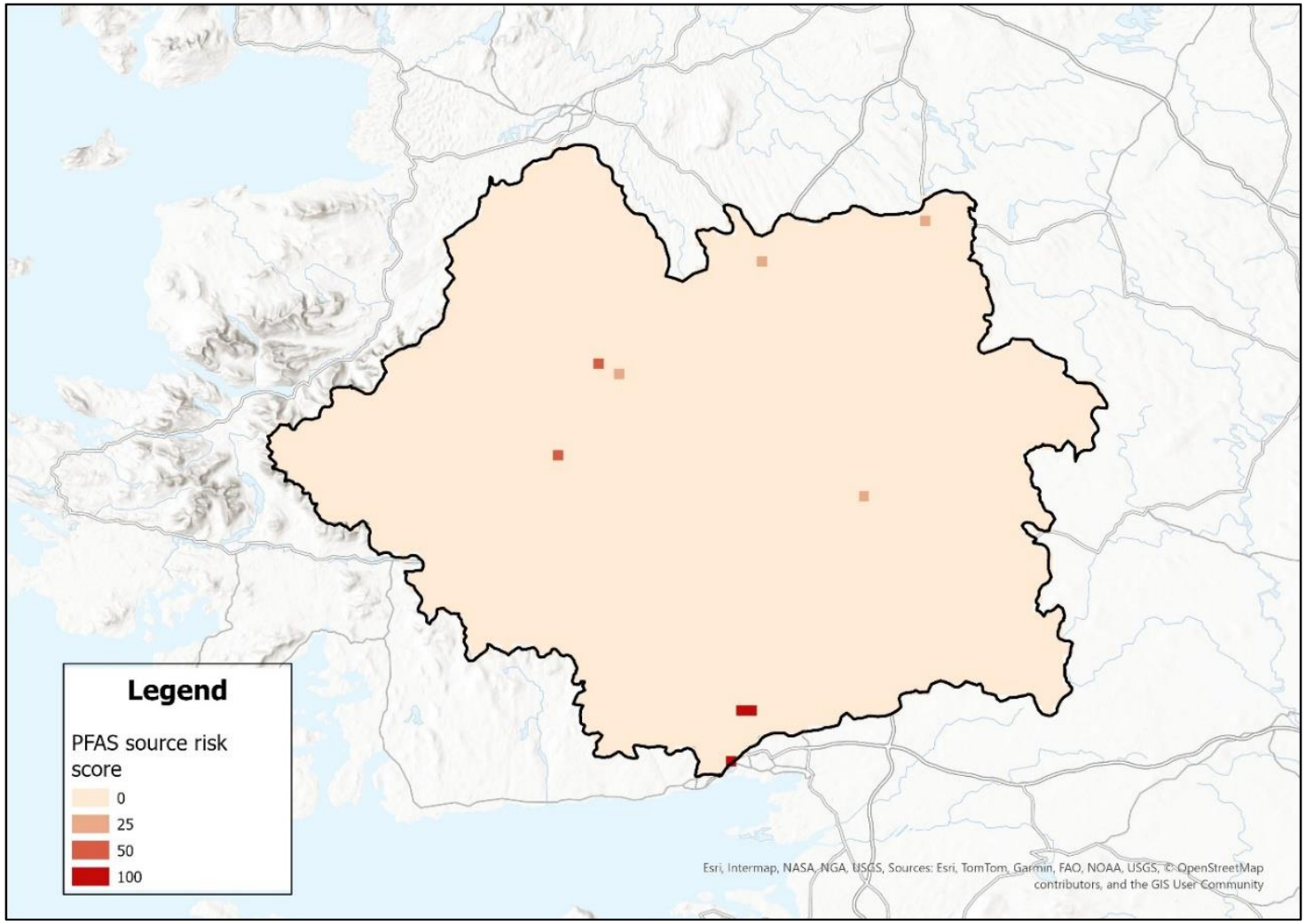


Figure 3- 20 Groundwater source risk raster (EPA [2025], HSA [2025] and ArcGIS Online [2025] Guelfo et al [2018])

If there are multiple sources in a 1km radius of each other in a catchment of a higher density of potential PFAS sources, the process of rasterising sources will average the risk scores in the same cell.

The final step before loading the raster into the suitability model is to allocate each risk score a 'suitability' from 1-10 in the transformation pane. As previously mentioned, suitability score of 0 indicates the lowest risk scenario or the scenario that is least likely to contribute to contamination and 10 indicates the highest risk scenario. Like the risk scores, the suitability scores were selected to standardise comparisons at equal relative intervals across different source types and allow for multiplication with other risk factors in the GIS model. The approach allows for a semi-quantitative assessment that identifies sites that may be highly susceptible to PFAS contamination. The suitability scores allocated to each source risk score is shown in Table 3- 4.

Table 3- 4 Suitability scores allocated to each source risk score

Source risk score	Suitability score
0	2
25	4
50	6
75	8
100	10

3.5.2 Pathway Analysis

The next step is to build an environmental setting map by first creating groundwater vulnerability and aquifer classification raster files. The purpose of this map is to identify the hydrogeological features of a catchment that would be more susceptible to PFAS contamination, once it enters the ground.

3.5.2.1 Groundwater

A raster of groundwater vulnerability was created after allocating each category a suitability score based on the susceptibility to PFAS contamination. An output cell size of 250m was selected as it gave good resolution to the image. The suitability scores were allocated as shown in Table 3- 5 and visually presented in Figure 3- 21.

Table 3- 5 Groundwater vulnerability suitability scores

Groundwater vulnerability category	Suitability score
Low	2
Moderate	4
High	6
Extreme	9
Rock at or near surface or karst Water	10

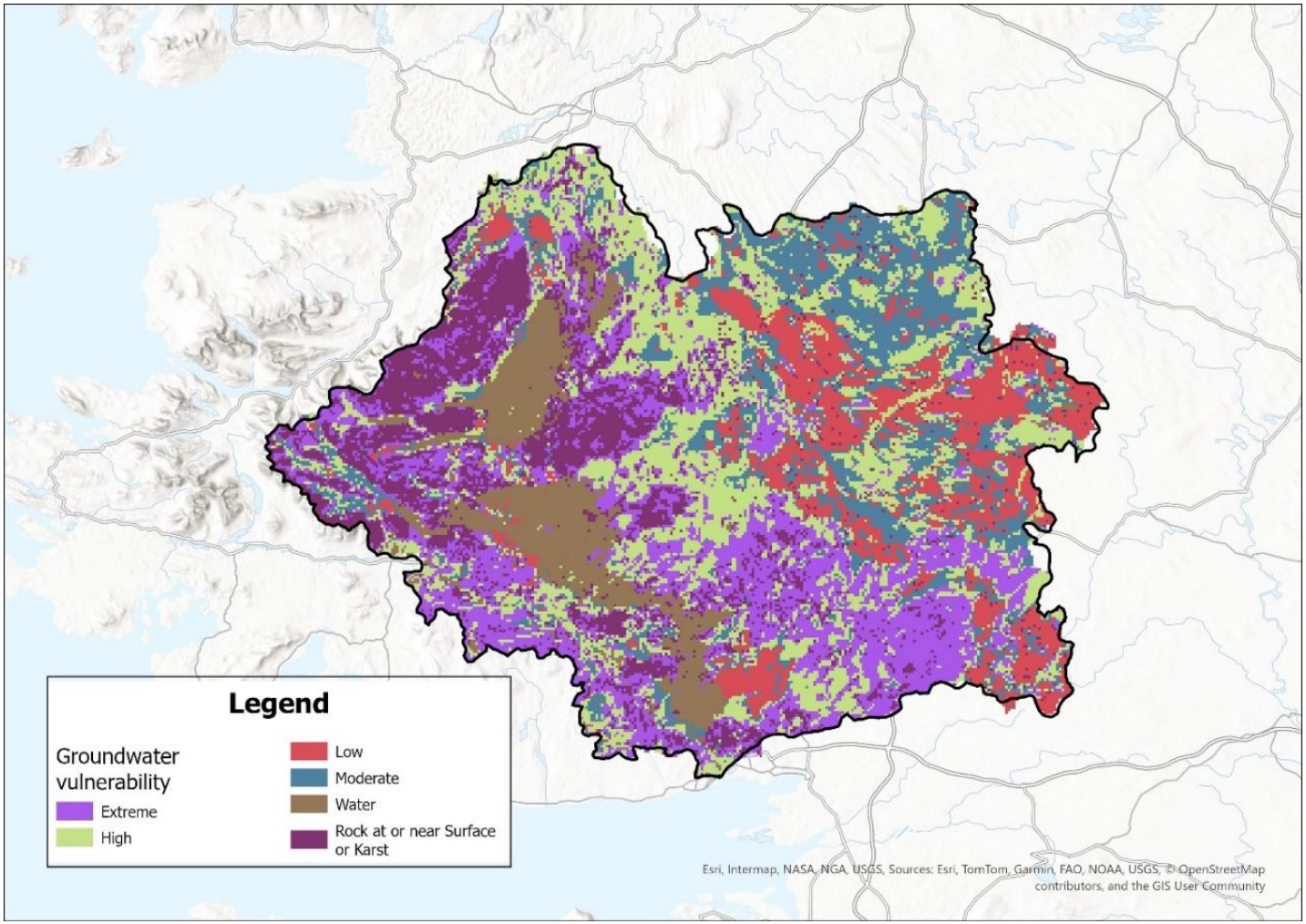


Figure 3- 21 Lough Corrib Groundwater Vulnerability Risk Raster (GSI, 2025)

Aquifer classification is also an important hydrogeological characteristic to consider when determining the potential risk of contamination. A regionally important or highly productive aquifer is the highest risk classification in terms of groundwater susceptibility to contamination. As a contrast, catchments that are underlain by poorly productive aquifers tend to drain via runoff, artificial drainage networks and the transition zone at the top of the bedrock, rather than via groundwater[167]. It is important to note that aquifer risk classification is regional and should be considered on a catchment-by-catchment basis. The suitability score was allocated based on the potential for PFAS contamination to reach sensitive receptors via the groundwater aquifer pathway. A raster with an output cell size of 1000m was created. The weighted scores were allocated as shown in Table 3- 6 and visually presented in Figure 3- 22.

Table 3- 6 Aquifer classification suitability scores (GSI, 2006)

Aquifer classification	Aquifer sub-classification	Suitability score
Regionally Important (R) Aquifers	Karstified bedrock (Rk)	10
	Fissured bedrock (Rf)	10
	Extensive sand & gravel (Rg)	10
Locally Important (L) Aquifers	Sand & gravel (Lg)	9
	Locally Important Karstified Bedrock (Lk)	9
	Bedrock which is Generally Moderately Productive (Lm)	7
	Bedrock which is Moderately Productive only in Local Zones (Ll)	5
Poor (P) Aquifers	Bedrock which is Generally Unproductive except for Local Zones (Pl)	2
	Bedrock which is Generally Unproductive (Pu)	1

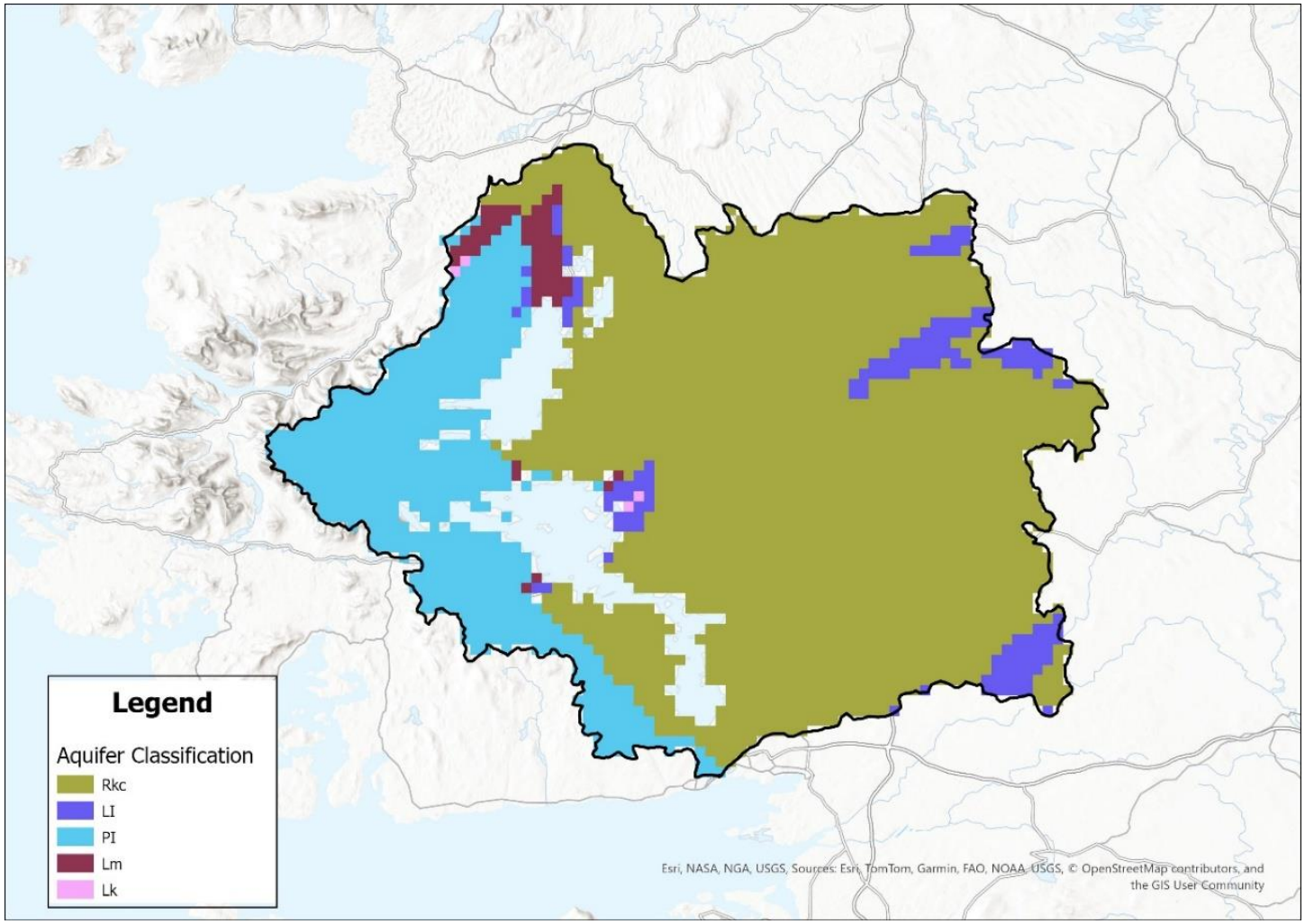


Figure 3- 22 Aquifer classification suitability raster (GSI, 2025)

3.5.2.2 Surface water

Pathway A – Infrastructure and Pathway B2 – Runoff will generally drain to surface water bodies such as tributaries, rivers, lakes and transitional waters. For the surface water risk map, all potential sources with the Pathway A and Pathway B2 were combined into a point layer. These points were then snapped to the closest surface water bodies using the Snapping Tool. The Trace Downstream tool is a Ready to Use tool in the ArcGIS Online geoprocessing service. It determines the path that water will take from a particular location to its furthest downhill path[177]. This tool was used to trace the rivers and surface water bodies that would be susceptible to PFAS contamination from point sources such as effluent outfalls, artificial drainage or stormwater outfalls. The output is shown in Figure 3- 23.

It is important to note that localised drainage channels and topography also have a significant impact on flow paths and directions to surface water bodies.

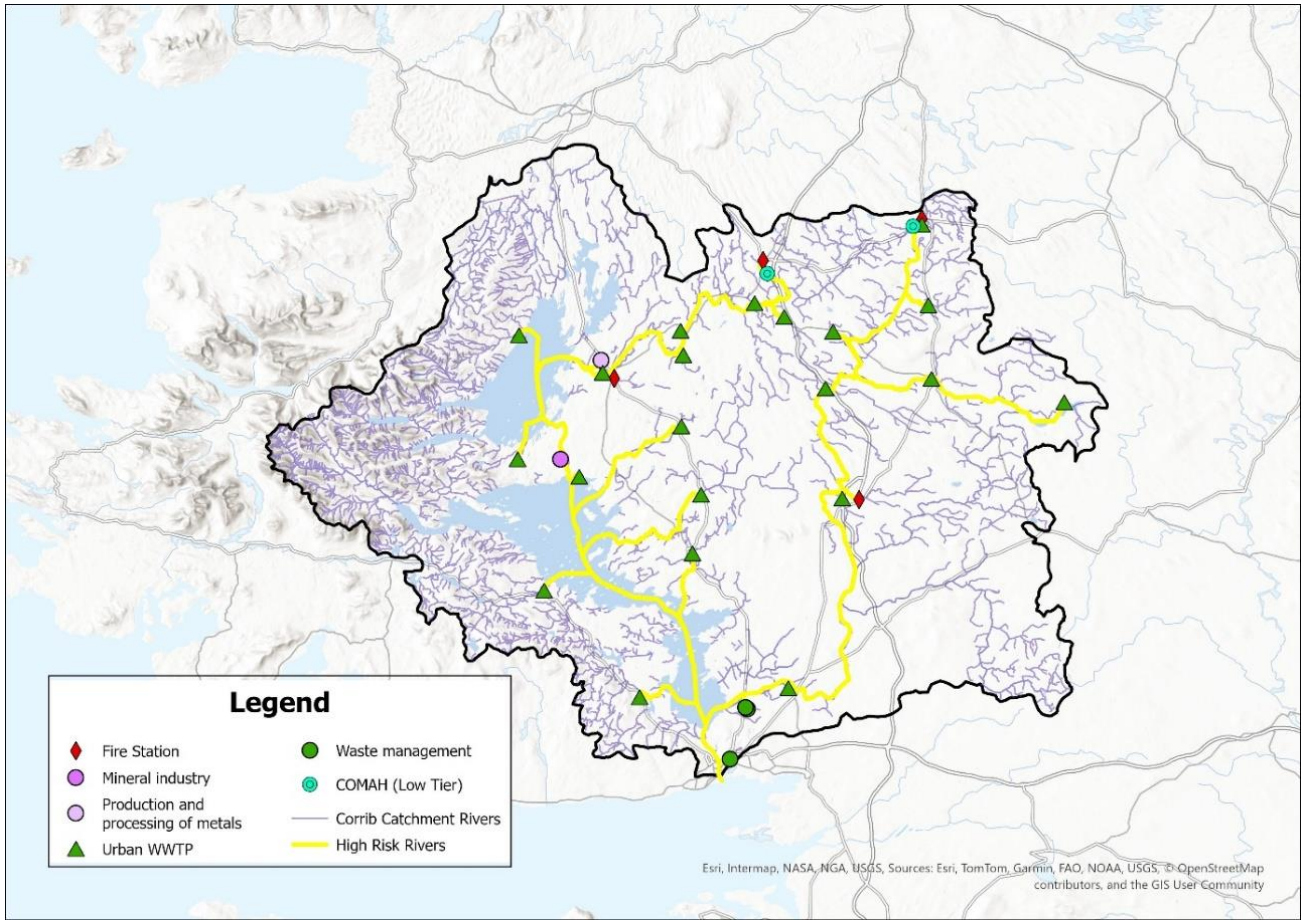


Figure 3- 23 Lough Corrib Catchment High Risk Rivers (EPA Maps [2025], HSA [2025], ArcGIS Online [2025] and EPA [2025])

3.5.3 Receptor Identification

If there is a valid source-pathway (SP) linkage, the possibility that the contamination can reach a sensitive receptor, then needs to be assessed. This can be determined by assessing the proximity of high-risk areas to sensitive receptors and the possibility for there to be a valid SPR linkage.

Figure 3- 24 shows the sensitive human health receptors in the Lough Corrib Catchment. These receptors were chosen based on the risk if was to be contaminated with PFAS. These include rivers and lakes designated for drinking water abstractions and PWSSPAs and GWSZOCs which indicate regions where human activities are restricted to ensure the protection of a drinking water bore. It also shows the rivers that are regulated under the European Communities (Quality of Salmonid Waters) Regulations (1988)[178]. These regulations are to govern the fishing of salmon and sea trout for consumption purposes. Other sensitive receptors from a food consumption perspective include agricultural land and residential areas. These have been included in the format of the CORINE Map.

As part of the INVEST p-FASST project, the EPA provided the 2023 Abstraction Register. The locations are also available on the EPA Leap Portal[173]. The register has the list of all abstractions reported to the EPA under the Water Environment (Abstractions and Associated Impoundments) Act 2022 and Water Environment (Abstractions and Associated Impoundments) Regulations 2024[179]. The legislation applies to abstractions for any purpose including drinking water supply, agricultural activities, industrial activities, commercial activities, recreational activities, aquaculture, mining and quarrying. These have also been included in Figure 3- 24 as they are potentially sensitive receptors to PFAS contamination.

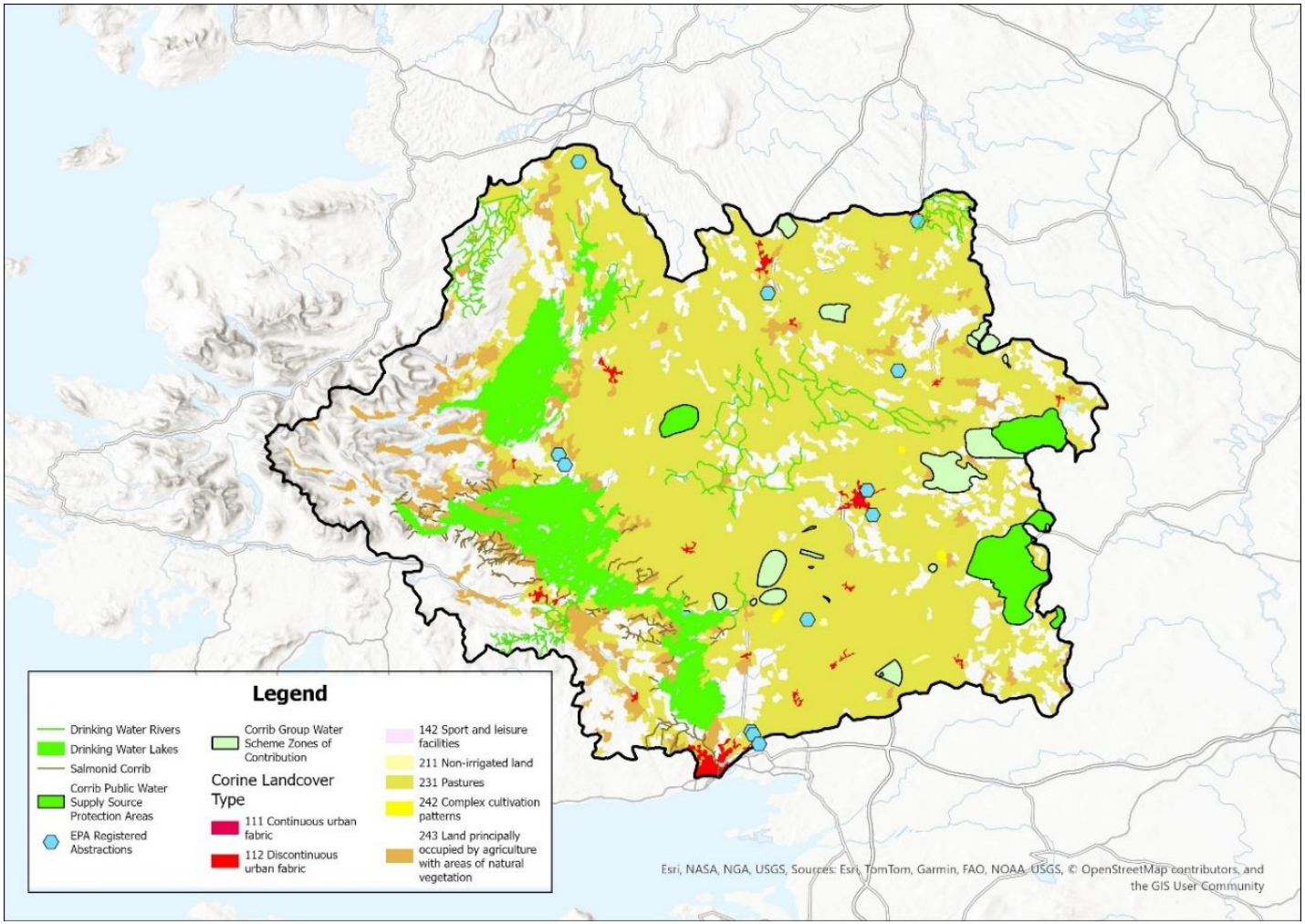


Figure 3- 24 Lough Corrib Human Health Sensitive Receptors (EPA Maps [2025] and EPA [2025])

Figure 3- 25 shows the sensitive ecological receptors in the Lough Corrib catchment. These include SACs, SPAs and NHAs. Lough Corrib and Lough Carra/Mask are considered both SPAs and SACs due to the ecological value of the habitat for birds and other flora and fauna species. NHAs are habitats or geological/geomorphological sites that are considered important for the species of plants and animals that need protection. The NHAs in the Lough Corrib catchment are all bogs, which are important for unique ecosystems and carbon sequestration purposes[180].

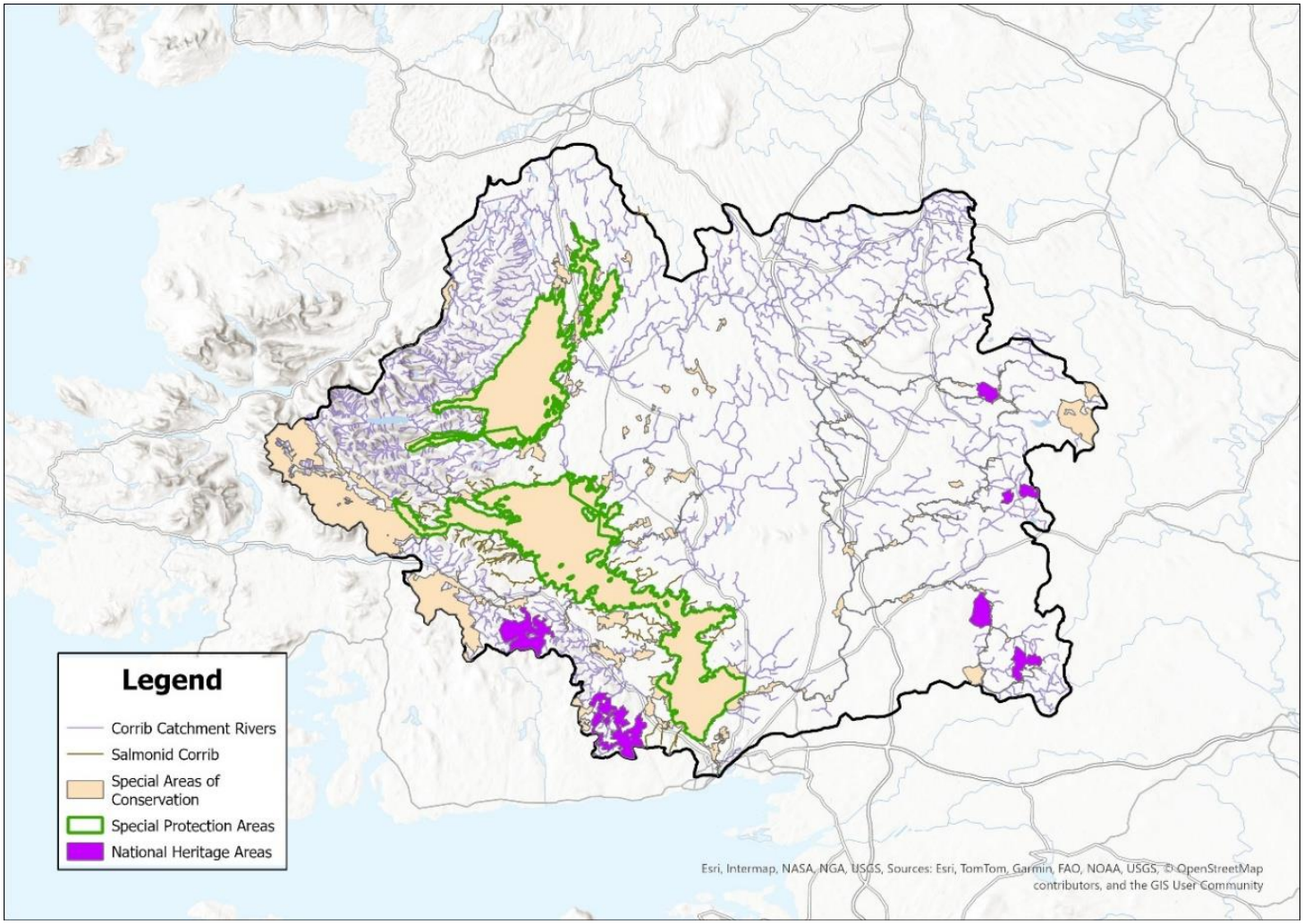


Figure 3- 25 Lough Corrib Ecological Sensitive Receptors (EPA Maps, 2025)

3.5.4 Risk Scoring Framework

To establish the multi-criteria risk tool for groundwater risk, the GIS 'Suitability Modeller' was used. The PFAS source risk score, groundwater vulnerability and aquifer classification raster layers were overlayed with equal weighting. In the transformation panes, the suitability scores were allocated for each layer. The modeler was then run to create a groundwater risk map, as shown in Figure 3- 26. The suitability model adds together the multiple criteria in each 250m^2 pixel to visually depict the susceptibility to PFAS contamination in the underlying aquifer. The output for each cell is a 'suitability score', as shown in the legend Figure 3- 26; the lowest possible suitability score is 6 because the lowest suitability score for each of the three raster layers was 2.

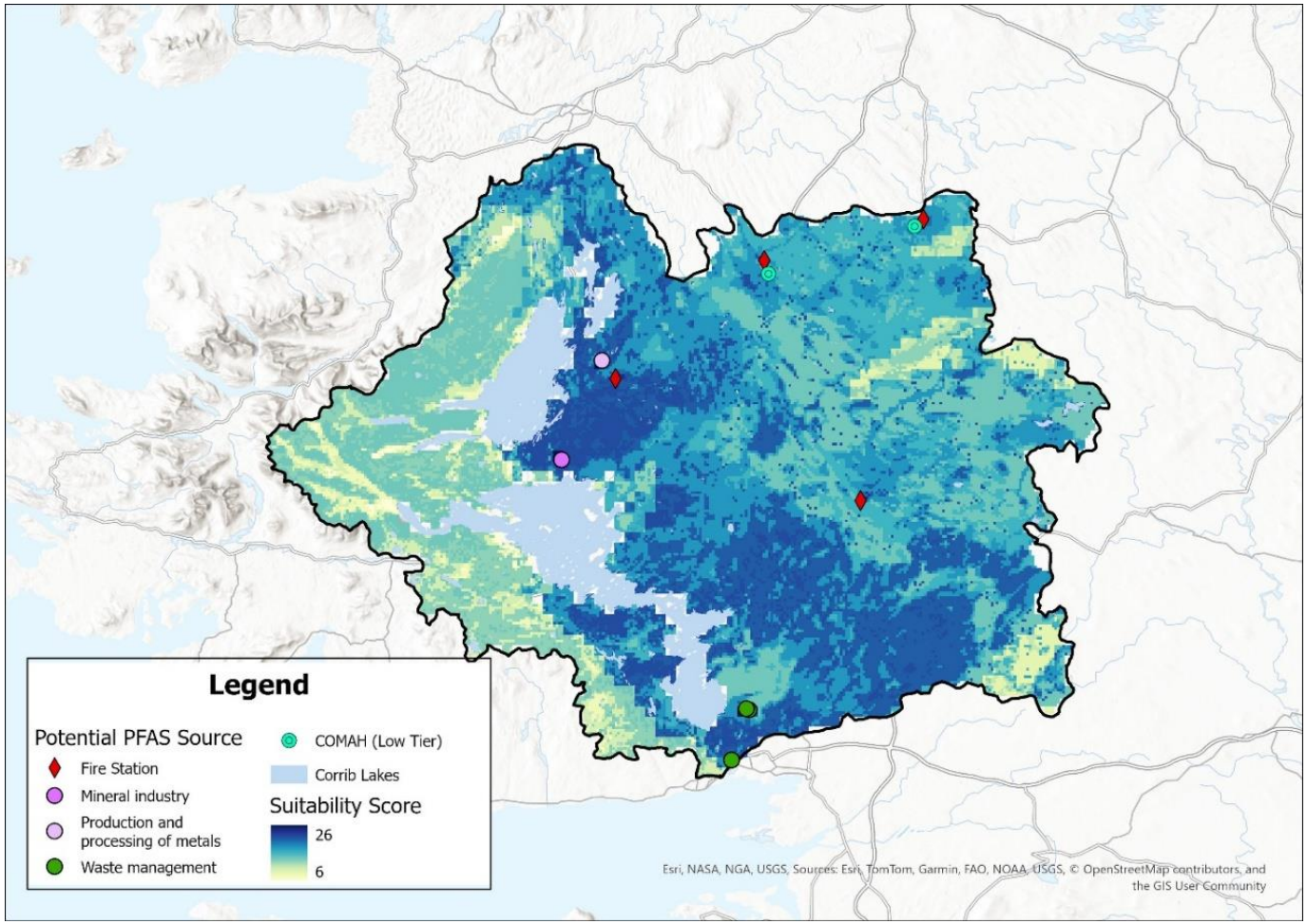


Figure 3- 26 PFAS groundwater risk map (EPA Maps [2025], GSI [2025], ArcGIS Online [2025] and HSA [2025])

As there is likely to be connectivity between groundwater aquifers and surface water bodies, the river network, including the “high risk rivers” established in Section 5.2, has been overlayed with potential PFAS sources with only Pathway A – infrastructure in Figure 3- 27.

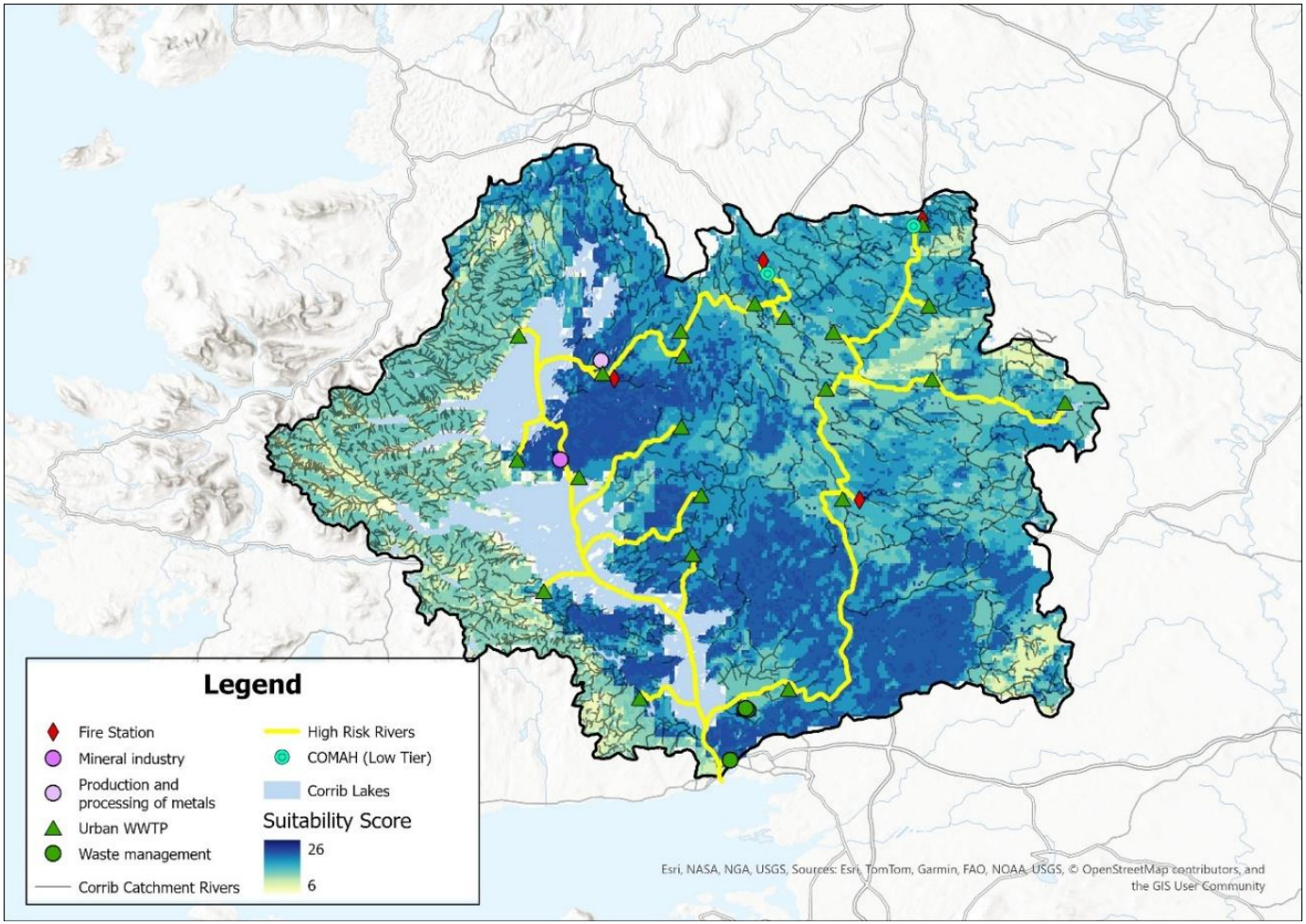


Figure 3- 27 PFAS Risk Map for Lough Corrib (EPA Maps [2025], GSI [2025], ArcGIS Online [2025] and HSA [2025])

Human health receptor layers were overlayed on the surface water risk map to determine whether there were any intersections with the high-risk river pathways. This was done using the 'Intersect' tool. The output of this tool indicated areas where there was high likelihood for any contamination to enter the drinking water source or protected area. The intersections shown in pink in Figure 3- 28 are between the high-risk river pathways and designated drinking water rivers and lakes. Further intersections are discussed in Section 6.

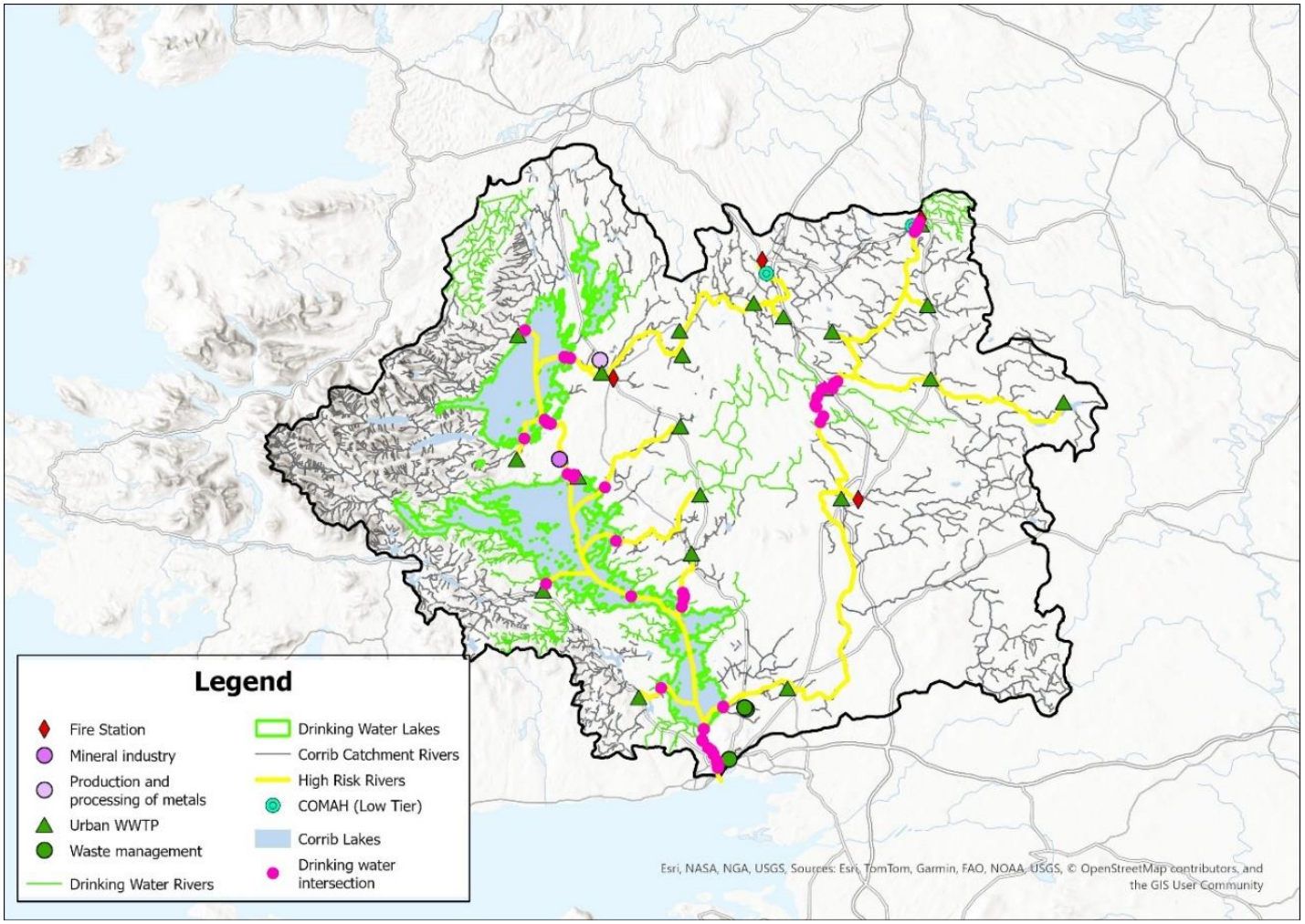


Figure 3- 28 Intersections between high-risk pathways and designated drinking water rivers and lakes (EPA Maps [2025], ArcGIS Online [2025] and HSA [2025])

To determine whether there are any intersections with sensitive receptors and elevated suitability scores in the groundwater risk map, all polygon layers, including the PWSSPA, GWSZOCs, EPA registered abstraction 1km buffers, SACs, SPAs and NHAs were overlayed on the groundwater risk map. Zonal statistics were run to average the risk score for each polygon. Figure 3- 29 shows the pixels in a PWSSPA. Each of these pixels has a unique score and the zonal statistics tool averages these scores to create an average for the polygon. The results are presented in Section 6.

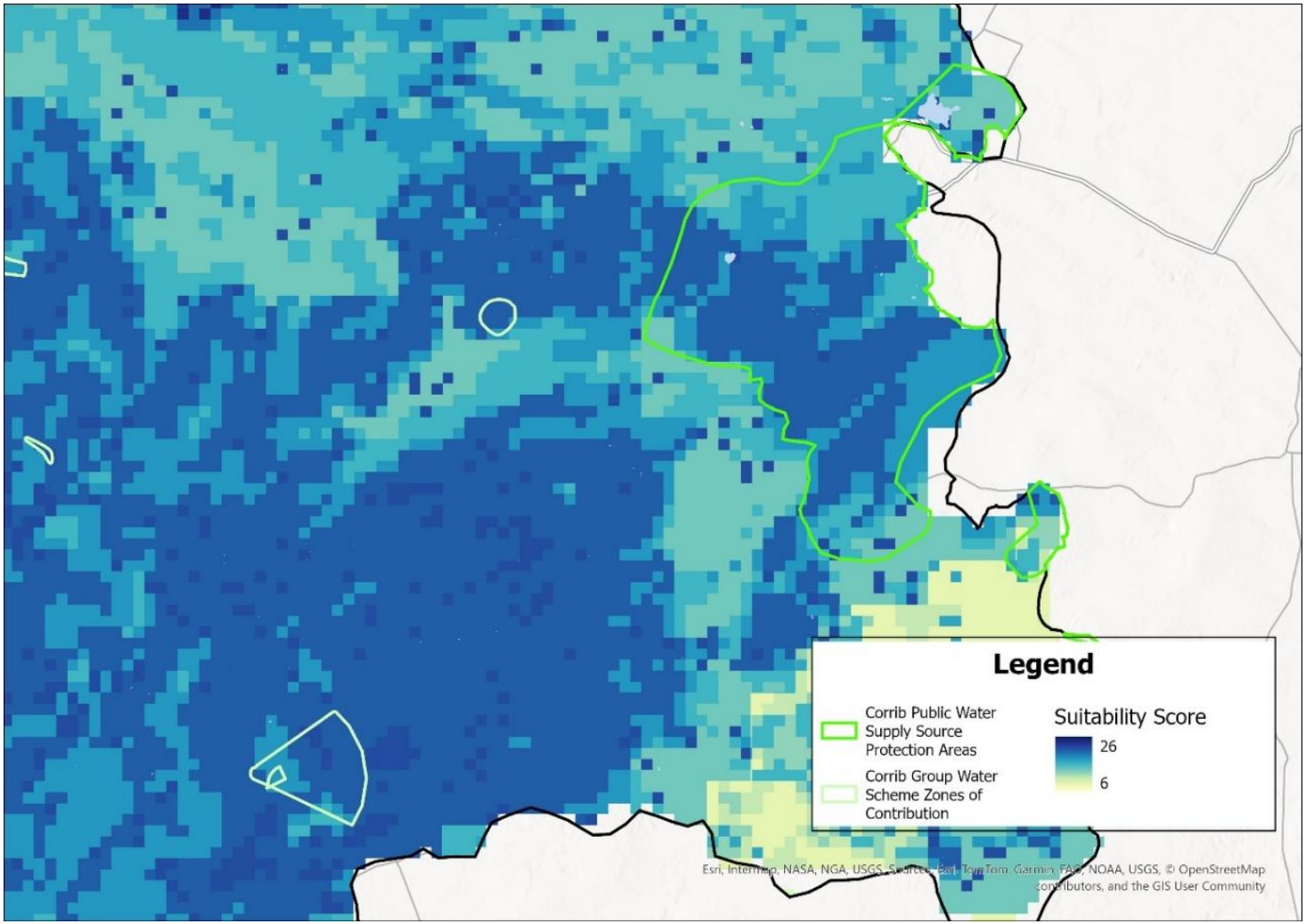


Figure 3- 29 Methodology to calculate the average risk for sensitive receptors (EPA Maps [2025] and GSI [2025])

3.5.5 Limitations, Assumptions and Potential Adjustments

This risk assessment method has several limitations including the lack of data surrounding the historical use of PFAS. This is because the uses of PFAS have only been unregulated until recently. As mentioned in Chapter 2. This is an important data gap as the historical use may have contributed to significant legacy contamination. This risk assessment has only used the currently known and potential point sources of PFAS, as outlined in Chapter 2.

There is also an assumption that all the identified potential point sources of PFAS are discharging into the surrounding environment. There is a possibility that individual sites are containing their PFAS loads or are treating their effluent prior to discharge.

This risk assessment methodology can be reviewed following validation with in-field PFAS sampling and analysis. While there are a couple of spot checks that have been completed in the Lough Corrib catchment to validate the predictions, adjustments may have to be made. The PFAS risk score assumptions were based of international literature and from in-field groundwater results. These could be revised iteratively as more investigations are done into Irish sources and sites. There is also currently an equal weighting of all the layers, including groundwater vulnerability, aquifer classification and the PFAS risk scores. These weighting can also be revised depending on the in-field results.

3.6 Risk Assessment Results

This section visually highlights the water bodies and water abstractions that are likely to be at risk of PFAS contamination in the Lough Corrib Catchment. It also presents the results of the multi-criteria risk tool developed in Section 5 to also identify sensitive ecological receptors that could be impacted by PFAS contamination.

3.6.1 Abstraction Risk Scores

The average suitability or risk scores were determined for all known abstractions in the Lough Corrib catchment using zonal statistics. The abstractions shown as blue pentagons in Figure 3- 30. Some of these abstractions are from surface water bodies, but the majority are from groundwater boreholes. Not all the EPA registered abstractions are for consumption purposes (eg. Quarrying and recreation), but they have been included on the map as the abstraction may mobilise PFAS contamination plumes from neighbouring sites and discharge them into the nearest surface water body. Bores designed for agriculture may also mobilise surrounding PFAS plumes, potentially from diffuse sources and redistribute them on land designed for livestock or crops.

The PWSSPAs and GWSPAs are also shown in Figure 3- 30 and are labelled from A to E and 1 to 20, respectively. Table 3- 7 and Table 3- 8 show the average risk scores for PWSSPAs and GWSPAs, which are designed for human consumption purposes and Table 3- 9 shows the average risk scores for registered EPA abstractions. The calculation of average risk scores is explained in the following sections.

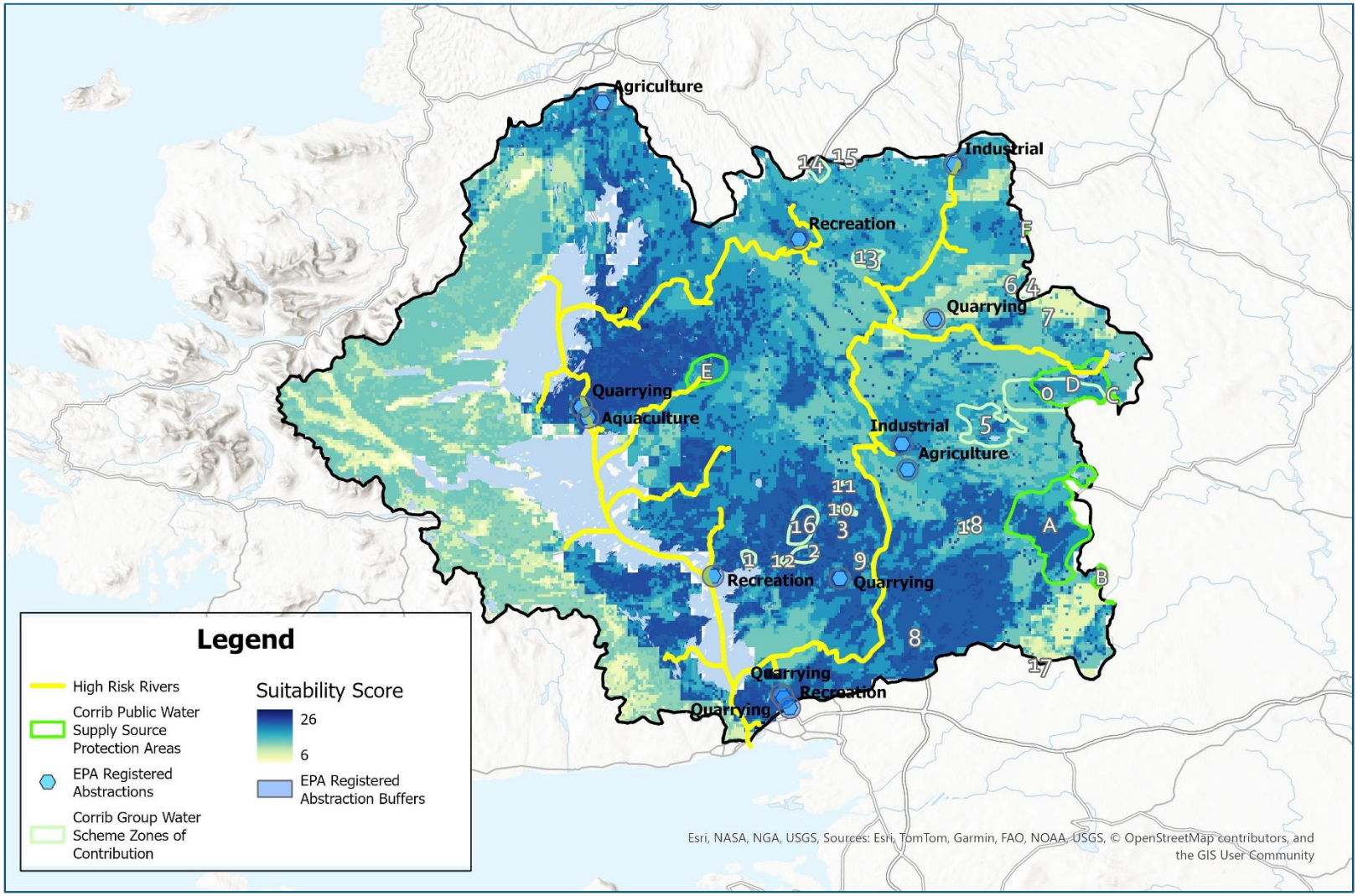


Figure 3- 30 Ground and surface water abstractions in the Lough Corrib Catchment overlayed on the ground and surface water risk maps (EPA Maps [2025], EPA [2025] GSI [2025])

Table 3- 7 Source Protection Areas Average Suitability Scores (EPA Maps [2025] and GSI [2025])

Identification	Source protection area	SPA ID	Size (km2)	Average Suitability Score
A	Mid-Galway PWS	IE_GSI_SPA_11	46	15
B	Mountbellew PWS	IE_GSI_SPA_2	2	12
D	Dunmore Glenamaddy PWS	IE_GSI_SPA_164	20	16
E	Kilmaine PWS	IE_GSI_SPA_248	7	17

Table 3- 8 Group Water Scheme Zone of Contribution Average Suitability Scores (EPA Maps [2025] and GSI [2025])

Identification	Group Water Scheme Zone	GWS ID	Size (km2)	Average Suitability Score
0	Gurteen Cloonmore GWS	IE_GSI_ZOC_59	24	16
1	Kilcoona Caherlistrane GWS	IE_GSI_ZOC_73	2	13
2	Cahermorris Glenreevagh GWS	IE_GSI_ZOC_74	3	13
3	Caherlea GWS	IE_GSI_ZOC_75	<1	13
4	Kiltevna GWS	IE_GSI_ZOC_86	2	14
5	Gallagh GWS	IE_GSI_ZOC_94	18	16
6	Toberowen Lissybroder GWS	IE_GSI_ZOC_96	1	18
7	Boyounagh Ballyedmond GWS	IE_GSI_ZOC_97	1	12
8	Carheenlea GWS	IE_GSI_ZOC_53	4	13
11	Anbally GWS	IE_GSI_ZOC_54	<1	14
12	Rusheens GWS	IE_GSI_ZOC_55	1	13
13	Claretuam_Belclare GWS	IE_GSI_ZOC_56	1	14
14	Balrobuckbeg GWS	IE_GSI_ZOC_58	<1	13
15	Irishtown GWS	IE_GSI_ZOC_152	3	18
17	Loughanemon Barnacarroll GWS	IE_GSI_ZOC_156	3	17
18	Cluide - Cahermorris	IE_GSI_ZOC_193	7	14
20	Feigh East and West	IE_GSI_ZOC_242	1	13

Table 3- 9 EPA Abstraction Risk Score Average (EPA [2025] and GSI [2025])

EPA Abstraction	Abstraction ID	Abstraction purpose	Pumping rate (m^3)	Average Suitability Score
Mcgraths Limestone Works Limited	R01601-01	Quarrying	50 (Groundwater)	21
Inland Fisheries Ireland	R01627-01	Aquaculture	2000 (River)	22
An abstractor	R00337-01	Agriculture (Drinking consumption, parlour and herd washing)	30 (Groundwater)	17
Baswal Limited	R01588-01	Agriculture (irrigation)	40 (Lake)	22
Roadstone Limited	R00254-01	Quarrying and other industrial manufacturing	8681 (Groundwater)	17
Galway Race Committee	R00307-01	Racetrack Irrigation / Buildings Supply / Fire Fighting	260 (Groundwater)	13
Claremorris Golf Club Limited	R01483-01	Watering of golf greens	35 (River)	14
Harrington Concrete and Quarries Unlimited Company	R00465-01	Quarrying	365 (Groundwater)	14
Transitions Optical Ltd	R01364-01	Industrial	70 (Groundwater)	15
Concrete Manufacturing Company Limited	R00482-01	Industrial other manufacturing	55 (Groundwater)	9
Dawn Meats Ireland Unlimited Company	R00388-01	Commercial – other Agri-Food	550 (River)	16

It was found that, not only did two PWSSPAs (Dunmore Glenamaddy PWS [D] and Kilmaine PWS [E]) have elevated average risk scores from the groundwater risk map, but they also intersected rivers that were determined to be high risk in terms of PFAS

contamination. This means that there is potential for PFAS contamination to enter the drinking water supply in these areas.

EPA Abstractions registered for use in aquaculture and for meat production have also been identified as having elevated average risk scores and are near high-risk rivers. The elevated average risk score for the Baswal abstraction is likely to have been skewed from overlaying an extreme vulnerability area and a regionally productive aquifer. Although there may not be an identified point source in this area, there may be diffuse sources, such as biosolids and pesticides that may contaminate this area. As such, the abstraction may be extremely susceptible to any form of contamination.

Figure 3- 31 shows the rivers and lakes that are designated surface water bodies for drinking water purposes. There are several intersections between these designated water bodies and identified high risk rivers. These are summarised in Section 6.2.

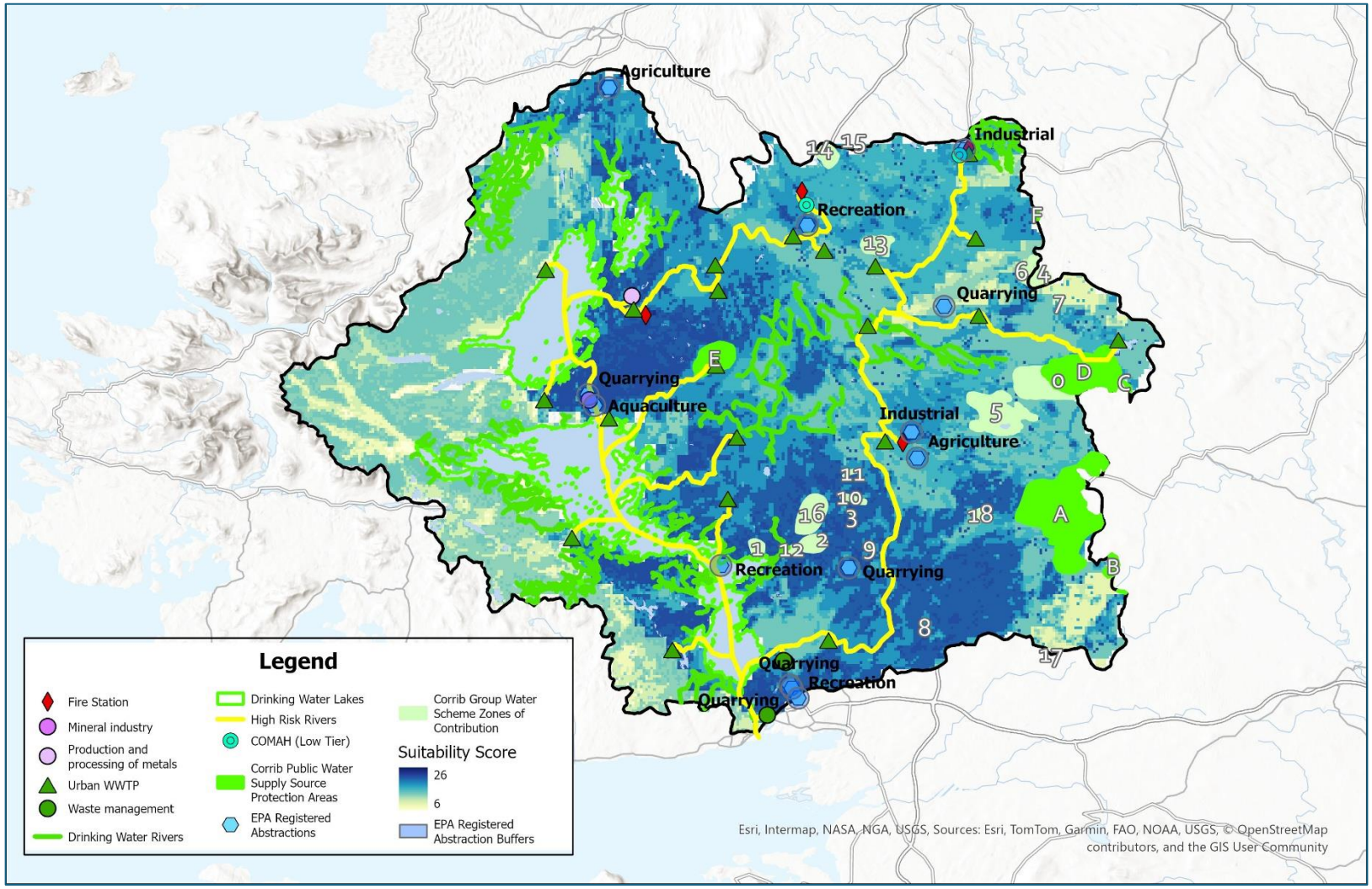


Figure 3- 31 High Risk Rivers and designated drinking water rivers and lakes (EPA Maps [2025], GSI [2025], ArcGIS Online [2025] and HSA [2025])

3.6.2 Vulnerable Human Health Receptors

Table 3- 10 summarises the receptors identified to be used for human consumption, including designated drinking water rivers, lakes, PWSSAs, aquaculture and food production abstraction bores, where they are at risk of being impacted by contamination. The table also identifies the potential PFAS sources that are located upstream from the receptors, having identified valid SPR linkages for each.

Table 3- 10 Vulnerable Human Health Receptors at risk of being impacted by PFAS contamination (EPA Maps [2025], GSI [2025], EPA [2025], HSA [2025] and ArcGIS Online [2025])

Location	Type	Purpose	Potential PFAS point sources
Corrib Upper	Lake	Article 7 Abstraction for Drinking Water	7 x upstream UWWTPs 2 x firefighting stations Production and processing of metals facility Lower tier COMAH site
Corrib Lower	Lake	Article 7 Abstraction for Drinking Water	21 x upstream UWWTPs 4 x firefighting stations 2 x lower tier COMAH sites 2 x waste management sites Production and processing of metals facility Minerals industry facility
CORRIB_020	River	Article 7 Abstraction for Drinking Water Salmonid River	21 x upstream UWWTPs 4 x firefighting stations 2 x lower tier COMAH sites 3 x waste management sites Production and processing of metals facility Minerals industry facility
CORRIB_010	River	Article 7 Abstraction for Drinking Water Salmonid River	1 x upstream UWWTP
CLARE (GALWAY)_020	River	Article 7 Abstraction for Drinking Water	5 x upstream UWWTPs Firefighting station Lower tier COMAH Site
DALGAN_010	River	Article 7 Abstraction for Drinking Water	1 x upstream UWWTP Firefighting station Lower tier COMAH Site
Dunmore Glenamaddy PWS	Groundwater Bore	Public Water Source Protection Area	1 x upstream UWWTP
Kilmaine PWS	Shallow wells and springs	Public Water Source Protection Area	1 x upstream UWWTP
Dawn Meats Ireland Unlimited Company	River abstraction	Commercial Purposes	1 x upstream UWWTP Firefighting station Lower tier COMAH Site
Inland Fisheries Ireland	River abstraction	Aquaculture	7 x upstream UWWTPs 2 x firefighting stations Production and processing of metals facility Lower tier COMAH site

3.6.3 Vulnerable Ecological Receptors

All the above lakes and rivers are also considered to be ecological surface water receptors as they intersect high risk rivers. Additional vulnerable ecological receptors have been included in Table 3- 11 and the associated potential PFAS sources upstream.

Table 3- 11 Vulnerable Ecological Receptors at risk of being impacted by PFAS contamination (EPA Maps [2025], GSI [2025], EPA [2025], HSA [2025] and ArcGIS Online [2025])

Location	Purpose	Potential PFAS sources
Lough Corrib	Special Area of Conservation - 000297 Special Protection Area - 004042	21 x upstream UWWTPs 4 x firefighting stations 2 x lower tier COMAH sites 2 x waste management sites Production and processing of metals facility Minerals industry facility
Lough Carra/Mask Complex	Special Area of Conservation – 001774 Special Protection Area -004062	7 x upstream UWWTPs 2 x firefighting stations Production and processing of metals facility Lower tier COMAH site
Slieve Bog	Natural Heritage Area - 000247	UWWTP
Robe	Ecological surface water receptor	5 x upstream WWTPs 2 x firefighting stations Production and processing of metals facility Lower tier COMAH Site
Rathkelly	Ecological surface water receptor	Firefighting station
Brookhill 30	Ecological surface water receptor	UWWTP
Ballindine	Ecological surface water receptor	UWWTP
Bellfield	Ecological surface water receptor	Firefighting station Lower tier COMAH Site
Cloonfad	Ecological surface water receptor	UWWTP
Carrowlough	Ecological surface water receptor	UWWTP
Glennamaddy	Ecological surface water receptor	UWWTP
Gortgarrow stream	Ecological surface water receptor	UWWTP
Sinking	Ecological surface water receptor	2 x UWWTPs
Clare (Galway)	Ecological surface water receptor	8 x UWWTPs 2 x firefighting stations 2 x waste management sites Lower tier COMAH Site
Nanny (Tuam)	Ecological surface water receptor	Firefighting station
Cloon 30	Ecological surface water receptor	2 x waste management sites

Location	Purpose	Potential PFAS sources
Terryland	Ecological surface water receptor	Waste management site
Ballycuirke Lough Stream	Ecological surface water receptor	UWWTP
Headford Stream 30	Ecological surface water receptor	UWWTP
Owenriff (Corrib)	Ecological surface water receptor	UWWTP
Black (Shrule)	Ecological surface water receptor	UWWTP
Kilmaine 30	Ecological surface water receptor	UWWTP
Cong (Canal)	Ecological surface water receptor	Mining industry
Rusheen_West	Ecological surface water receptor	UWWTP
Glensaul	Ecological surface water receptor	UWWTP

3.7 Risk Assessment Validation

This section summarises the existing surface water, groundwater and sediment data taken from routine EPA WFD testing, INVEST p-FASST sampling and sediment sampling, taken as part of the TERRACHEM EPA Research project[95]. These results can be used to validate the risk maps, where possible.

3.7.1 Surface Water

3.7.1.1 Sampling

In the Lough Corrib catchment, a total of 126 individual samples has been collected and analysed for PFOS, and 118 individual samples were analysed for PFOA by the Environmental Protection Agency (EPA) since 2019, when they started to routinely test rivers and lakes as part of the WFD. The results of these samples were obtained from the Catchments.ie website[181].

As part of the DCU citizen science sampling campaign, three samples were taken in the Lough Corrib catchment and analysed by the University of Birmingham for a total of 37 PFAS compounds, listed in Appendix A.

3.7.1.2 Results

Of the 126 PFOS samples taken, there were detections above the laboratory limit of detection (LOD) for 26 samples, making the average detection frequency 17%. The average concentrations ranged from <0.13ng/L to 0.265ng/L in the catchment, which is below the WFD Environmental Quality Standard (EQS) of 0.65ng/L for PFOS.

Of the 118 individual samples collected and analysed for PFOA in the same locations, there were detections above the laboratory LOD for 63 samples, making the average detection frequency 61%. The average concentrations ranged from <0.13ng/L to 0.64ng/L. There is currently no EQS for PFOA as part of the WFD.

The average concentrations for PFOS and PFOA from the EPA sampling campaigns are shown in Figure 3- 32.

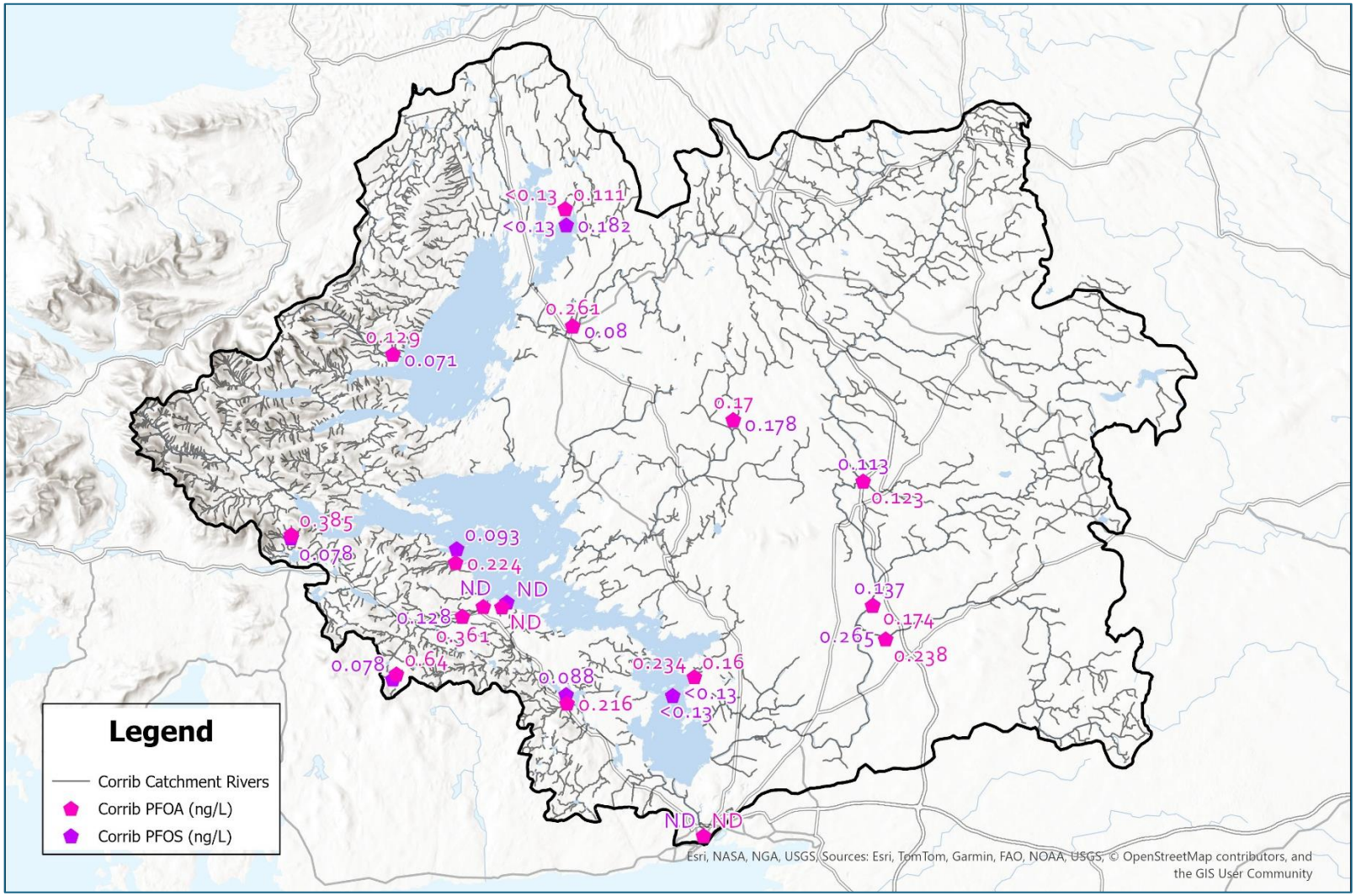


Figure 3- 32 PFOS and PFOA Concentrations in the Lough Corrib Catchment surface water bodies (EPA, 2019-2025)

In all 3 citizen science samples analysed, there were no detections above the laboratory LOD for PFOS or PFOA. However, when the concentrations of all 37 compounds were added together, the concentrations were 0 ng/L (WBS32), 0.034 ng/L (WBS36) and 182.23 ng/L (WBS31). These are shown in Figure 3- 33.



Figure 3- 33 Lough Corrib Citizen Science Sum of 37 PFAS Results

3.7.1.3 Results Analysis

The results were overlayed the surface water risk and potential sources map to determine whether there are any trends and whether the predicted high risk surface water bodies can be validated. This map is shown in Figure 3- 34.

There were 5 linkages between the identified potential PFAS point sources and the analytical results from both the EPA and the citizen science samples, as shown in Table 3- 12. However, there were also 10 results that do not have obvious point sources, as shown in Table 3- 13. As part of the Water Framework Directive, the EPA monitors most waterbodies in Ireland. If a waterbody is at risk of not meeting their WFD objectives by 2027, chemically or physically, the EPA needs to conduct an evidence-based process to identify the significant pressures that may be impacting the waterbody[182]. Each water body with a detection of PFAS above the laboratory LOD was investigated further to determine what the significant pressures may be.

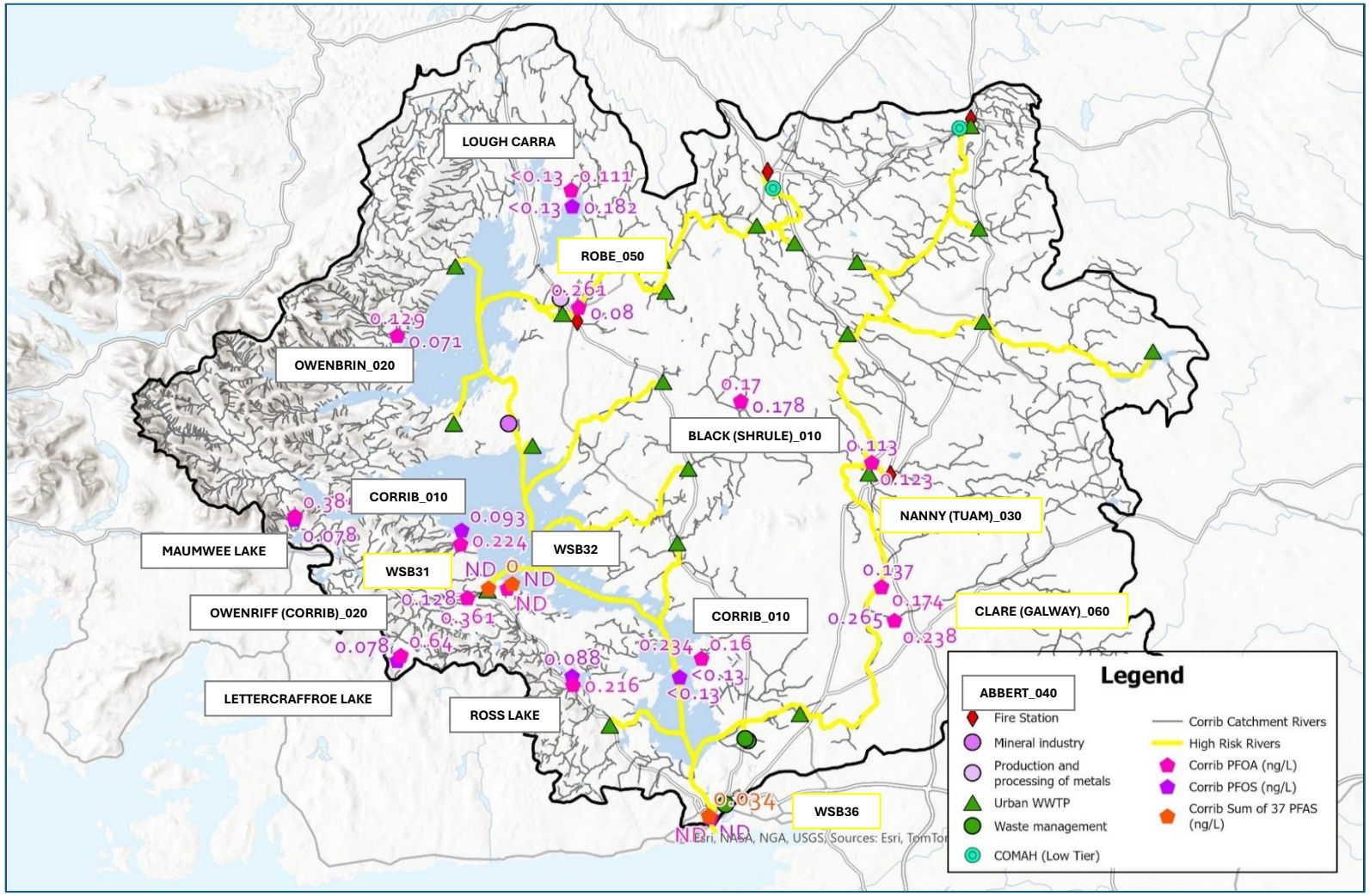


Figure 3- 34 Surface Water Potential PFAS Sources, Pathways and Analytical Results (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

Table 3- 12 Results with potential point sources upstream ((EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

Sample ID	Waterbody	Concentrations (ng/L)			Potential PFAS Point Source/s	WFD Status	WFD Risk	WFD Significant Pressures
		Max	Min	Mean				
ROBE – 30R01-0600, Akit Bridge	ROBE_050	PFOS – 0.24 PFOA – 1.63	PFOS – <0.13 PFOA – <0.13	PFOS – 0.08 PFOA – 0.26	4 x WWTPs Fire station Lower tier COMAH	Moderate	At risk	Urban wastewater Channelisation[183]
NANNY (TUAM) – 30N01-0300, u/s Weir Bridge	NANNY (TUAM)_030	PFOS – 0.28 PFOA – 0.46	PFOS – <0.13 PFOA – <0.13	PFOS – 0.113 PFOA – 0.123	Fire station	Poor	At risk	Channelisation[184]
CLARE (GALWAY) – 30C01-0800, Corrofin Bridge	CLARE (GALWAY)_060	PFOS – 0.62 PFOA – 0.45	PFOS – <0.13 PFOA – <0.13	PFOS – 0.137 PFOA – 0.174	7 x WWTPs 2 x fire stations Lower tier COMAH	Poor	Not at risk	Channelisation[184]
WBS31	OWENRIFF (CORRIB)_020	-	-	Sum of 37 – 182.23	WWTP	Poor	At risk	Nutrients[185]
WBS36	CORRIB_020	-	-	Sum of 37 – 0.034	All Corrib sources	Good	Not at risk	-

Table 3- 13 Results with no identified PFAS point source upstream (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

Sample ID	Waterbody	Concentrations (ng/L)			Potential PFAS Point Source/s	WFD Status	WFD Risk	WFD Significant Pressures
		Max	Min	Mean				
Carra – WE_03_ 347_0060 _Op	Lough Carra	PFOS 0.54 PFOA 0.23	PFOS <0.13 PFOA <0.13	PFOS 0.18 PFOA 0.11	None identified	Good but all surrounding rivers are moderate	Not at risk but all surrounding rivers are	Unknown anthropogenic pressures Agriculture – pastures, , insecticides, septic tanks, sheep dips, grassland herbicides, slurry or chemical fertiliser[186]
OWENBRIN – 03O01-0200, Bridge u/s Lough Mask	OWENBRIN_0 20	PFOS 0.14 PFOA 0.3	PFOS <0.13 PFOA <0.13	PFOS 0.071 PFOA 0.129	None identified	Moderate	At risk	Agriculture, nutrients, overgrazing and forestry[187]
Maumwee Lake – WE_30_343_ 0020_S	Maumwee Lake	PFOS 0.14 PFOA 0.73	PFOS <0.13 PFOA 0.14	PFOS 0.078 PFOA 0.385	None identified	Good	At risk	Land drainage Overgrazing[188]
Corrib Upper Station 10 – WE_30_666b_ 0110_Op	Barnagorteeny Stream/Lough Corrib	PFOS 0.16 PFOA 0.38	PFOS <0.13 PFOA <0.13	PFOS 0.093 PFOA 0.224	None identified	Good	Not at risk	None identified[189]
OWENRIFF (CORRIB) – 30O02-0100, 1km u/s Oughterard Bridge	OWENRIFF (CORRIB)_020	PFOS 0.25 PFOA 0.68	PFOS <0.13 PFOA <0.13	PFOS 0.128 PFOA 0.361	None identified	Poor	At risk	Agriculture Channelisation[190]
Ross GY – WE30_345_ 0100_Op	Ross Lake	PFOS 0.2 PFOA 0.52	PFOS <0.13 PFOA <0.13	PFOS 0.088 PFOA 0.216	None identified	Poor	At risk	Invasive species[190]
Corrib Lower – WE_30_666a_ 0170_S	Annaghdown/ Lough Corrib	PFOS <0.13 PFOA 0.33	PFOS <0.13 PFOA 0.15	PFOS <0.13 PFOA 0.234	None identified	Good	Not at risk	None identified[189]
ABBERT – 30A01-0500, Bridge at Bullaun	ABBERT_040	PFOS 2.37 PFOA 1.49	PFOS <0.13 PFOA <0.13	PFOS 0.265 PFOA 0.238	None identified	Good	Not at risk	Previously – agriculture, septic tanks and domestic wastewater discharge[184]
BLACK (SHRULE) – 30B02-0100, Bridge at Kilshanvy	BLACK (SHRULE)_010	PFOS 1.13 PFOA 1.32	PFOS <0.13 PFOA <0.13	PFOS 0.178 PFOA 0.17	None identified	Poor	At risk	Sediments, nutrients[185]
Lettercraffroe – WE_30_344_ 0020_Op	Lettercraffroe Lake	PFOS 0.14 PFOA 0.78	PFOS <0.13 PFOA 0.45	PFOS 0.078 PFOA 0.64	None identified	Good	In review	Forestry felling[190]

The majority of the 10 positive detections had agriculture, runoff and septic tanks as being the identified significant pressures. The concentrations for the detections with unidentified point sources (highest mean of 0.265ng/L for PFOS and 0.64ng/L for PFOA) are within the same magnitude as those with identified potential point sources (highest mean of 0.137ng/L for PFOS and 0.26ng/L for PFOA). This indicates that diffuse PFAS sources, such as agricultural runoff, biosolids, pesticides and

herbicides are as significant as point sources. Septic tanks may also be an important point source that was not considered in this investigation, due to lack of public data availability on locations.

3.7.2 Groundwater

In 2020, the EPA monitored 197 groundwater wells across Ireland for PFAS and found very low levels. There were no detections above the laboratory limit of detection in the Lough Corrib catchment.

In the absence of groundwater data, it is recommended that Dunmore Glenamaddy PWS and Kilmaine PWS are tested to verify the results Section 3.6. These receptors were identified as being at risk of being impacted by PFAS contamination identified in Table 3- 10 Although not from a human health perspective, the McGraths Limestone Works, Inland Fisheries and Baswal Limited abstractions could also be tested for the purposes of validation.

3.7.3 Sediment

3.7.3.1 Sampling

The Marine Institute collected 120 inland and transitional sediments between 2018 and 2022[95]. Three of these samples were taken within the Corrib Catchment. The samples were analysed for a total of 39 PFAS compounds and the results were supplied to DCU Water Institute by Dr Yulong Ma and Professor Stuart Harrad. The list of these compounds is included in Appendix A.

3.7.3.2 Results

As the samples were taken from the sediments of riverine locations, the results were overlayed the surface water risk and potential point sources map to determine whether there are any trends and whether the predicted high risk surface water bodies can be validated. This map is shown in Figure 3- 35.

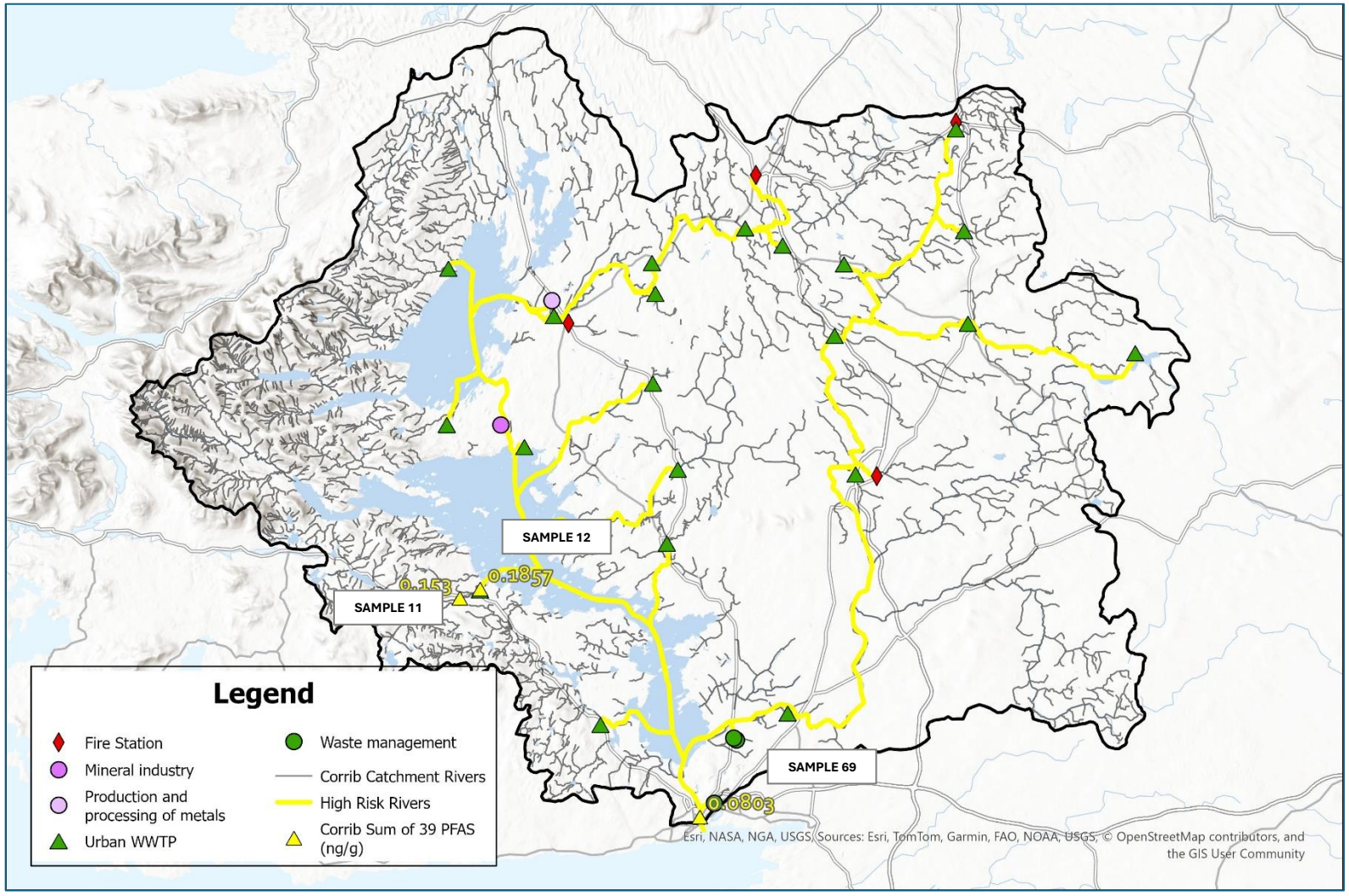


Figure 3- 35 Corrib Sediment Results from Ma et a (2025) (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

3.7.3.3 Results Analysis

For all three samples, there was also an equivalent surface water sample in the same location. It should be noted that these were not taken at the same time so the concentrations and type of PFAS detected may be influenced by different environmental factors, such as the river flow and season[165].

Sediment sample 69 and citizen science surface water sample WBS36 are both located in the Corrib_020 water body, at the drainage point of the catchment, meaning that there is potential for all the identified sources in the catchment to have contributed to the detections. The results are compared in Figure 3- 36. The highest concentration in the sediment sample was PFOA (0.028 ng/g) and the highest was 6:2 diPAP in surface water (0.38ng/L). 6:2 diPAP is a compound used in cosmetics, food packaging and paper processing[15,191–193]. There were detections above the laboratory LOD for PFHpS, PFUdS and 6:2 diPAP in both samples.

Sediment sample 12 and citizen science surface water sample WBS31 are both located in the Owenriff (Corrib)_020 water body, which are both located immediately downstream of the Oughterard WWTP. It is likely that this is the main point source of the PFAS detections. The results are compared in Figure 3- 37. The highest concentration in the sediment sample was PFBA (0.13ng/g) and the highest was 6:2 FTS in surface water (180.29ng/L). 6:2 FTS has been linked to a large number of PFAS sources, including personal care products, as a replacement in AFFFs, the manufacturing of metal products, plastic and rubber and waterproofed textiles[15,194]. The high concentration and wide range of potential sources could indicate that the source of the contamination is from a waste source, such as the WWTP. The 6:2 FTS concentration is elevated when compared to the average municipal WWTP concentration in the US[16]. There were detections above the laboratory LOD for PFBA, PFPeS, PFHpS, PFNA, FOSA, N-MeFOSA, 6:2 FTS, HFPO-DA and PFECHS in both samples. PFOA and PFOS were not detected above the laboratory LOD in the surface water sample, but the elevated concentrations of 6:2 FTS highlight the importance of testing for a larger suite of PFAS compounds.

Sediment sample 11 and EPA sampling location Owenriff (Corrib) are both located approximately 1km upstream of the Oughterard WWTP. While the sediment sample was analysed for all 39 compounds, the EPA sampling location only was analysed for PFOS and PFOA. The results are compared in Figure 3- 38. The highest concentration in the sediment sample was PFBA (0.08ng/g) and the highest was PFOA (0.39ng/L). PFOA was detected above the laboratory LOD in both samples. This location does not have an identified potential point source upstream. It is possible that the source of the contamination at this location is a diffuse source, rather than a point source.

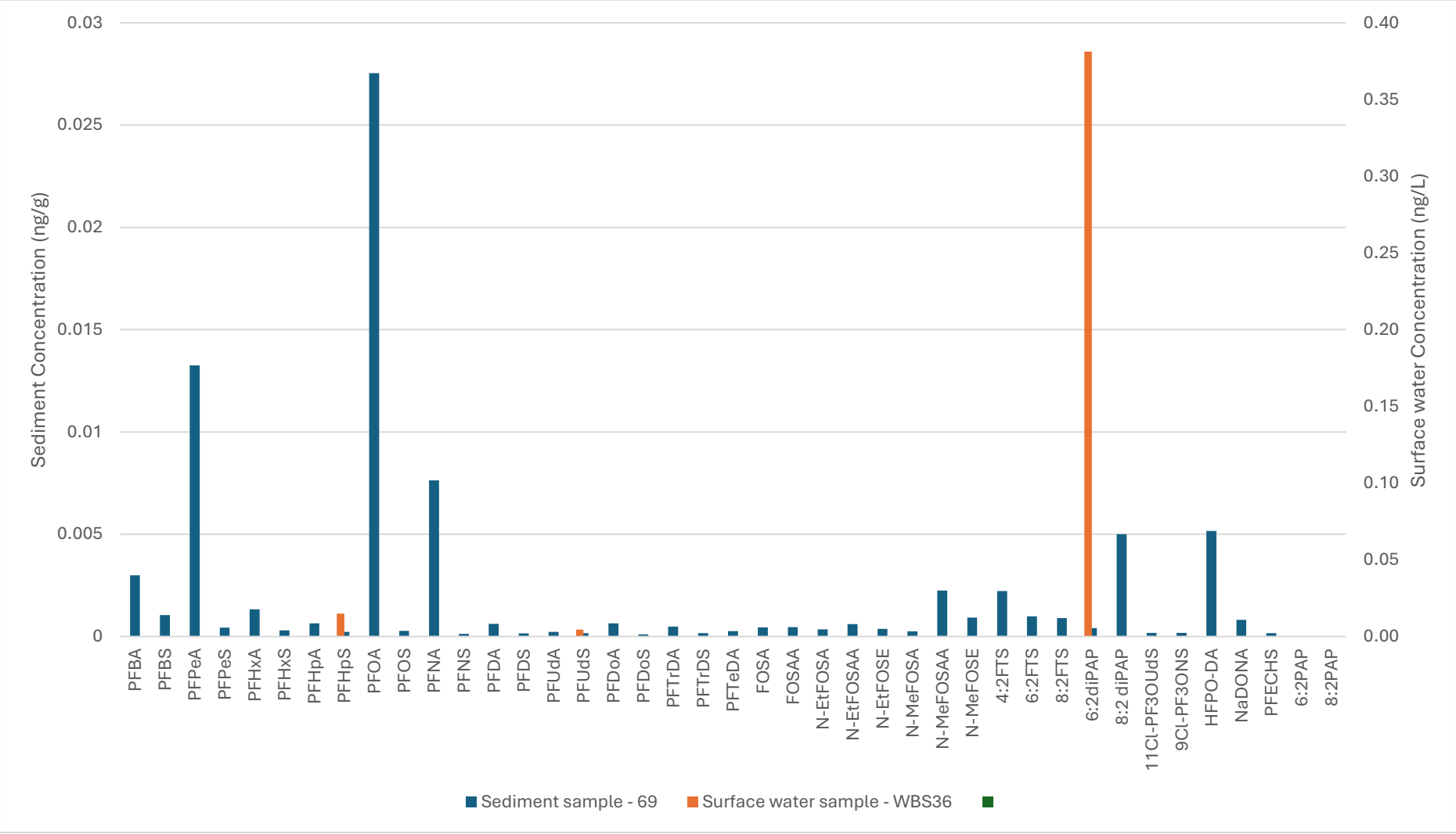


Figure 3- 36 Surface water and sediment comparison (Corrib_020) (Ma., Et al 2025)

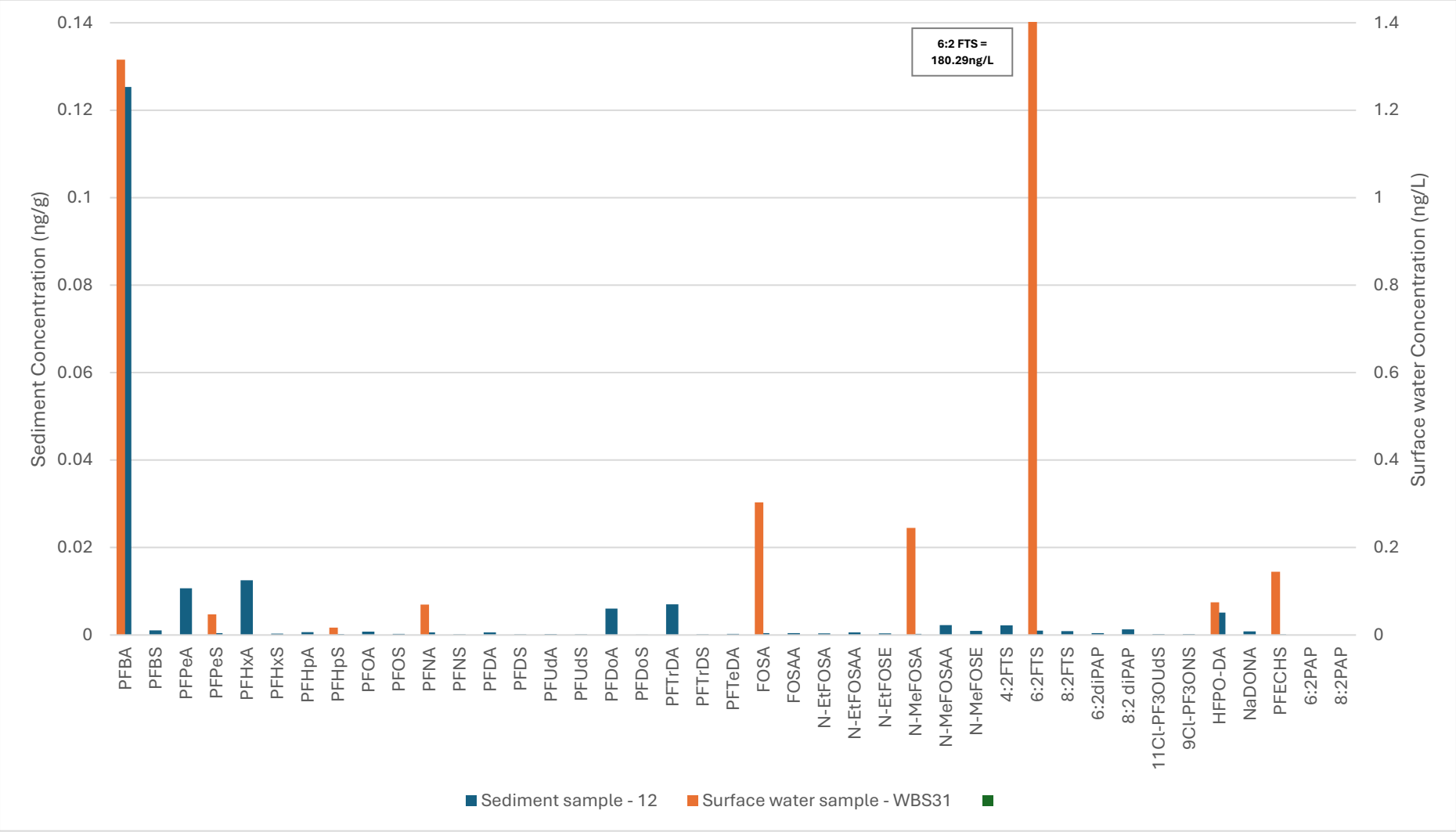


Figure 3- 37 Surface water and sediment comparison (Owenriff [Corrib]_020 – downstream of Oughterard WWTP) (Ma., Et al 2025)

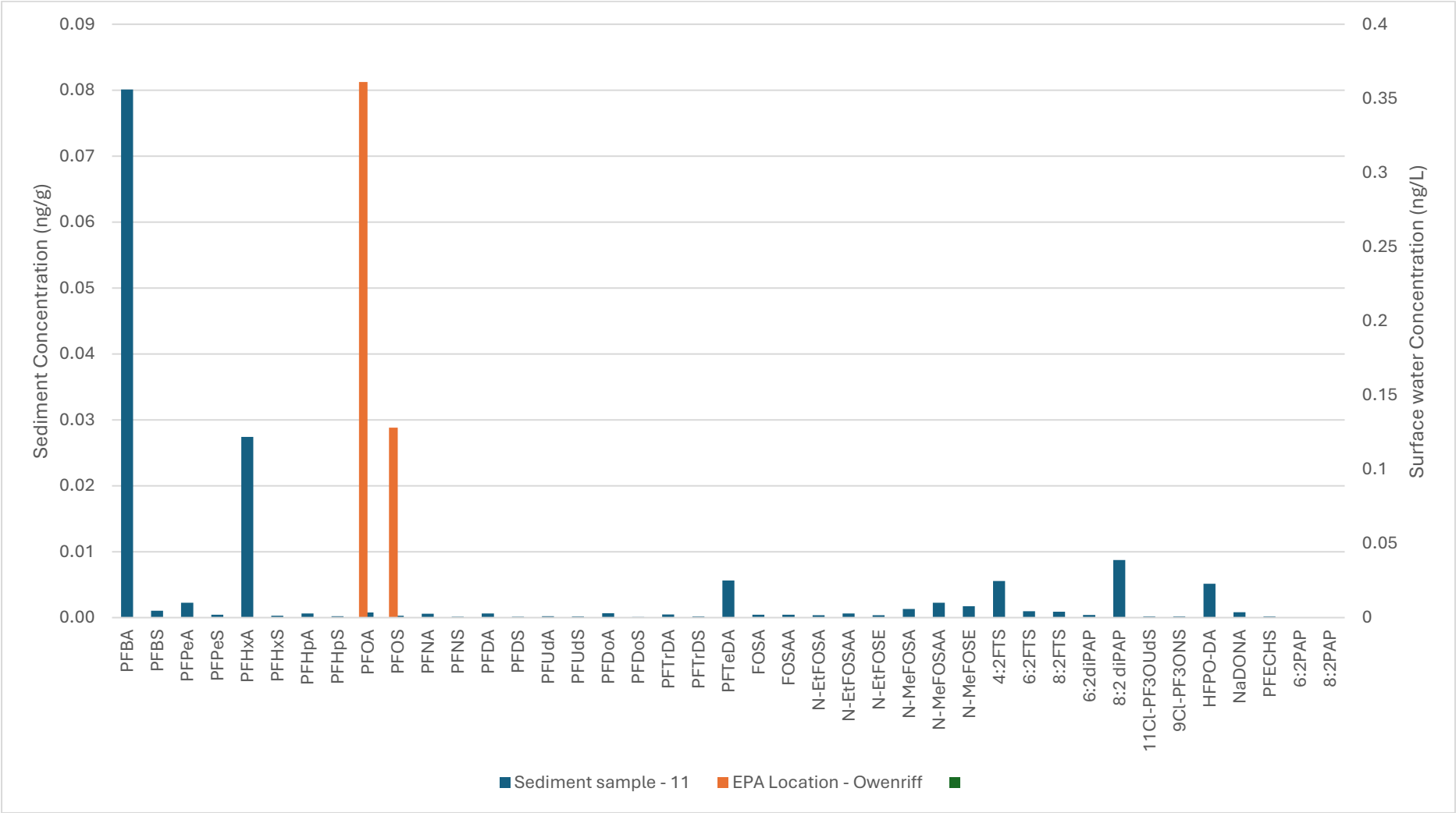


Figure 3- 38 Surface water and sediment comparison (Owenriff [Corrib]_020 - upstream of Oughterard WWTP) (Ma., Et al 2025)

3.7.4 Additional Sampling

In Section 3.6.2, 10 vulnerable human health receptors were identified, with valid SPR linkages. 4 locations have had samples taken and analysed in the same waterbody or downstream. These are identified in Table 3- 14. Each location has been reviewed, and additional sampling has been recommended to further assess the risk that may be posed to the drinking water supplies.

Table 3- 14 Vulnerable Human Health Receptors at risk of being impacted by PFAS contamination, available results and recommended additional sampling (EPA Maps [2025], GSI [2025], EPA [2025], HSA [2025] and ArcGIS Online [2025])

Location	Purpose	Potential PFAS point sources	Available results	Additional sampling
Corrib Upper Lake	Article 7 Abstraction for Drinking Water	7 x upstream UWWTPs 2 x firefighting stations Production and processing of metals facility Lower tier COMAH site	Corrib Upper Station 10 - PFOS and PFOA WBS31 - 37 analytes	Analyse for broader suite of analytes Repeat analysis
Corrib Lower Lake	Article 7 Abstraction for Drinking Water	21 x upstream UWWTPs 4 x firefighting stations 2 x lower tier COMAH sites 2 x waste management sites Production and processing of metals facility Minerals industry facility	Corrib Lower – PFOS and PFOA	Analyse for broader suite of analytes
CORRIB_020 River	Article 7 Abstraction for Drinking Water Salmonid River	21 x upstream UWWTPs 4 x firefighting stations 2 x lower tier COMAH sites 3 x waste management sites Production and processing of metals facility Minerals industry facility	WBS36 - 37 analytes	Repeat analysis
CORRIB_010 River	Article 7 Abstraction for Drinking Water Salmonid River	1 x upstream UWWTP	No analysis	Analyse for broad suite of analytes
CLARE (GALWAY)_020 River	Article 7 Abstraction for Drinking Water	5 x upstream UWWTPs Firefighting station	CLARE (GALWAY) – 30C01-0800, Corrofin	Analyse for broader suite of analytes and

Location	Purpose	Potential PFAS point sources	Available results	Additional sampling
		Lower tier COMAH Site	Bridge – PFOS and PFOA (downstream)	further upstream
DALGAN_010 River	Article 7 Abstraction for Drinking Water	1 x upstream UWWTP Firefighting station Lower tier COMAH Site	No analysis	Analyse for broad suite of analytes
Dunmore Glenamaddy PWS – Groundwater bore	Public Water Source Protection Area	1 x upstream UWWTP	No analysis	Analyse for broad suite of analytes
Kilmaine PWS – Shallow wells and springs	Public Water Source Protection Area	1 x upstream UWWTP	No analysis	Analyse for broad suite of analytes
Dawn Meats Ireland Unlimited Company River	Commercial Purposes	1 x upstream UWWTP Firefighting station Lower tier COMAH Site	No analysis	Analyse for broad suite of analytes
Inland Fisheries Ireland River abstraction	Aquaculture	7 x upstream UWWTPs 2 x firefighting stations Production and processing of metals facility Lower tier COMAH site	No analysis	Analyse for broad suite of analytes

3.8 Conclusions

In this Chapter, the characteristics of PFAS compounds were reviewed to understand the risks that they may pose to the environment and/or human health. This information is important to consider when conducting a site specific or sub-catchment investigations, as identifying the presence of certain PFAS compounds groups or characteristics may assist in refining a potential contamination source.

A risk assessment conceptual framework was developed by identifying and assessing the potential sources of contamination at a site, the migration pathways and the receptors the contamination could impact upon. Risk scores and predominant environmental pathways were allocated to the potential PFAS sources identified in Chapter 2. Sensitive receptors for human and ecological health in Ireland were also identified before all the national data was compiled and stored in a Microsoft Excel and GIS database.

A catchment-wide investigation for the Lough Corrib catchment was conducted to develop a methodology for a multi-criteria risk-based tool, before eventually being upscaled to a nation-wide investigation. Two risk maps were created to assess the major potential SPR linkages in the catchment. A surface water risk map was developed using the 'Trace Downstream' tool. The output of this tool is a multi-line map that highlights surface water bodies that are at 'high risk' of PFAS contamination from upstream point sources. The groundwater risk map was developed using the 'Suitability Modeller' to spatially indicate areas that are more susceptible to PFAS contamination. Groundwater vulnerability, aquifer classification and risk scores for potential PFAS sources were overlayed and weighted equally. Sensitive receptors, such as drinking water rivers and food production abstractions, were identified and overlayed to investigate the possibility of being impacted by PFAS contamination.

The maps were interrogated visually and statistically using average suitability scores to identify where high-risk river pathways and high-risk hydrogeological areas intersect with sensitive receptors. It was determined that 8 surface and ground

drinking water abstractions in the Lough Corrib Catchment were at risk of being impacted by PFAS contamination. 2 abstractions used for food production were also identified as being high risk. Lough Corrib and Lough Carra, which are SACs and SPAs and the Slieve Bog, which is a NHA, are also at risk of contamination.

This work lead to the investigation of the severity and likelihood of contamination, looking at the highest risk scenarios and identify locations where monitoring has taken place in this catchment and where additional monitoring may be required.

The final purpose of this Chapter was to compare in-field data with the predicted results in the Lough Corrib Catchment to validate and refine the assessment approach. A total of 126 and 118 surface water samples has been analysed for PFOS and PFOA in the catchment, respectively. 3 citizen science samples were also collected. In alignment with the rest of the country, the average detection rate of PFOS in the catchment is 17%, compared to 61% for PFOA. In the citizen science samples, there were no detections of PFOS or PFOA, however in WBS31, the $\sum_{37}$ PFAS concentration was 182.23ng/L. WBS31 is directly located downstream of a WWTP, and the elevated concentration emphasises the importance of testing for a broader suite of PFAS compounds. After the results were overlayed on the surface water risk maps, 5 potential SPR linkages to point source of PFAS were made, mainly to WWTPs. However, there were also 10 locations where there were no obvious point sources. Following a review of the WFD significant pressures, it was found that many of these water bodies were impacted by agriculture, runoff and septic tanks. As the concentrations with unidentified point sources were within the same magnitude as those with potential point sources, it was determined that diffuse sources were just as significant as point sources in the Lough Corrib Catchment. In future revisions of the risk assessment methodology, it is recommended that diffuse sources are included. Additional samples were recommended to refine the results in the Lough Corrib Catchment.

Chapter 4 – The Occurrence of PFAS in the Irish Environment

4.1 Introduction

This Chapter combines publicly available PFAS monitoring data and newly acquired results from this project to evaluate the presence and distribution of PFAS contamination across Ireland. Drawing on datasets from the Water Framework Directive (WFD) and groundwater and surface water samples taken as part of the INVEST p-FASST project, this Chapter provides a consolidated view of the occurrence of PFAS in the Irish surface water and groundwater. The sample locations were informed by Chapter 1 and 2 of this thesis to investigate potential sources of PFAS in the Irish environment.

The outcomes of this analysis inform a set of targeted recommendations for future monitoring and help refine the understanding of major PFAS sources in Ireland.

4.1.1 Aim

The aim of this chapter is to critically assess the existing PFAS monitoring data in Ireland from publicly available sources, including the WFD datasets and new data generated by this project. It also aims to evaluate how well these datasets align with the spatial risk assessment developed in Chapter 3, using the Lough Corrib Catchment as a case study to validate the model and guide recommendation for future monitoring and management.

4.1.2 Objectives

The objectives of this Chapter are to:

- Summarise existing PFAS monitoring data for Ireland;
- Identify spatial and chemical data gaps in the current monitoring coverage;
- Summarise and review the monitoring data obtained as part of the INVEST p-FASST project;
- Highlight potential linkages between elevated PFAS concentrations and potential point sources determined in Chapter 2;
- Propose enhancements to Ireland's PFAS monitoring strategy based on evidence.

4.2 Water Framework Directive Results

4.2.1 Surface Water

As part of the European Union (EU) Water Framework Directive (WFD), a range of different elements are monitored to assess the status of both surface and groundwater bodies[195]. A range of elements contribute to the status of surface water, including biological quality, physio-chemical quality, hydromorphological quality and the presence of priority substances, priority hazardous substances and river basin specific pollutants. PFOS was flagged as a priority substance to be monitored in rivers, lakes, transitional and coastal waters in water, sediment and biota in the national WFD monitoring program. PFOA was also added to the suite by the EPA and the testing in surface water bodies commenced in 2019. Over 2000 samples have been taken and analysed for PFOS and PFOA. The results were downloaded from Catchments.ie[181], summarised and analysed in a nation-wide Excel spreadsheet. Most samples have been taken in Mayo, Clare and Donegal. A summary of the number of samples taken per county is shown in Figure 4 - 1.

As the number of samples taken per county may be impacted by the size of the county and the number of monitoring stations, the detection rate was calculated as a standardised indicator of PFOS and PFOA contamination in each county. The detection rate is the rate at which contaminants are measured above the laboratory limit of detection (LOD). These results are presented in Figure 4 - 2. Louth has a 100% detection rate for PFOA, as only one sample was taken. However, 20 samples were taken and 100% of them had PFOA detected above the laboratory LOD. In every county, PFOA was detected at a higher rate than PFOS, apart from Waterford and Wexford, where PFOS and PFOA were detected at the same rate. This could be attributed to the global restriction of PFOS and its derivatives in 2009 under the Stockholm Convention[196]. PFOA is only currently being phased out under the EU Persistent Organic Pollutants (POPs) Regulation[5]. These observations were also made in a UK freshwater catchment where PFOA concentrations were higher than PFOS by several ng/L[165]. Earnshaw et al (2014) also note that the phase-out of the production and uses of PFOS indicate that the emissions in Europe are primary from consumer use and wastes.

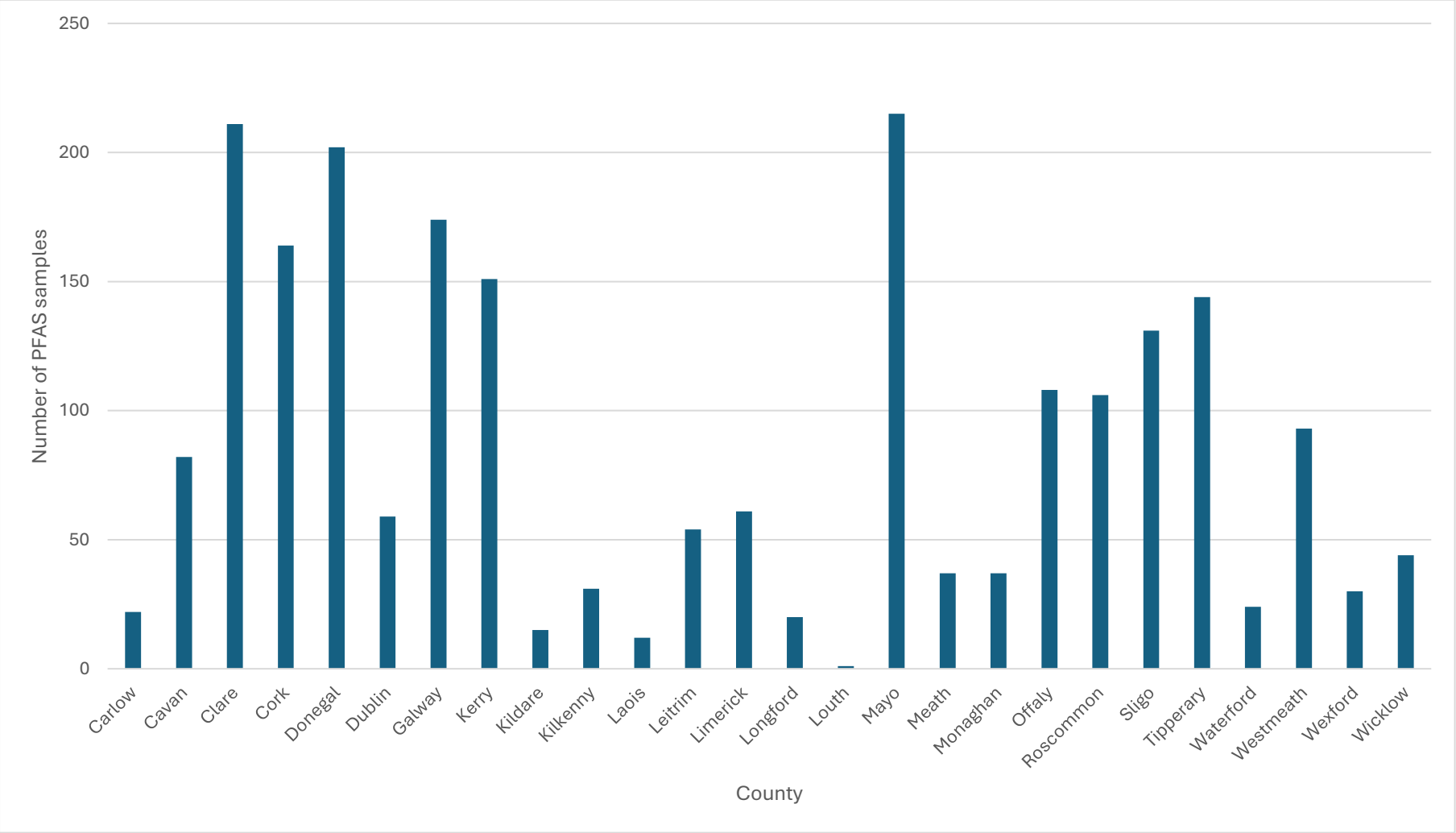


Figure 4 - 1 Number of PFAS Samples taken in each Republic of Ireland county (EPA, 2019 - 2025)

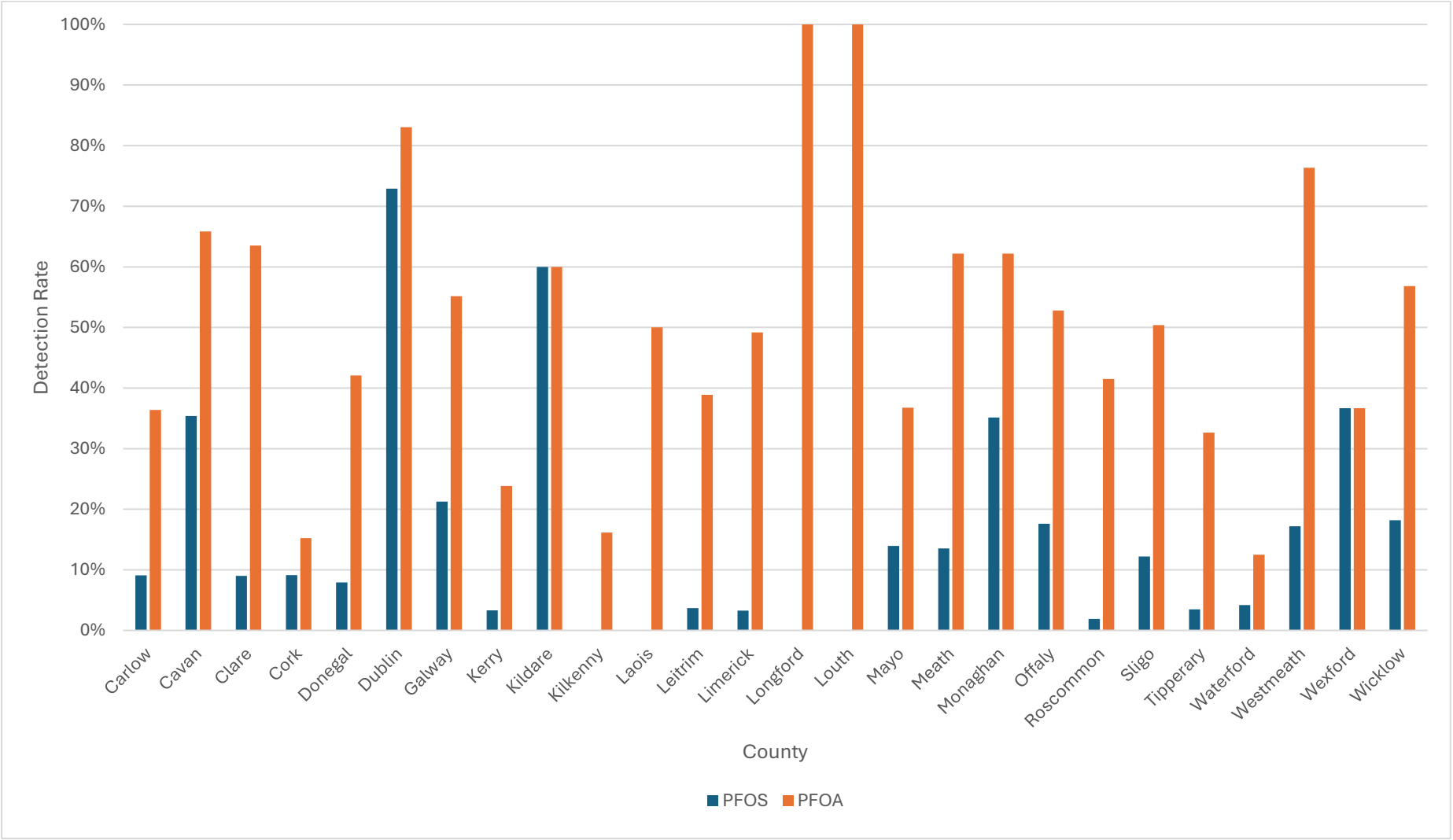


Figure 4 - 2 Detection rate of PFOS and PFOA in surface water samples in each Republic of Ireland county (EPA,2019 - 2025)

The results for each county were compiled to find the maximum, minimum and mean concentrations for both PFOS and PFOA. The maximum PFOS concentration was 51.7ng/L, detected in the Two Pot River in Cork, immediately downstream of the Cork Airport and the maximum PFOA concentration was 49ng/L in the Brosna River in Westmeath. Upstream of this monitoring point is the Mullingar Urban Wastewater Treatment Plant (WWTP) and a hazardous waste management facility. These could be potential sources for the high concentrations of PFOA at this location. The WFD review of the Brosna River also indicates that urban run-off is a significant pressure on the waterbody.

The mean concentrations in each county for PFOS and PFOA are shown in Figure 4 - 3 and Figure 4 - 4, respectively. The counties with the highest average PFOS concentrations are Dublin (1.99ng/L) and Cork (1.7ng/L), which is due to the high number of potential PFAS point sources. The national average for PFOS concentrations in the surface waters tested is 0.38 ng/L, with a detection rate of 14%. The counties with the highest average PFOA concentrations are Westmeath, Dublin and Offaly. Due to the consistently high concentrations of PFOA observed at the Butler's Bridge monitoring location, the average results at Westmeath may be skewed. However, there are still many potential PFAS sources in these three counties. The national average for PFOA concentrations in the surface waters tested is 0.65 ng/L, with a detection rate of 46%.

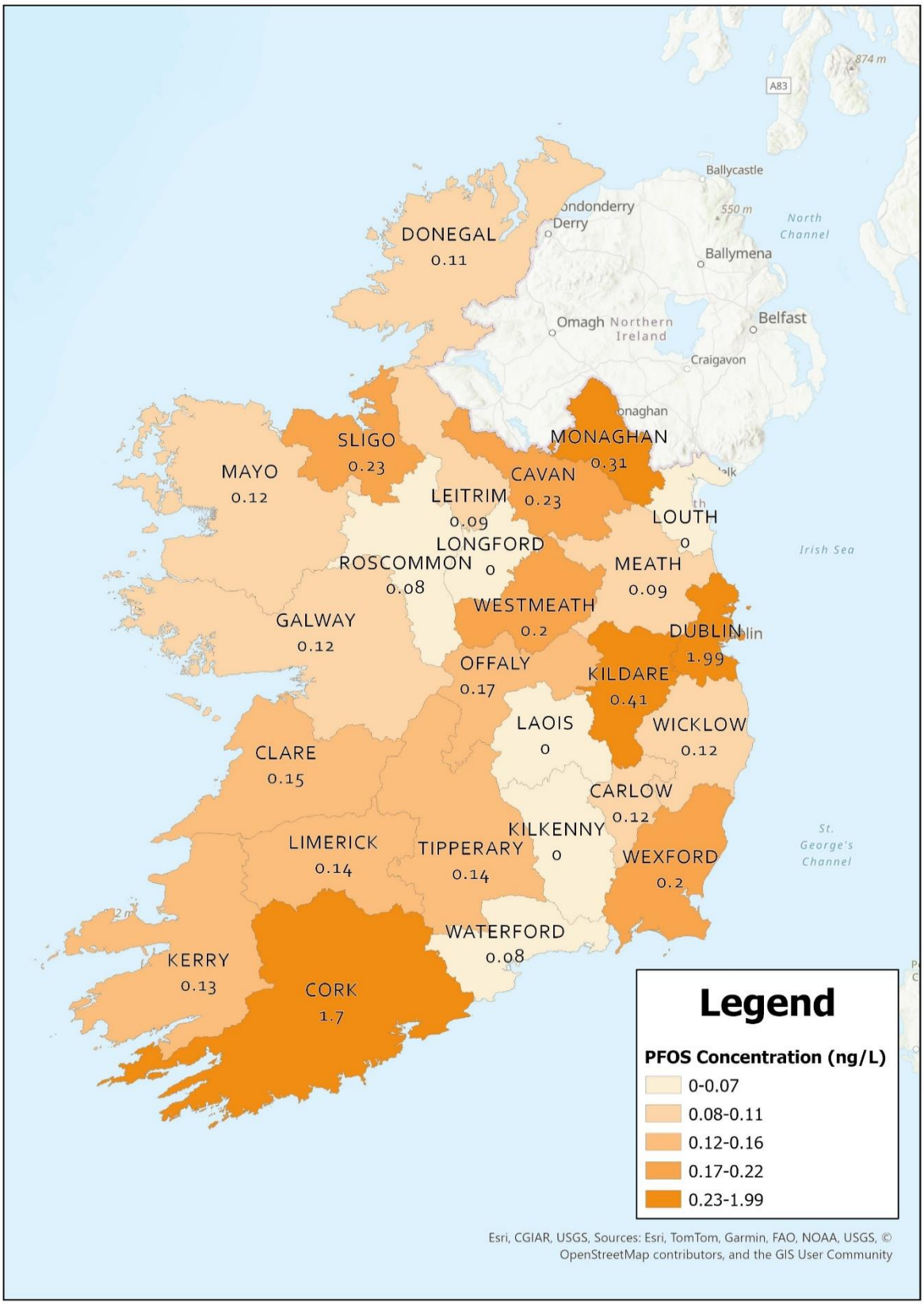


Figure 4 - 3 Mean PFOS surface water concentrations for each Republic of Ireland county (EPA, 2025)

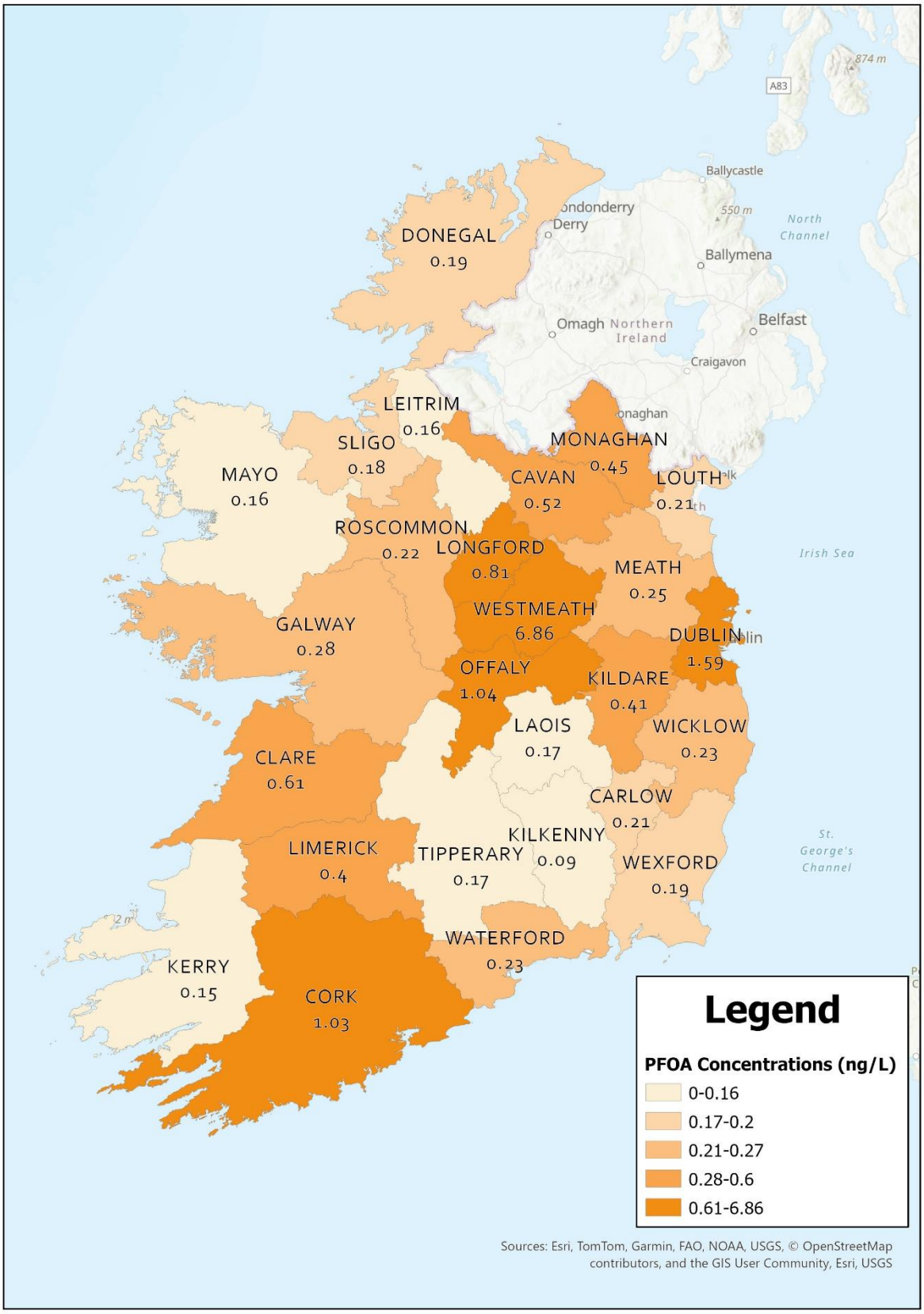


Figure 4 - 4 Mean PFOA surface water concentrations for each Republic of Ireland county (EPA, 2025)

As part of an additional monitoring campaign, the EPA monitored 16 sites for 48 PFAS compounds in 2024 and 2025. The 48 PFAS that were analysed are included in Appendix A. These sites were in Dublin, Mayo, Westmeath, Clare, Carlow and Cork and were predominantly selected based on their historical PFOS and PFOA results. The results were downloaded from Catchments.ie[181], compiled and compared to potential sources and historical results. Some sites have since been resampled for the 20 compounds identified in the Drinking Water Directive. The results from the first sampling round are presented in Figure 4 - 5.

The two rivers with the highest reported concentrations (Two Pot and Sluice) are directly located beside Cork and Dublin Airports, respectively. The results from the 2024 and 2025 sampling campaign with extended suites were compared and the results are presented in Figure 4 - 6. PFOS, PFPeS, PFNA, PFOA, PFHpA, PFHxA and PFPeA were detected in all 4 samples and could be an indicator PFAS fingerprint of Irish airports. PFecHS was also detected (7.55ng/L) in the Sluice River in 2024. PFecHS is used as a hydraulic fluid additive to prevent corrosion, especially in aircraft systems[68].

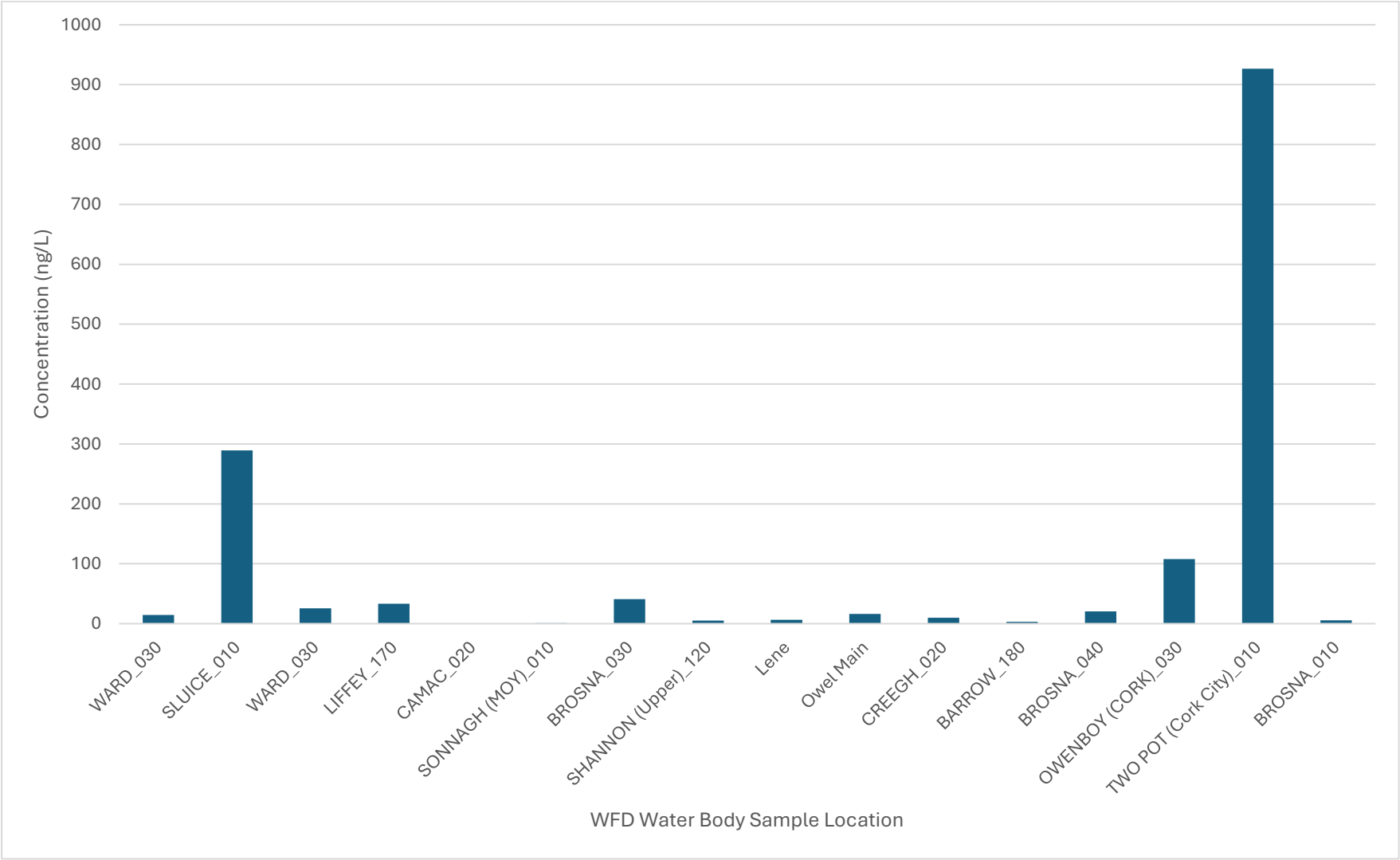


Figure 4 - 5 Sum of 48 PFAS Compounds Concentrations (ng/L) (EPA, 2024 and 2025)

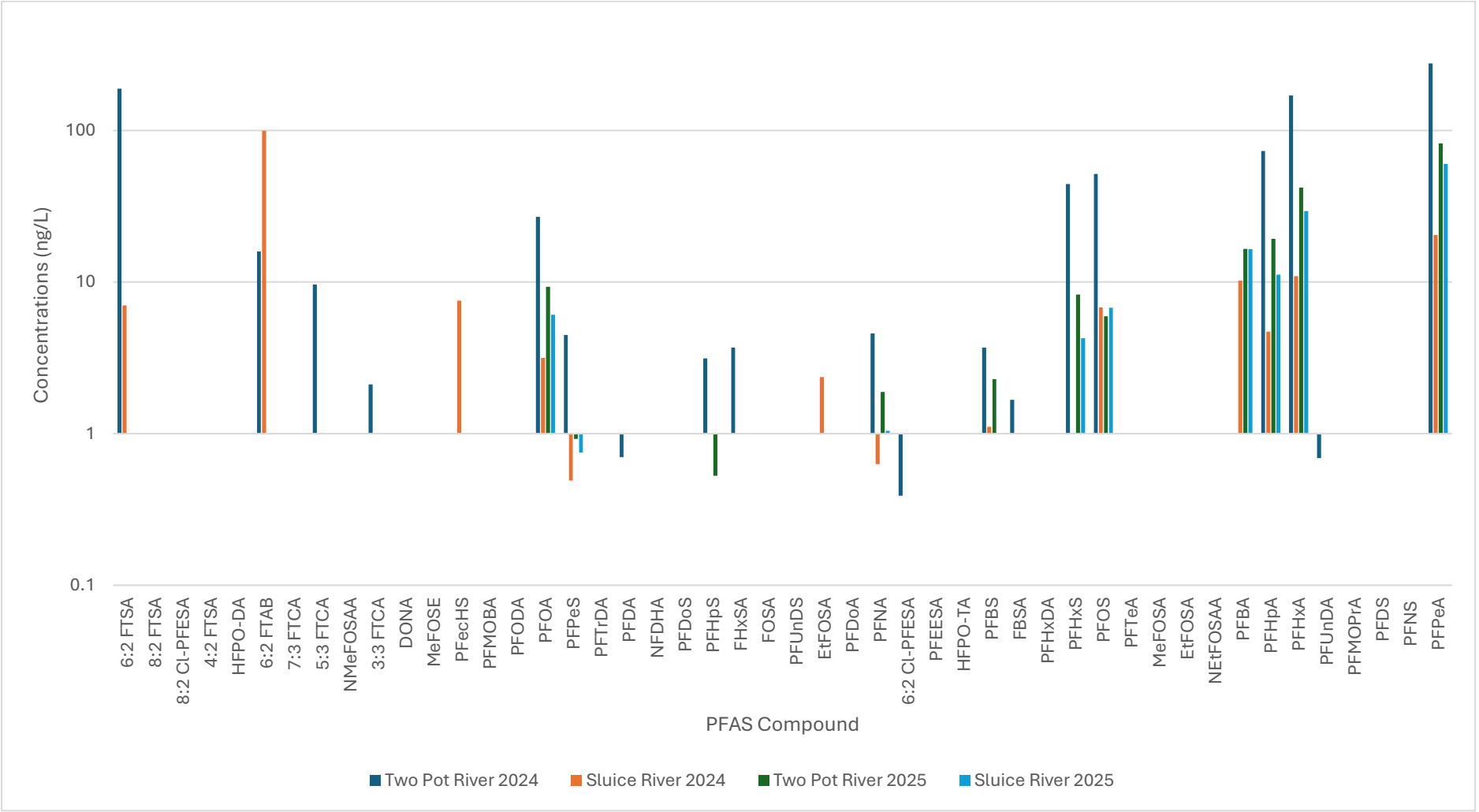


Figure 4 - 6 Concentrations of Two Pot River and Sluice River (EPA, 2025)

4.2.2 Groundwater

As part of Ireland's National Water Quality Program[195], chemical quality is tested in groundwater for a standard suite three times a year. These analytes include pH, temperature, dissolved oxygen and heavy metals. The EU identified a watch list for groundwater parameters as part of a voluntary programme, which was completed in Ireland in 2020. The watch list includes pesticides, organic compounds and 12 PFAS compounds (including PFOS and PFOA). It is currently proposed that this additional suite is to be tested every 6 years. The results were provided by the EPA.

Out of a total of 197 samples that were taken, there were 2 samples that had compounds detected above the laboratory LOD. It is to be noted that the LOD was 10 ng/L, which is higher than many concentrations in the surface water results. As such, where no PFAS was detected doesn't necessarily mean that there is no contamination present. PFPA, PFHxS and PFOS were detected at the Curragh Military Base in Kildare ($\sum_{12}$ = 36.1ng/L). The likely source of this contamination is the use of AFFFs for training purposes[80,197]. PFBA was detected at Kerry Foods Manufacturing in Wicklow ($\sum_{12}$ = 85 ng/L). It is unknown what the source of contamination is at this location.

4.3 INVEST p-FASST Sampling

4.3.1 Surface Water

4.3.1.1 Sampling

As part of the INVEST p-FASST project, a minimum of 10 surface water samples were proposed to be sampled. Chapters 1 and 2 were used to inform the locations of samples across Ireland. A total of 11 surface water sample sites were selected based on a variety of potential sources, including downstream of a chemical manufacturing plant, a military base, airports and an oil refinery. Other samples were selected based on elevated PFOS and PFOA concentrations in the WFD EPA results. As part of the project, a sampling protocol was developed and followed when taking the samples. The protocol involves a comprehensive quality assurance and quality control (QA/QC) plan, including taking field and equipment blanks, to ensure the reliability and validity of results. The samples were prepared for analysis by Dublin City University (DCU) using solid phase extraction (SPE) and sent for the analysis of 37 PFAS compounds by the University of Birmingham (UOB) using Liquid Chromatography/Mass Spectrometry (LC/MS). The list of 37 compounds is included in Appendix A.

As part of a DCU Water Institute sampling campaign for the Permatox project[2], a citizen science campaign was undertaken to gather surface water samples across Ireland. 10 samples were selected to be analysed for the 37 PFAS compounds listed in Appendix A by the UOB. The sites were selected to get a broader spatial spread of results. While the samples were not collected with PFAS protocols in place, field blanks were taken. These blanks picked up any cross-contamination that may have taken place during sampling. The results of the blanks were then subtracted from the total concentrations that were detected. These samples were extracted and analysed using the same methodologies as the INVEST p-FASST samples.

[2] The Permotox project is a current DCU Water Institute project to determine the impact, sources, and quantity of PMTs and vPvMs on water quality in Ireland (https://dcuwater.ie/projects/permotox/)

At the time of writing this thesis, 4 surface water samples and all 10 citizen science samples were analysed. The locations are shown in Figure 4 - 7 and the results are presented in Section 4.1.2.



Figure 4 - 7 Surface water sampling locations (INVEST p-FASST and Permatox, 2024 – 2025)

4.3.1.2 Results

For the surface water samples taken, apart from WBS11, all were found to have at least one PFAS compound detected above the laboratory limit of detection (LOD). The LODs for each compound ranged from 0.0025ng/L (PFUdS) to 0.105ng/L (PFBA). The highest total PFAS concentration was in SW10 ($\sum_{37}$ 1044.97ng/L), which is a river downstream of an oil refinery where PFOA-containing AFFFs are stored, based on the POPs regulation. The concentrations for all the compound groups are shown in Figure 4 - 8. The most frequently detected compound was N-MeFOSA (a precursor), which was detected in 11 samples. The occurrences of each compound in the 14 surface water samples are shown in Figure 4 - 9.

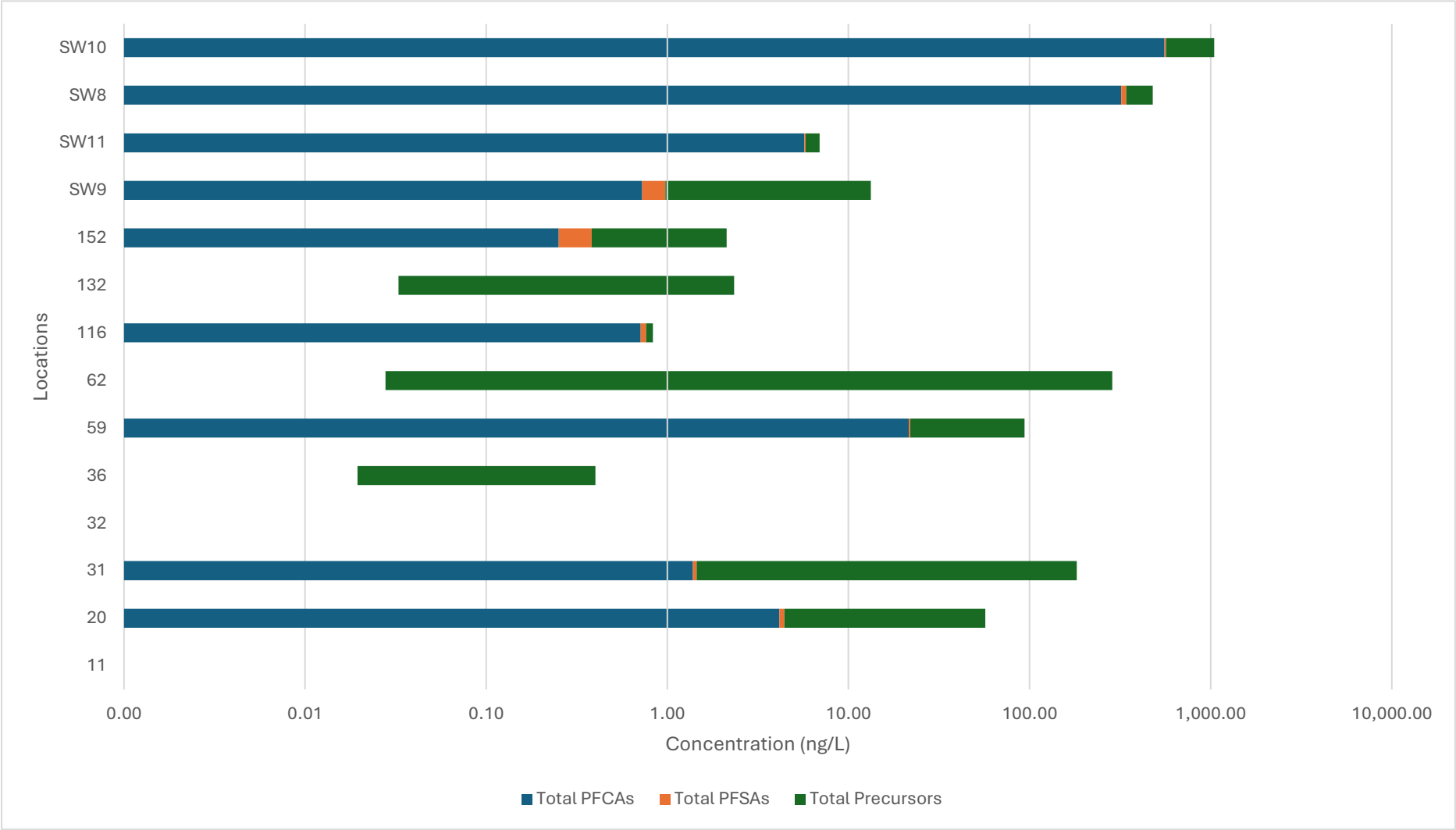


Figure 4 - 8 Surface Water Samples Results (INVEST p-FASST and Permatox, 2024 – 2025)

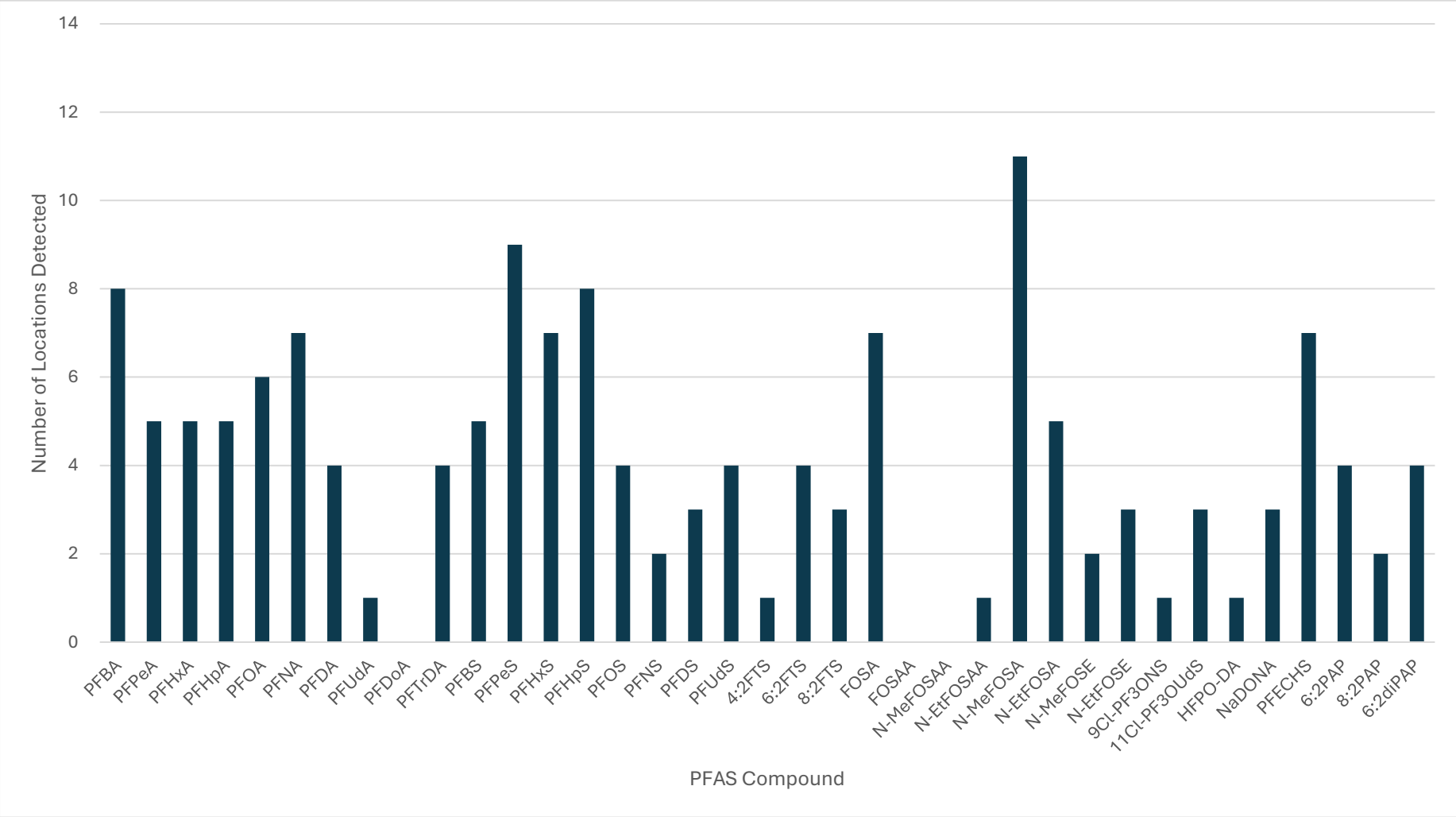


Figure 4 - 9 Occurrence of PFAS compounds at 14 sample sites (INVEST p-FASST and Permatox, 2024 – 2025)

4.3.1.3 Results Analysis

The results were overlayed the potential PFAS sources map to determine whether there were any valid SPR linkages and trends between the results. Due to the large number of potential PFAS point sources, an example of this map is shown for Cork City in Figure 4 - 10. The yellow lines indicate 'high risk' rivers as classified by the risk map methodology outlined in Chapter 3. There are strong potential linkages between the oil refinery and SW10 and Cork Airport and SW8.

There were 7 linkages between the identified potential PFAS point sources and the analytical results from both the citizen science samples and INVEST p-FASST surface water samples, as shown in Table 4 - 1. However, there were also results that didn't have obvious point sources (WBS32, WBS36, WBS62, WBS116, WBS132 and WBS152). However, most of these results were at smaller concentrations than those with potential point sources identified. The citizen science sample with the highest concentration was WBS62. There is no obvious point source or pathway in the close vicinity of the sample, however the water body is surrounded by farmland. It is possible that land spreading practices or herbicide/pesticide use could have contributed to the contamination, however further site-specific investigations would be required to determine the source.

Table 4 - 1 Citizen Science Sample Results, potential PFAS point sources and WFD significant pressures (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025]))

Sample ID	Waterbody	Concentrations ($\sum_{37}$ ng/L)	Potential PFAS Point Sources	WFD Significant Pressures
WBS11	Lough Derravaragh, Westmeath	0	-	-
WBS20	Glyde_060, Louth	57.02	Upstream WWTP	Urban WWTP[198]
WBS31	Owenriff (Corrib)_020, Galway	182.5	Upstream WWTP	Urban WWTP[175]
WBS32	Lough Corrib, Galway	0.003	-	-
WBS36	Corrib_020, Galway	0.4	Urban runoff	Unknown
WBS59	Mayne_010, Dublin	93.82	Airport (AFFFs)	Unknown[199]
WBS62	Glyde_020, Monaghan	286.04	Agricultural runoff (no identified point sources in proximity)	Unknown
WBS116	Ballinacurra, Cork	0.83	Unknown	Unknown
WBS132	Liffey_080, Newbridge	2.33	Urban runoff	Unknown
WBS152	Barrow_160, Carlow	2.12	Urban runoff	Unknown
SW8	Two Pot Creek	479.19	Airport (AFFFs)	Moderate/at risk Anthropogenic pressures[200]
SW9	Ringaskiddy/Cork Harbour	13.3	Pharmaceuticals manufacturing	Moderate/at risk Anthropogenic pressures[201]
SW10	White Bay Beach/Cork Harbour	1044.97	Oil refinery (AFFFs)	No risk identified
SW11	Little Island/Lough Mahon	6.93	Chemical manufacturing facilities	Moderate/at risk Urban wastewater[200]

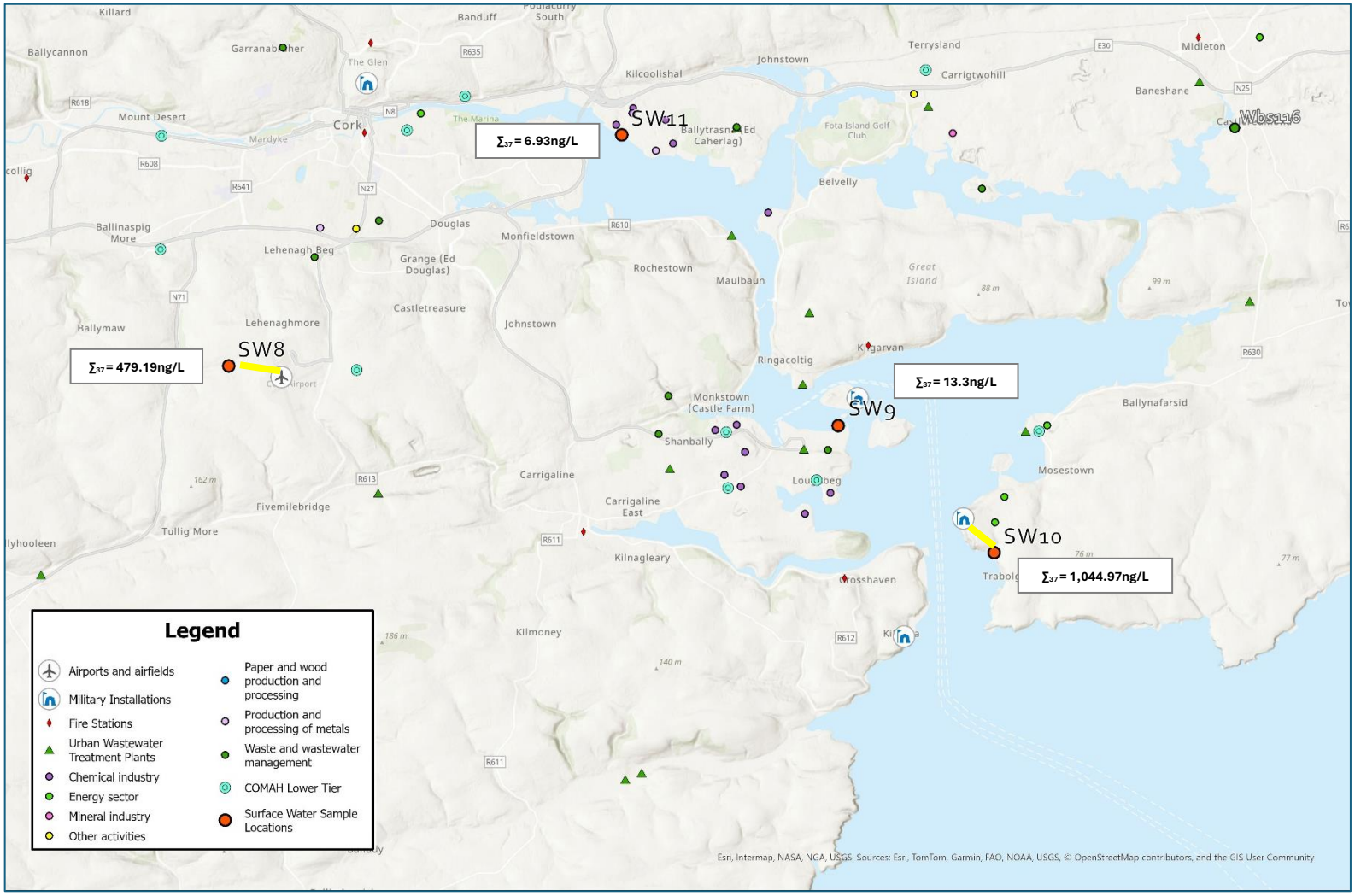


Figure 4 - 10 Surface water samples and potential point sources in Cork City. (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

4.3.2 Groundwater

4.3.2.1 Sampling

Project industrial partner, Arup, conduct quarterly groundwater monitoring of a well network owned by Uisce Éireann. The wells were installed as part of the Lead in Drinking Water Mitigation Plans in Dublin, Galway and Limerick Cities. The objectives of the monitoring programme are to establish baseline conditions of groundwater quality prior to and monitor during the commencement of orthophosphate treatment. A total of 13 groundwater wells were sampled across the three city networks. The wells were selected based on well screen depth, groundwater vulnerability and proximity to potential sources. The samples were taken following the decontamination of the pump between each sample location and purging of the well. All appropriate field blanks and equipment blanks were taken, and the results were subtracted from the concentrations detected.

The locations of sampled wells are shown in Figure 4 - 11 and are overlayed the GSI groundwater vulnerability[169] map in Dublin, Limerick and Galway in Figure 4 - 12, Figure 4 - 13 and Figure 4 - 14, respectively. The details of the well installations and groundwater vulnerability is shown in Table 4 - 2.

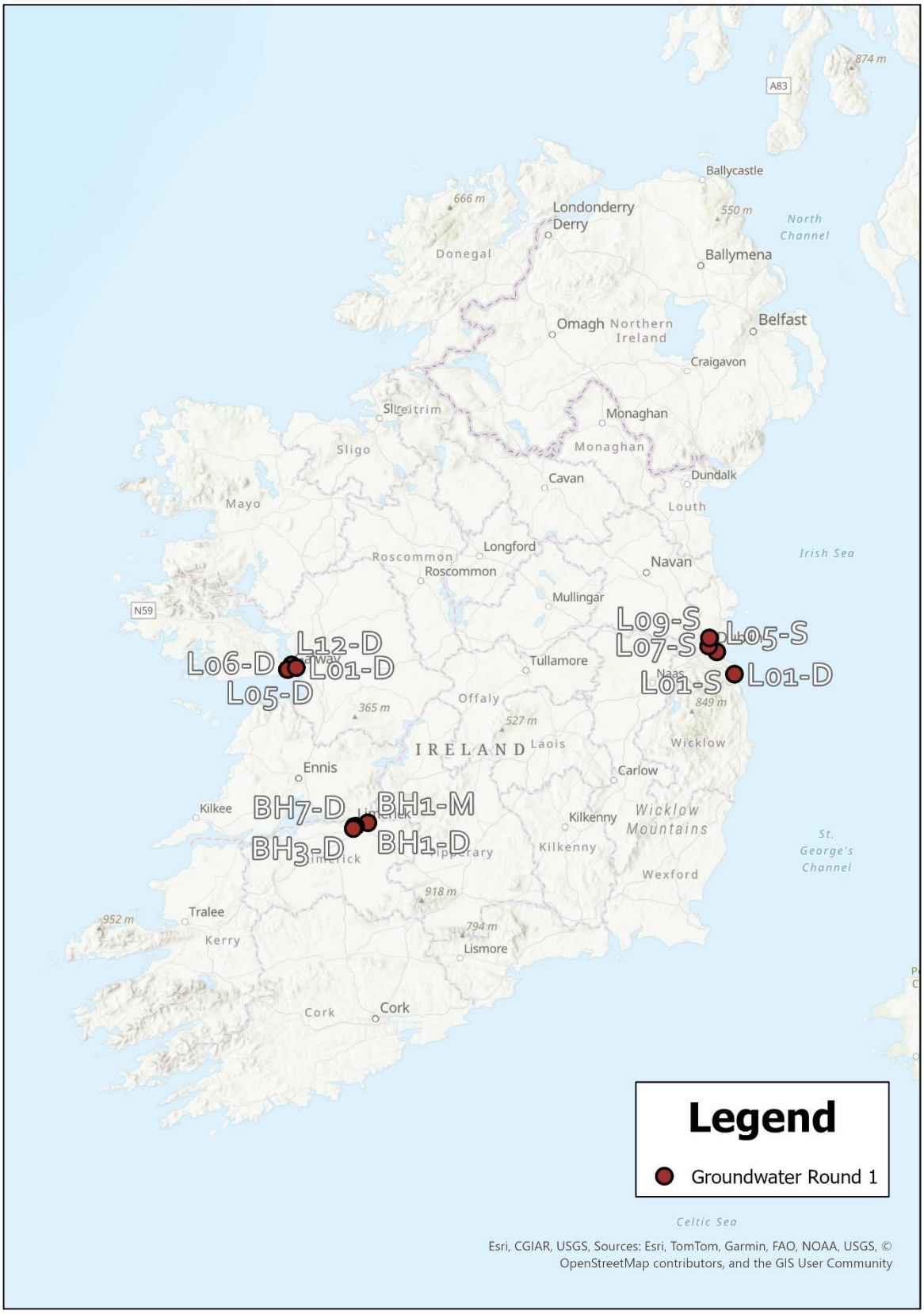


Figure 4 - 11 Groundwater Sample Locations (Arup, 2025)

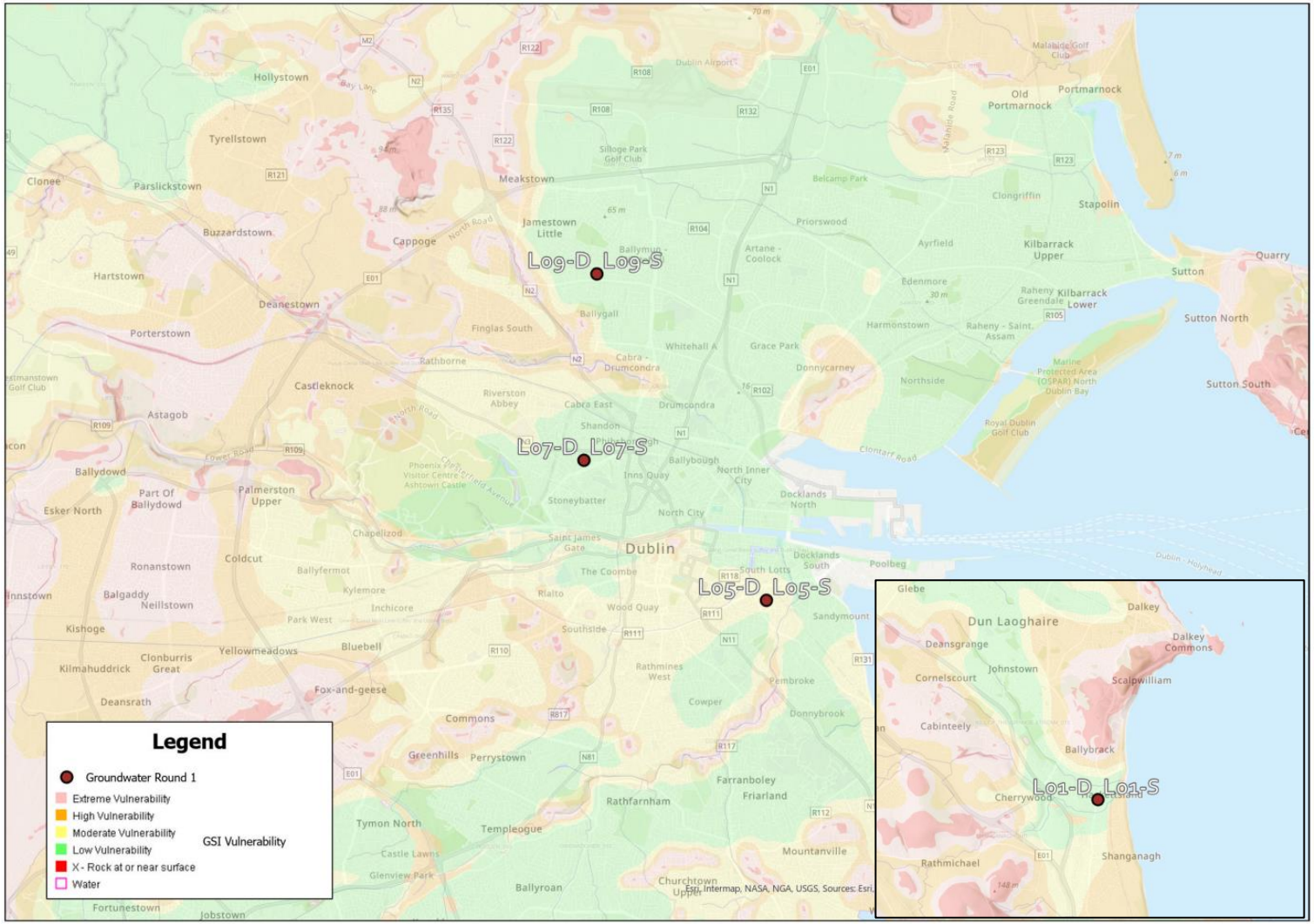


Figure 4 - 12 Groundwater Wells Sampled in Dublin (Arup, 2025 and GSI, 2025)

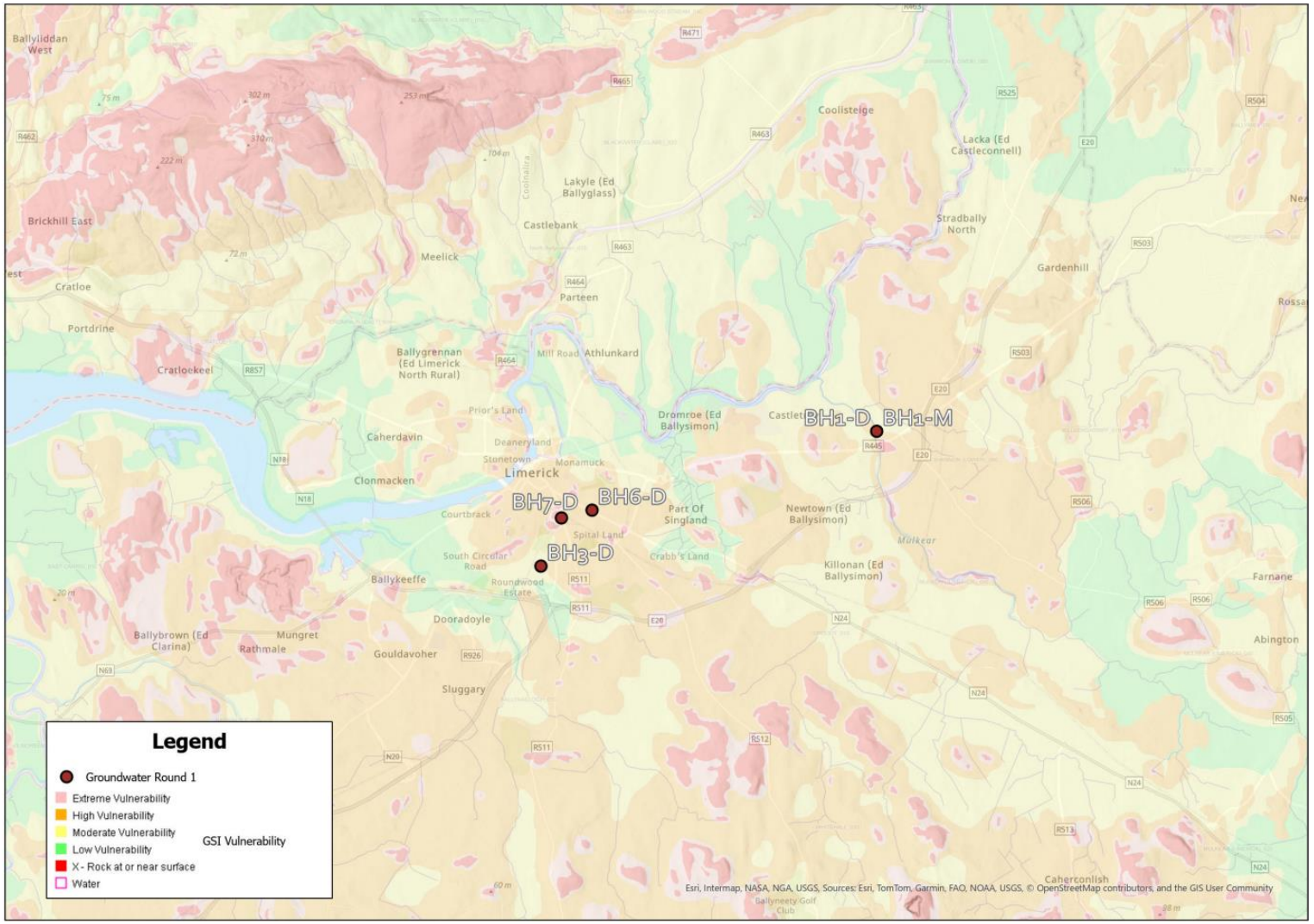


Figure 4 - 13 Groundwater Wells Sampled in Limerick (Arup, 2025 and GSI, 2025)

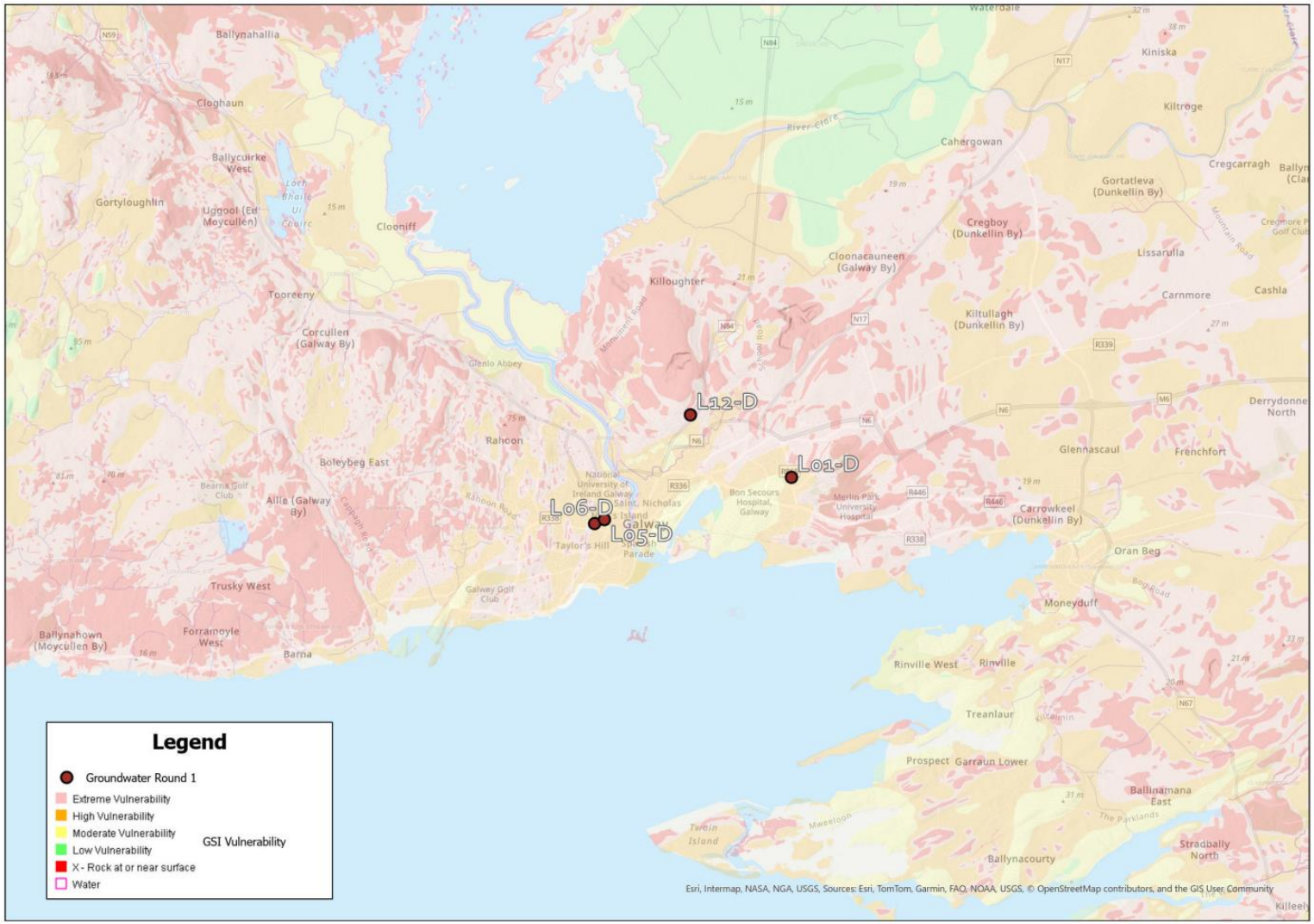


Figure 4 - 14 Groundwater wells sampled in Galway (Arup, 2025 and GSI, 2025)

Table 4 - 2 Groundwater well details (Arup, 2025 and GSI, 2025)

Location	Well ID	Well screen depth (mbgl)	Screened lithology	Groundwater vulnerability
Ballybrack, Dublin	L01-S L01-D	2.8-4.38 19.5-22.5	Metamorphic till Granite bedrock	Low
Ballsbridge, Dublin	L05-S L05-D	4.1-7.1 12-18	Limestone till Limestone bedrock	Low
Cabra, Dublin	L07-S L07-D	2.8-3.6 13.6-19.6	Limestone till Limestone bedrock	Low
Ballymun, Dublin	L09-S L09-D	2.3-4.1 15.5-21.5	Limestone till Limestone bedrock	Low
Castletroy, Limerick	BH1-M BH1-D	5.73 7.25 Total depth	Limestone till Limestone/mudstone bedrock	Moderate
Colbert Avenue, Limerick	BH3-D	9.52 Total depth	Limestone bedrock	Moderate
Mulgrave Street, Limerick	BH6-D	6.08 Total depth	Volcaniclastic Rocks	High
Colbert Station, Limerick	BH7-D	6.62 Total depth	Limestone bedrock	Extreme
Ballybane, Galway	L01-D	15-24	Limestone bedrock	High
University Hospital, Galway	L05-D	5-11	Granite bedrock	High
University Hospital, Galway	L06-D	5.5-11.5	Granite bedrock	Extreme
Ballinfole Park, Galway	L12-D	6-12	Limestone bedrock	Extreme

4.3.2.2 Results

At the time of writing this thesis, 3 Dublin (L01-S, L01-D and L07D) and 4 Limerick (BH1-M, BH3-D, BH6-D and BH7-D) groundwater samples were analysed. In all 7 samples, there were detections above the laboratory LOD for at least one PFAS compound. The highest total PFAS concentration was in BH7-D in Limerick ($\sum_{37}$ 49.23ng/L). This well is located directly beside the Limerick (Colbert) Train Station in an area of extreme groundwater vulnerability. The concentrations for all the compounds are shown in Figure 4 - 15. The most frequently detected compound was PFPeS, which was detected in all 7 samples. The occurrence of each compound in the 7 groundwater samples is shown in Figure 4 - 16.

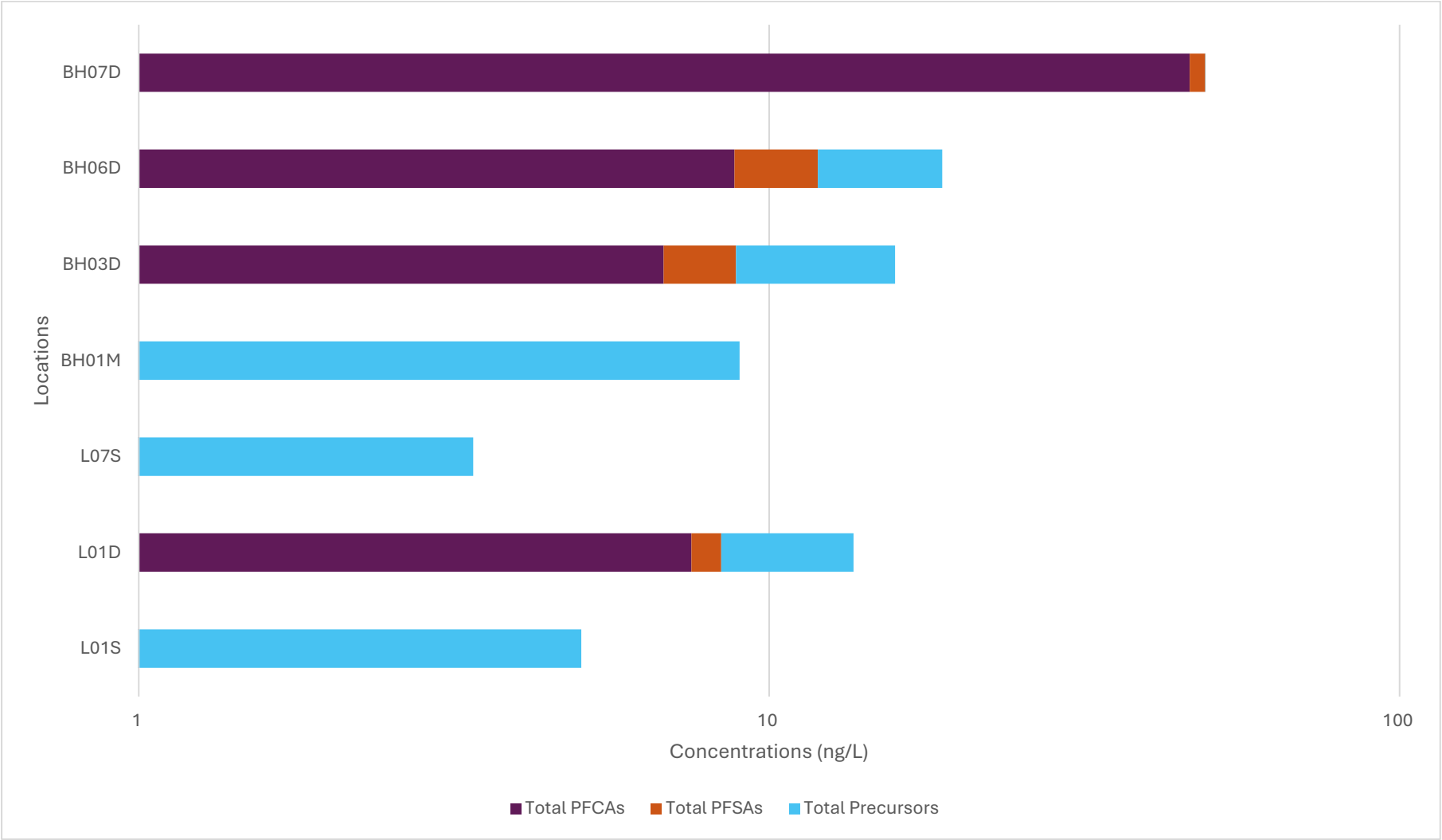


Figure 4 - 15 *PFAS Compounds detected in Groundwater Samples*

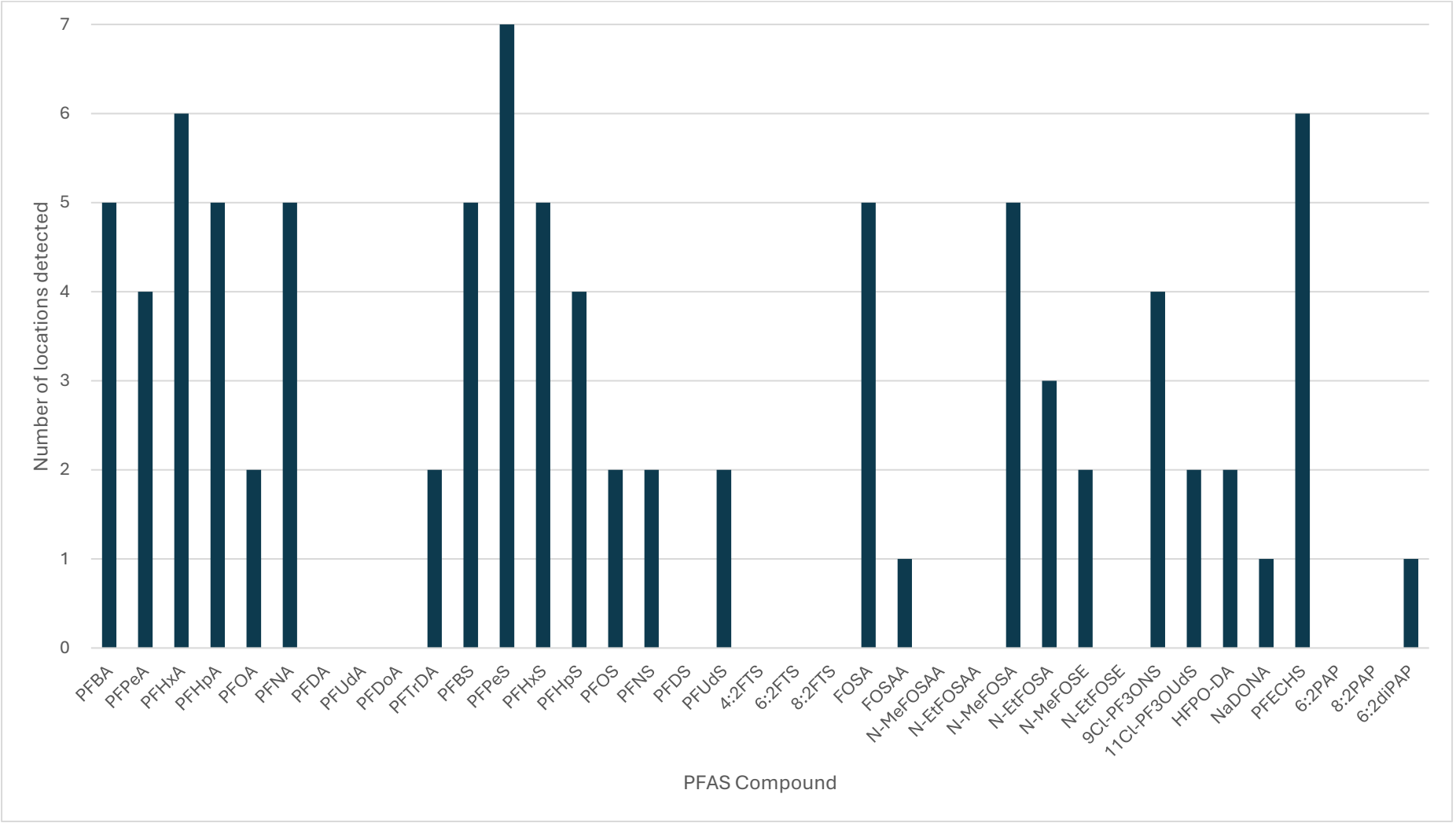


Figure 4 - 16 Occurrence of PFAS Compounds in 7 Groundwater Samples

4.3.2.3 Results Analysis

The results were overlayed the potential PFAS sources map to determine whether there were any valid SPR linkages and trends.

Considering the regional groundwater flow being towards the west in Limerick, only BH07 had a linkage with an upgradient source of the Colbert Train Station maintenance yard and railway tracks. Considering the groundwater vulnerability in this area is extreme, it is likely that any spillages of hydraulic fluids, cleaning materials, foams or herbicides in the maintenance yard would be directly released into the underlying aquifer. All the other potential PFAS point sources identified in Table 4 - 3 were either upgradient or cross-gradient of the groundwater wells.

It is also to be noted that FOSA is detected in five locations. All these five locations were on grass verges or in parks. FOSA is an active ingredient in sulfuramid, an insecticide that may currently or historically have been used in parks to maintain the grass[202].

Table 4 - 3 Groundwater Concentrations and potential sources (EPA Maps [2025], GSI [2025], HSA [2025], ArcGIS Online [2025] and Defence Forces Barracks [2025])

Sample ID	Location	Concentrations ($\sum_{37}$ ng/L)	Potential PFAS Point Sources (within 1km of location)
L01-S	Ballybrack, Dublin	5.03	None identified
L01-D	Ballybrack, Dublin	13.61	None identified
L07-S	Cabra, Dublin	3.39	Military installation (900m) and fire station (800m)
BH01-M	Castletroy, Limerick	11.10	Pharmaceuticals facility and WWTP pumping station
BH03-D	Colbert Avenue, Limerick	19.14	Military installation (1km) and Colbert Train Station maintenance yard (identified in the field) (1km)
BH06-D	Mulgrave Street, Limerick	23.16	Fire station (600m) and Colbert Train Station (600m). Car wash visually identified during field investigation (~200m).
BH07-D	Colbert Station, Limerick	53.08	Colbert Train Station maintenance yard (identified in the field) (50m), fire station (500m) and military installation (900m).

4.4 Conclusions

The purpose of this Chapter was to combine and summarise publicly available PFAS monitoring data in Ireland and newly acquired results from the project to evaluate the presence and distribution of PFAS contamination in surface water bodies and groundwater across Ireland.

In this Chapter, existing PFAS monitoring data for Ireland was summarised. Over 2000 PFOS and PFOA surface water samples have been taken by the EPA since 2019 as part of the WFD and 197 groundwater samples were taken in 2020 for 12 PFAS compounds. The data was collated and analysed in a nation-wide spreadsheet to identify spatial trends and data gaps in the current monitoring coverage. It was found that a disproportionate number of samples had been taken in each county, with Mayo, Clare and Cork having the most samples and Louth and Laois having the least. To understand the occurrence of PFOS and PFOA, the detection rate was used as a standardised indicator for comparison. Longford had a 100% detection rate of PFOA in the 20 samples taken and, in every county, PFOA was detected at either a higher or equal rate when compared to PFOS. This could be attributed to the historical bans and phasing out of PFOS since 2009, whereas PFOA is only recently being phased out under the EU POPs Regulation.

The highest PFOS concentration in Ireland was detected in the Two Pot River in Cork (51.7 ng/L), downstream of Cork Airport, and the highest PFOA concentration was in the Brosna River in Westmeath (49 ng/L). This contamination could possibly be linked to the WWTP or hazardous waste management facility upstream. The national average for PFOS concentrations in the surface waters tested is 0.38 ng/L, with a detection rate of 14%. The highest PFOS concentrations were detected in Dublin and Cork. The national average for PFOA concentrations in the surface waters tested is 0.65 ng/L, with a detection rate of 46%. The highest PFOA concentrations were detected in Westmeath, Offaly and Dublin. In an additional sampling round in selected sites, a broader suite of compounds was analysed. The two locations with the highest concentrations were both downstream of airports. PFOS, PFPeS, PFNA, PFOA, PFHpA, PFHxA and PFPeA were detected in all 4

samples and could be an indicator PFAS fingerprint of Irish airports. PFecHS was also detected (7.55ng/L) in the Sluice River in 2024. PFecHS is used as a hydraulic fluid additive to prevent corrosion, especially in aircraft systems.

Out of 197 groundwater samples, only 2 had compounds above the laboratory LOD. PFPA, PFHxS and PFOS were detected at the Curragh Military Base. The likely source of this contamination is the use of AFFFs for training purposes. PFBA was also detected in a relatively high concentration (85ng/L) at a food manufacturing plant in Wickow, however a further site-specific investigation would be required to determine the source of contamination.

As part of the INVEST p-FASST project, data from 11 surface water samples and 13 groundwater samples have been taken so far. These sample locations were informed by the results of Chapters 1 and 2 and access restrictions. An additional 10 samples taken as part of a citizen science campaign, were also analysed. All the samples were analysed for a suite of 37 compounds. At the time of writing this thesis, 4 surface water samples, 10 citizen science samples and 7 groundwater samples had been analysed, and the results were reviewed.

The highest $\sum_{37}$ PFAS concentration in surface water was downstream of an oil refinery in Cork (1,044.97ng/L), where PFOA-containing AFFFs are stored. The highest $\sum_{37}$ PFAS concentration in groundwater was downgradient from a railway maintenance yard in Limerick (53.08ng/L), which was in an area of extreme groundwater vulnerability. The most frequently detected PFAS compound in was N-MeFOSA in surface water and PFPeS in groundwater. FOSA was also detected in 5 groundwater samples. FOSA is an active ingredient in sulfuramid, an insecticide.

Potentially valid linkages were made between positive detections and potential point sources of PFAS for 7 surface water samples and 1 groundwater sample. These linkages included WWTPs, airports, oil refineries and maintenance yards.

Chapter 5 – Conclusions and Recommendations

5.1 Introduction

The overall aim of this thesis is to understand major sources of PFAS in Ireland, risks and implications for Irish water bodies, particularly those used for drinking water purposes. This chapter will summarise the key findings, limitations and conclusions of the preceding four chapters. It will also provide recommendations for monitoring and regulation and provides suggestions on a strategy for PFAS management in Ireland. It is recommended that all industrial sites that have been identified as potential sources conduct a PFAS audit to determine whether there are any valid SPR linkages between PFAS containing materials to environmental receptors. A suggested template is provided in Appendix B. Finally future research directions are suggested based on the findings of this thesis.

5.2 Summary of Key Findings

5.2.1 Sources of PFAS

A mini literature review was conducted to understand the current state of knowledge on PFAS sources. It was found that they are produced and used globally in a multitude of industries, including pharmaceutical, chemical, metals and information technology manufacturing. PFAS compounds can enter the environment via point and diffuse sources. For the purposes of this thesis, PFAS sources were categorised into five categories – anthropogenic, industrial, civil, agricultural and municipal. Waste management facilities, such as landfills, compost facilities, incinerators and wastewater treatments plants are significant sources of PFAS. These facilities aid in the bioaccumulation and transformation of PFAS compounds from anthropogenic and industrial waste before either leaching into the groundwater, being released into the air or being discharged into surface water bodies respectively. Industrial effluent from facilities that either produce or process PFAS and facilities that use PFAS in chemicals or manufacturing metals, ICT and electronics, AFFFs, chemicals, pharmaceuticals, treated paper and wood

products, textiles and air conditioning units can also be significant sources of PFAS. Effluent can be discharged into surface water bodies and leaks from pipework, tanks or spills of PFAS containing chemicals may leach into the groundwater. Gaseous emissions from some industries may also contain PFAS.

Locations where AFFFs may be stored, used or released, such as fire-fighting stations, training areas, military bases, and airports are also major sources. AFFFs may be present at locations where bulk fuels, oil or solvents are stored such as industrial facilities, petrol stations and refineries and power plants.

Stormwater overflows are conduits for urban surface water runoff and sewage system overflows, which are both known sources of PFAS. As such, they are point sources of PFAS. Where there are misconnections or cracks, the stormwater drains could leak into the underlying groundwater.

Major diffuse sources of PFAS are pesticides, herbicides and bio-solids from wastewater treatment plants. Once these sources are used on vegetation or spread on agricultural land, major pathways would include runoff and infiltration to groundwater, depending on underlying soil type. Other diffuse sources include runoff from urban areas, where there are no stormwater overflows or drains and the historic use of PFAS that has led to legacy contamination.

5.2.2 PFAS in Ireland

Based on Ireland's industrial profile, land use and infrastructure, there are a large variety of potential PFAS sources. From existing case studies in Ireland, there are several known sources of PFAS including waste management facilities, fire-training facilities, fire stations, airports, petroleum refineries and sites with PFOA stockpiles >50kg. As PFAS is not manufactured in Ireland, many compounds are imported. Following a review of the ECHA REACH database, it was found that 57 known PFAS compounds are currently being imported into Ireland in quantities between 28,145 and 280,260 tonnes per year. 15 of these compounds were either classified as persistent, bio-accumulative and/or toxic. It was found that most compounds were used as heat transfer liquids and intermediate compounds in the chemicals manufacturing industries.

Potential primary and secondary sources in Ireland were identified using publicly available databases, compiled and imported into ArcGIS Pro. Most of the potential point sources were urban wastewater treatment plants, firefighting stations and solid waste management facilities. Spatial analysis showed that Cork had the most potential point sources when compared to other counties and Dublin had the highest density of potential point sources. Following the identification of potential point sources, risk scores and predominant environmental pathways were allocated to each potential source group in preparation for the risk assessment.

5.2.3 Risk Assessment

To develop and test a methodology for a multi-criteria risk-based tool, a catchment wide investigation for the Lough Corrib catchment was conducted. This tool can be upscaled to a nation-wide investigation. Both surface water and groundwater risk maps were developed to indicate areas that are more susceptible to PFAS contamination. The sensitive receptors, such as drinking water abstractions and vulnerable ecosystems were overlayed to determine whether any were at higher risk of being impacted by contamination. It was determined that 8 drinking water abstractions in the Lough Corrib catchment were at risk of being impacted by PFAS contamination. 2 abstractions for food production, and 3 sensitive ecological areas were also identified as being high risk.

5.2.4 PFAS in the Irish environment

A review of publicly available PFAS monitoring data in Ireland was undertaken to understand the nature and extent of contamination in Ireland. Over 2000 PFOS and PFOA surface water samples taken by the EPA as part of the WFD since 2019. Every county had PFOA detected a higher or equal rate when compared to PFOS. The national average for PFOS concentrations in the surface waters tested was 0.38 ng/L, with a detection rate of 14%. The highest PFOS concentrations were detected in Dublin and Cork. The national average for PFOA concentrations in the surface waters tested is 0.65 ng/L, with a detection rate of 46%. The highest PFOA concentrations were detected in Westmeath.

The EPA has also tested several locations for a broader suite of PFAS compounds. Some of these locations included surface water bodies draining from Cork and Dublin airport. It all 4 samples, PFOS, PFPeS, PFNA, PFOA, PFHpA, PFHxA and PFPeA were detected. This could be a fingerprint of Irish airports.

As part of the INVEST p-FASST project, 4 surface water samples, 10 citizen science samples and 7 groundwater samples from across Ireland were analysed and the results were reviewed. The most frequently detected PFAS compound was N-MeFOSA in surface water and PFPeS in groundwater. FOSA was also detected in 5 groundwater samples. FOSA is an active ingredient in sulfuramid, an insecticide. Potentially valid linkages were made between positive detections and potential point sources of PFAS for 7 surface water samples and 1 groundwater sample. These linkages included WWTPs, airports, oil refineries and railway maintenance yards.

Results in the Lough Corrib Catchment were examined and compared to potential point sources. Potentially valid linkages were made between positive detections and potential point sources of PFAS for 5 surface water samples. However, 10 locations with positive detections of PFAS had no obvious point sources. It is inferred that these detections could be from diffuse sources in the catchment. The concentrations at these locations were in the same magnitude as those with potential point sources.

5.3 Limitations

While this research provides a robust foundation for understanding PFAS contamination in Ireland, several limitations must be acknowledged.

The availability and granularity of publicly accessible data constrained the precision of source identification and spatial analysis. Currently, PFAS is not included in the identified list of contaminants on the PRTR. As such, assumptions regarding certain economic activities were conducted to identify types of sites that may process, use or store PFAS. It is possible that not all identified sites process, use or store PFAS, however it is considered acceptable to identify sites that will need to audit their site

to determine whether there are any linkages from sources to environmental receptors. Conversely, some sites that do process, use or store PFAS might not fit within the Scope of the PRTR Regulation, such as the manufacturing of semi-conductors. Other potential sources, such as greywater reuse, residential compost, septic systems and historical fire locations are also not readily available in public databases.

Assumptions were made based on international literature in Chapter 3 regarding the inability for conventional wastewater treatment processes to remove PFAS. This was not verified to be the case in Irish industrial and municipal wastewater treatment plants. Testing the effluent was not within the scope of this project.

The risk assessment methodology requires further refinement and validation for national application. The methodology primarily focused on known and potential point sources of PFAS. However, the analysis of results in the Lough Corrib catchment identified that many positive PFAS detections could be linked to other pressures such as agriculture, runoff and septic tanks, which weren't included in the methodology. Further, the concentrations from these unidentified diffuse sources were found to be within the same magnitude as the identified point sources, indicating their significant impact on the concentrations in surface water bodies.

Additionally, the limited scope of PFAS monitoring data, both in terms of compound diversity and geographic coverage, may underrepresent the true extent of contamination. The data processed in Chapter 4 was largely dependent on WFD data that primarily monitored PFOS and PFOA. One of Chapter 3's objectives included reviewing PFAS characteristics to understand the risks they pose to the environment. Due to the limited number of sites analysed for a larger range of compounds, this objective could not be fully achieved.

These limitations highlight the need for expanded monitoring efforts, improved data transparency, and continued methodological development.

5.4 Future Research Directions

Considering the key findings and limitations of this research, the following sections outline proposed directions for the INVEST p-FASST project and other future research.

5.4.1 Risk Assessment Model

In the next revision of the multi-criteria risk assessment model, it is important to include septic tanks as additional point sources and to also include diffuse sources, such as urban runoff or agricultural pressures. A land use raster, such as that from the CORINE map, could be included in the suitability modeller and the land uses can be risk ranked using values from international literature. It is also important that if this model is to be used in future catchments, universal risk scoring and ranking will be required. This should be considered when assigning risk scores for land use.

The model also used equal weighting for all layers for the suitability model, including PFAS source risk score, groundwater vulnerability, and aquifer classification. These weightings can be revised using the findings from Chapter 4. Groundwater vulnerability and aquifer productivity should be weighting should be increased, as it was found that diffuse sources have the potential to impact water bodies to the same magnitude as point sources.

5.4.2 Sampling

For the groundwater risk map, there weren't sufficient results in the Lough Corrib catchment to validate and refine the assumptions made regarding risk ranking, particularly for groundwater vulnerability and aquifer classification. Future validation efforts should also include more extensive groundwater sampling. It is recommended to focus on areas identified as "high risk" by Chapter 3's groundwater map, particularly those with "Extreme" of "high" vulnerability or "Regionally Important" aquifers.

The recommended sampling in the Lough Corrib Catchment should be implemented and fed back into the model to validate the findings. The iterative process of prediction, sampling, analysis, and model refinement is crucial for

strengthening the overall risk assessment methodology. It is desirable to undertake seasonal or long-term monitoring campaigns at key validation sites to provide a more dynamic and robust understanding of how PFAS contamination can change temporally, and it'll allow for a better assessment of how the models predictions hold up under varying environmental conditions.

Validation could be enhanced if the full suite of PFAS was consistently analysed across all validation samples, especially in areas identified as "high risk". The risk posed by the full spectrum of PFAS compounds cannot be fully validated without this. For the highest risk point sources identified in Chapter 3 (eg. Military facilities, chemical manufacturing plants and landfills), targeted investigations should be conducted to verify the assumption that they present the highest risk to the environment. An investigation of this kind should involve specific sampling of effluent before and after treatment and direct observations of discharge practices, to validate the assumptions that PFAS isn't removed from conventional treatment.

To further understand the impact that agricultural sources, such as pesticides, fertilisers and biosolids, have on PFAS concentrations in the environment, it is recommended that analysis of Irish soils, biosolids and composts is completed. A full life cycle assessment of PFAS would be beneficial to understanding how the compounds move and transform in the Irish environment. This investigation could include testing land spreading material, underlying soils, underlying groundwater and nearby surface water bodies.

5.5 Key Recommendations for PFAS Management in Ireland

Based on the findings of the research, and particularly the results from the Lough Corrib Catchment, four key recommendations are proposed to guide the national management of PFAS in Ireland. These recommendations focus on enhancing monitoring, regulatory control, risk assessment, and scientific understanding to support evidence-based decision-making and sustainable water protection. The recommendations are summarised in Table 5-1.

5.5.1 Recommendation 1 (R1): Establish a Comprehensive PFAS Monitoring and Data Programme

The current PFAS monitoring framework in Ireland is limited to PFOS and PFOA, resulting in significant data gaps regarding the presence, distribution, and behaviour of other PFAS compounds. Findings from Chapter 4 indicate that compounds such as 6:2 FTS and PCECHS, among others, were detected at notable concentrations downstream of wastewater treatment plants and airports, yet these compounds are not routinely included in national monitoring schemes.

It is therefore recommended that a comprehensive national PFAS monitoring programme be established to include, at a minimum, the twenty PFAS compounds identified in the proposed Drinking Water Guidelines (DWG), and where feasible, an extended suite of commercially available PFAS compounds. Monitoring should encompass both surface and groundwater, with particular attention to high-risk areas such as those identified in the Lough Corrib catchment, where multiple drinking water abstractions, food production sites, and sensitive ecosystems have been identified as being at risk.

This enhanced monitoring will improve Ireland's capacity to meet forthcoming regulatory obligations, support early detection of contamination, and provide a robust dataset for modelling and mitigation planning.

5.5.2 Recommendation 2 (R2): Implement Mandatory PFAS Audits for High-Risk Industrial Sites

Industrial, municipal, and waste management activities have been identified as key contributors to PFAS release into the environment. To strengthen source control, it is recommended that all identified high-risk facilities - including airports, fire stations, landfills, wastewater treatment plants, and chemical processing sites - undertake a mandatory PFAS audit using a standardised template, such as the one provided in Appendix B.

These audits should assess the presence and use of PFAS-containing materials, potential pathways to the environment, and existing control measures. The results should be submitted to the Environmental Protection Agency (EPA) or relevant local

authority to inform the establishment of a national PFAS source inventory. Integration of this information into the Pollutant Release and Transfer Register (PRTR) or an equivalent PFAS database will enhance regulatory oversight and support targeted mitigation strategies.

5.5.3 Recommendation 3 (R3): Develop and Validate a National PFAS Risk Assessment Model

The multi-criteria risk assessment model developed for the Lough Corrib Catchment proved effective in identifying areas of elevated PFAS vulnerability. However, further refinement and validation are required for national application. It is recommended that the model be expanded to incorporate additional point and diffuse sources, including septic tanks, urban runoff, and agricultural pressures. Land use data (e.g., CORINE maps) should be integrated into the suitability model, with land use categories ranked according to risk scores derived from international literature.

Furthermore, model parameters such as aquifer vulnerability and productivity should be reweighted based on findings from Chapter 4, which indicated that diffuse sources may contribute PFAS contamination of similar magnitude to point sources. The refined model should undergo validation through targeted sampling campaigns in selected high-risk catchments, using an iterative approach of prediction, measurement, and model adjustment. Once validated, the tool can be applied nationally to inform catchment management planning and regulatory policy.

5.5.4 Recommendation 4 (R4): Advance Research on PFAS Sources, Pathways and Removal Technologies

There remains a critical need for further research into the fate, transport, and treatment of PFAS compounds in the Irish environment. This includes investigation into both point and diffuse sources, as well as the effectiveness of existing treatment technologies. It is recommended that future research address the following key areas:

1) Treatment performance: Evaluate the efficiency of Irish industrial and municipal wastewater treatment plants in removing PFAS compounds by testing influent and effluent streams and assessing treatment by-products.

2) Diffuse sources: Quantify PFAS accumulation in agricultural soils, biosolids, and composts to assess contributions from land spreading and runoff.

3) Life-cycle analysis: Conduct comprehensive studies of PFAS movement from source to receptor, including transformation and persistence in environmental media.

4) Long-term monitoring: Implement seasonal and longitudinal sampling in high-risk catchments, such as Lough Corrib, to assess temporal variations and validate risk model predictions.

5) Remediation technologies: Investigate and pilot emerging PFAS removal technologies suitable for Irish conditions.

Such research will enhance understanding of PFAS behaviour and inform the development of effective management, treatment, and remediation strategies tailored to Irish environmental contexts.

Table 5- 1 Summary of Recommendations and Implementation Timeframes

Recommendation	Focus Area	Timeframe	Intended Outcome
R1: Comprehensive PFAS Monitoring and Data Programme	Expansion of national PFAS monitoring to include extended compound suite and groundwater	1–3 years	Improved national data coverage and regulatory readiness
R2: Mandatory PFAS Audits	Industrial and municipal source identification and control	In 2 years	National PFAS source inventory and enhanced mitigation planning
R3: National PFAS Risk Assessment Model	Catchment-scale risk mapping and model validation	2–4 years	Scalable national risk tool for planning and policy integration
R4: Research on PFAS Sources and Removal	Understanding PFAS fate, pathways, and treatment	3–6 years	Evidence base for improved mitigation and remediation strategies

5.6 Conclusions

This thesis has explored the multifaceted nature of PFAS contamination, with a particular focus on its sources, environmental pathways, and presence in the Irish context. Through a targeted literature review, PFAS compounds were found to originate from a wide array of industries and activities, including pharmaceuticals, chemicals, metals, ICT manufacturing, and firefighting operations. These compounds enter the environment via both point and diffuse sources, with waste management facilities, industrial effluent, and stormwater overflows identified as significant contributors.

In Ireland, although PFAS is not manufactured domestically, substantial quantities are imported annually, with several compounds classified as persistent, bioaccumulative, and/or toxic. Using spatial analysis and publicly available datasets, this study identified and mapped potential PFAS sources across the country, revealing Cork as having the highest number of potential point sources and Dublin the highest density. A risk-based methodology was developed and tested within the Lough Corrib catchment, highlighting several drinking water abstractions, food production sites, and sensitive ecosystems at risk of PFAS contamination.

Monitoring data reviewed from the EPA and the INVEST p-FASST project confirmed the widespread presence of PFAS in Irish surface and groundwater, with PFOA detected more frequently than PFOS. Notably, PFAS fingerprints were observed near major airports, and linkages were established between positive detections and known point sources such as WWTPs, refineries, and maintenance yards. However, the detection of PFAS in areas without obvious point sources suggests the influence of diffuse sources and legacy contamination.

Overall, this research underscores the complexity of PFAS contamination in Ireland and the need for comprehensive, catchment-wide risk assessment tools to inform future monitoring, mitigation, and policy development. The methodology developed herein provides a scalable framework for national application, contributing to a

more informed and proactive approach to managing PFAS risks in the Irish environment.

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Appendix A – Analysis Suites

Table A - 1 Environmental Protection Agency Sum of 48 Compounds Analytes Suite

Compound Abbreviation	PFAS Compound
4:2 FTSA	1H,1H,2H,2H-Perfluorohexanesulphonic acid
6:2 FTSA	1-Octanesulfonic acid, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-
8:2 FTSA	3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-Heptadecafluorodecanesulphonic acid
6:2 Cl-PFESA	Perfluoro(2-((6-chlorohexyl)oxy)ethanesulfonic acid)
PFMOBA	Perfluoro-4-methoxybutanoic acid
HFPO-DA	2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoic acid
HFPO-TA	Perfluoro-2,5-dimethyl-3,6-dioxanonanoic acid
DONA	4,8-Dioxa-3H-perfluorononanoic acid
6:2 FTAB	2-[dimethyl-[3-tridecafluorooctylsulfonylamino)propyl]azaniumyl]acetate
7:3 FTCA	2H,2H,3H,3H-Perfluorodecanoic acid
5:3 FTCA	2H,2H,3H,3H-Perfluorooctanoic acid
3:3 FTCA	4,4,5,5,6,6,6-Heptafluorohexanoic acid
FOSA	Perfluorooctanesulfonamide
EtFOSA	Ethylperfluorooctanesulfonamide
MeFOSA	Heptadecafluoro-N-methyloctanesulphonamide
EtFOSAA	Ethyl-N-[(heptadecafluorooctyl)sulphonyl]glycine
NEtFOSAA	N-Ethyl-N-[(heptadecafluorooctyl)sulphonyl]glycine
NMeFOSAA	2-(N-Methylperfluorooctanesulfonamido)acetic acid
MeFOSE	N-Methylperfluorooctanesulfonamidoethano
FBSA	Perfluorobutylsulphonamide
FHxSA	Perfluorohexanesulfonamide
PFMOPrA	Perfluoro-3-methoxypropanoic acid
PFecHS	Perfluoro-4-ethylcyclohexane
NFDHA	Perfluoro-3,6-dioxaheptanoic acid
PFEESA	Perfluoro(2-ethoxyethane)sulfonic acid
PFBA	Perfluoro butanoic acid
PFPeA	Perfluorovaleric Acid
PFHxA	Perfluoro hexanoic acid
PFHpA	Perfluoro heptanoic acid
PFOA	Perfluorooctanoic acid
PFNA	Perfluoro nonanoic acid
PFDA	Perfluoro decanoic acid
PFUnDA	Perfluoro undecanoic acid
PFDoA	Perfluoro dodecanoic acid
PFTrDA	Perfluorotridecanoic acid
PFTeA	Perfluorotetradecanoic acid
PFHxDA	Perfluorohexadecanoic acid

PFODA	Perfluorooctadecanoic acid
PFBS	Perfluorobutanesulfonic acid
PFPeS	Perfluoropentanesulfonic acid
PFHxS	Perfluorohexanesulfonic acid
PFHpS	Perfluoroheptanesulfonic acid
PFOS	Perfluorooctane sulfonic acid
PFNS	perfluorononanesulfonic acid
PFDS	perfluorodecane sulfonic acid
PFUnDS	Perfluoroundecanesulfonic acid
PFDoS	Perfluorododecanesulfonic acid

Table A - 2 INVEST pFASST Project Sum of 37 Compounds Analytes Suite

Compound Abbreviation	PFAS Compound
PFBA	Perfluoro butanoic acid
PFPeA	Perfluorovaleric Acid
PFHxA	Perfluoro hexanoic acid
PFHpA	Perfluoro heptanoic acid
PFOA	Perfluorooctanoic acid
PFNA	Perfluoro nonanoic acid
PFDA	Perfluoro decanoic acid
PFUdA	Perfluoro undecanoic acid
PFDoA	Perfluoro dodecanoic acid
PFTrDA	Perfluorotridecanoic acid
PFBS	Perfluorobutanesulfonic acid
PFPeS	Perfluoropentanesulfonic acid
PFHxS	Perfluorohexanesulfonic acid
PFHpS	Perfluoroheptanesulfonic acid
PFOS	Perfluorooctane sulfonic acid
PFNS	Perfluoro nonanoic acid
PFDS	Perfluorodecane sulfonic acid
PFUdS	Perfluoroundecanesulfonic acid
4:2FTS	4:2 Fluorotelomer sulfonic acid
6:2FTS	6:2 Fluorotelomer sulfonic acid
8:2FTS	8:2 Fluorotelomer sulfonic acid
6:2diPAP	6:2 polyfluoroalkyl phosphate diester
FOSA	Perfluorooctanesulfonamide
FOSAA	Perfluorooctane sulfonamidoacetic acid
N-MeFOSA	N-Methyl Perfluorooctane Sulfonamide
N-EtFOSA	N-Ethylperfluorooctanesulfonamide
N-MeFOSAA	2-(N-Methylperfluorooctanesulfonamido)acetic acid
N-EtFOSAA	N-Ethyl-N-[(heptadecafluorooctyl)sulphonyl]glycine
N-MeFOSE	N-Methylperfluorooctanesulfonamidoethanol
N-EtFOSE	N-Ethyl Perfluorooctane Sulfonamido Ethanol
6:2PAP	6:2 Fluorotelomer phosphate monoester
8:2PAP	8:2 Fluorotelomer phosphate monoester
9Cl-PF3ONS	11-Chloroperfluoro-3-oxaundecanesulfonic acid
11Cl-PF3OUdS	9-chlorohexadecafluoro-3-oxanonane-1-sulfonate
HFPO-DA	Hexafluoropropylene oxide dimer acid (Gen X)
NaDONA	Sodium 4,8-dioxa-3H-perfluorononanoate
PFECHS	Perfluoroethylcyclohexane sulphonate

Table A - 3 TerraChem Project Sum of 39 PFAS Compounds Analysis Suite

Compound Abbreviation	PFAS Compound
PFBA	Perfluoro butanoic acid
PFPeA	Perfluorovaleric Acid
PFHxA	Perfluoro hexanoic acid
PFHpA	Perfluoro heptanoic acid
PFOA	Perfluorooctanoic acid
PFNA	Perfluoro nonanoic acid
PFDA	Perfluoro decanoic acid
PFUdA	Perfluoro undecanoic acid
PFDoA	Perfluoro dodecanoic acid
PFTrDA	Perfluorotridecanoic acid
PFTeDA	Perfluorotetradecanoic acid
PFBS	Perfluorobutanesulfonic acid
PFPeS	Perfluoropentanesulfonic acid
PFHxS	Perfluorohexanesulfonic acid
PFHpS	Perfluoroheptanesulfonic acid
PFOS	Perfluorooctane sulfonic acid
PFNS	Perfluoro nonanoic acid
PFDS	Perfluorodecane sulfonic acid
PFUdS	Perfluoroundecanesulfonic acid
PFDoS	Perfluorodecane sulfonic acid
PFTrDS	Perfluorotridecanesulfonic acid
FOSA	Perfluorooctanesulfonamide
FOSAA	Perfluorooctane sulfonamidoacetic acid
N-EtFOSA	N-Ethylperfluorooctanesulfonamide
N-EtFOSAA	N-ethylperfluorooctanesulfonamidoacetic acid
N-EtFOSE	N-Ethyl Perfluorooctane Sulfonamido Ethanol
N-MeFOSA	N-Methyl Perfluorooctane Sulfonamide
N-MeFOSAA	N-methylperfluorooctane sulfonamidoacetic acid
N-MeFOSE	N-Methylperfluorooctanesulfonamidoethanol
4:2 FTS	4:2 Fluorotelomer sulfonic acid
6:2 FTS	6:2 Fluorotelomer sulfonic acid
8:2 FTS	8:2 Fluorotelomer sulfonic acid
6:2 diPAP	6:2 polyfluoroalkyl phosphate diester
8:2 diPAP	8:2 polyfluoroalkyl phosphate diester
11Cl-PF3OUdS	11-Chloroperfluoro-3-oxaundecanesulfonic acid
9Cl-PF3ONS	9-chlorohexadecafluoro-3-oxanonane-1-sulfonate
HFPO-DA	Hexafluoropropylene oxide dimer acid (Gen X)
NaDONA	Sodium 4,8-dioxa-3H-perfluorononanoate
PFECHS	Perfluoroethylcyclohexane sulphonate

Appendix B – PFAS Industrial Site Audit Template

1. Introduction and purpose

This PFAS Audit template can be used to inform a desk-based environmental review at a licensed facility to determine the potential presence of per- and polyfluoroalkylated substances (PFAS) at the site. Where presence is proven, a preliminary risk assessment of any potential PFAS containing materials or process can be undertaken to determine whether there are any viable source, pathway and receptor (SPR) linkages that would present a potential risk to the environment or human health and would warrant further investigation.

1.1 Scope of Works

The PFAS Audit should include the following:

- A review of activities recorded on the Industrial Emissions Licence and in planning documents to determine whether PFAS is used in or may be a by-product from site activities.
- Review of chemical data sheets, firewater risk assessment reports, water quality reports, or other relevant additional information to determine whether PFAS may have been used in the past or if it could be present as a minor constituent of products/waste from current site activities.
- Preliminary (qualitative) risk assessment to determine potential pathways for PFAS compounds to enter the environment; and
- Highlight where there are any potential risks of PFAS compounds being emitted from the sites.

2. Data Collection

This Audit is in line with Irish EPA best practice[149], a risk-based assessment of known or suspected contaminated land and groundwater issues should be undertaken. The risk assessment methodology follows a staged approach, designed to address key elements in succession, if required. This PFAS Audit outline only addresses Stage 1: Site Characterisation & Assessment. This Audit will consist of a qualitative risk assessment.

A critical part of the assessment is developing a Conceptual Site Model (CSM). It is established in Stage 1 and reviewed as additional information, and data is acquired throughout the assessment process. The CSM describes the potential sources of contamination at a site, the migration pathways and the receptors the contamination could impact upon. If a valid SPR linkage exists, then the pollutant linkage will need to be characterised and assessed.

The first part of the Audit and to develop a CSM is collecting data on potential PFAS sources on site and pathways for those sources to be transported to receptors, such as surface or groundwater bodies. It is preferable that the CSM is diagrammatic, however matrices can also be effective.

The following sections provide examples on the types of data to collect and recommended sources.

2.1 PFAS Sources

Review and summarise reports to determine what licensed activities may involve PFAS-containing materials at the subject site. Where available, it is recommended that the following reports are reviewed:

- Annual Environmental Reports (EPA LEAP Online)
- Industrial Emissions Licences (EPA LEAP Online)
- Fire Water Risk Assessments (EPA LEAP Online)
- Historical fire incidents and spills (EPA LEAP Online)
- The following is industry specific and may be available at the site that is being audited:

- Safety Data Sheets of potentially-PFAS containing materials.
- Process flow diagrams
- Waste disposal records

If necessary, it may be useful to physically inspect facilities and processes to identify PFAS sources. If further knowledge is required, engage with an environmental engineer or consultant.

Figure B - 1 is a generic visual CSM of potential PFAS sources and pathways at industrial sites and Table B - 1 gives examples of potential sources that may be found at an industrial site.

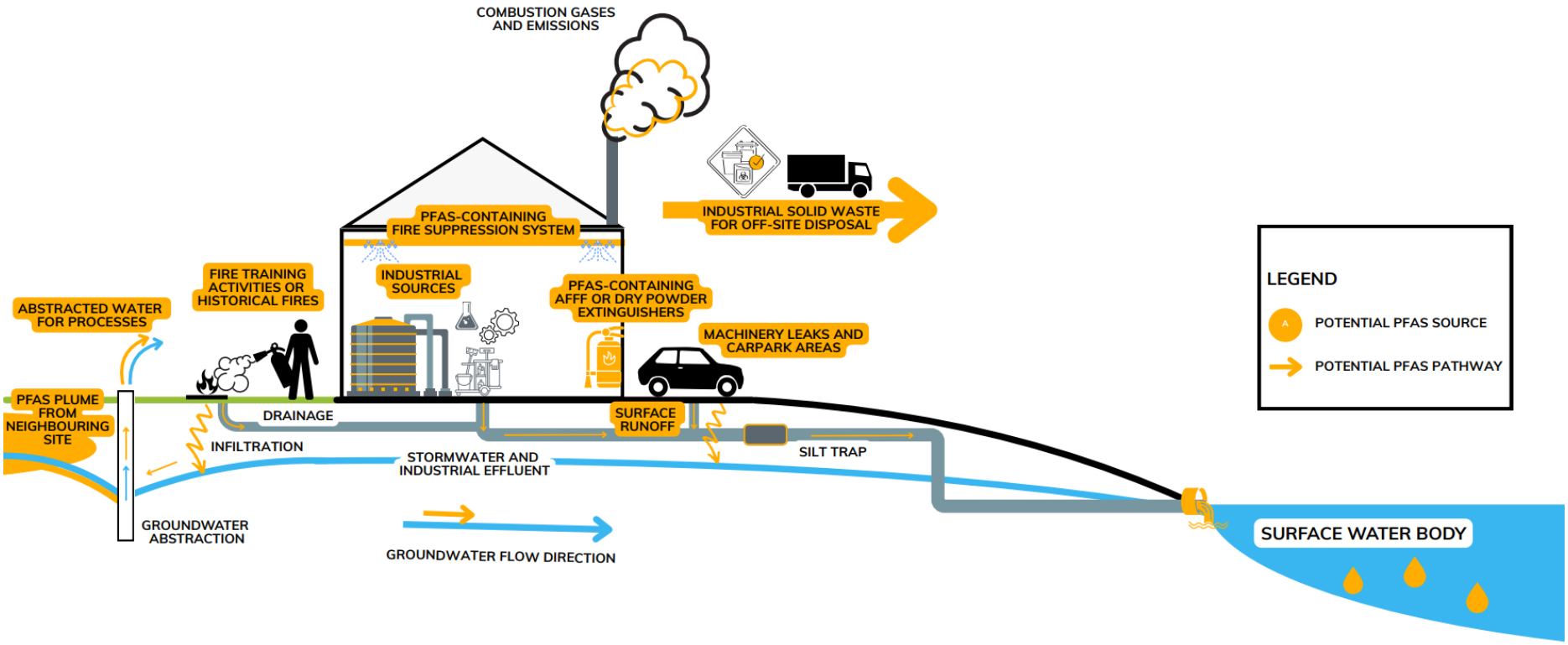


Figure B - 1 Potential PFAS sources and pathways associated with industrial site

Table B - 1 Potential sources that may be present on an industrial site

Number	Potential Source	Details of Potential Use	Source of information	Reference and further information
1	PFAS-containing aqueous film-forming foams and powders	Current and historical fire-fighting foams, foam concentrates and powders may contain PFAS. This may include fire suppression systems. Some foams and powders may be labelled as "PFOA-free" or "PFOS-free". These products may use other PFAS compounds as regrettable substitutions.	Firewater Risk Assessments Safety Data Sheets	Kissa, E (2001), Fluorinated Surfactants and Repellents, Marcel Dekker, Inc. Sweco (2020), Determining Historic and Current PFAS Levels in AFFF in the Republic of Ireland, https://www.epa.ie/publications/monitoring--assessment/waste/PFAS-in-fire-fighting-foam-report-web-version.pdf Figuiere et al (2025)[203]
2	Contaminated firewater from historical fires and testing	If the AFFFs have been used or tested on an unsurfaced area (eg. For training), it is likely that PFAS will have entered the soil or the groundwater beneath the site.	Firewater Risk Assessments Safety Data Sheets Historical fire incident reports	Kissa (2001) Sweco (2020)
3	Storage and use of chemicals and materials that may contain PFAS	Solvents, cleaning chemicals, lubricants, hydraulic fluids and oils, stockpiles of waste etc. It is to be noted that, under the REACH guidelines, a manufacturer does not need to stipulate whether a product contains less than 0.1% weight of substances on the candidate list. As a result,	Safety Data Sheets Industrial Emissions Licence	Swedish Chemicals Agency (KEMI) (2015), Occurrence and use of highly fluorinated substances and alternatives, Report 7/15

Number	Potential Source	Details of Potential Use	Source of information	Reference and further information
		safety data sheets may not report whether the product contains PFAS. For example, the manufacture of phosphate ester-based hydraulic fluids for the aviation industry involves the use of PFOS as an additive, with the PFOS level being less than 0.1%. The addition of PFOS allows the hydraulic fluid to prevent fire, corrosion and evaporation.		
4	Machinery and maintenance	Hydraulic fluids and soils, cleaning chemicals Surface run-off from carpark areas or road surfaces are a known source of PFAS (Murakami, 2009) and compounds may sorb to silt particles and be retained in the silt trap.	Safety Data Sheets Industrial Emissions Licence	Swedish Chemicals Agency (KEMI) (2015), Occurrence and use of highly fluorinated substances and alternatives, Report 7/15 Murakami, M et al. (2009), Evaluation of wastewater and street runoff as sources of perfluorinated surfactants, Chemosphere 74, 487-493
5	Combustion gases	Alternative fuels and incinerators may contain PFAS compounds such as the following: • Solid recovered fuel (plastic, paper, textiles and wood) and incineration of waste • Secondary liquid fuels (solvents, paint sludges, oils and organic liquids)	Safety Data Sheets Industrial Emissions Licence	Swedish Chemicals Agency (KEMI) (2015), Occurrence and use of highly fluorinated substances and alternatives, Report 7/15 Norden (2013), Per- and Polyfluorinated Substances in the Nordic Countries

2.2 Potential PFAS Migration Pathways

To understand how PFAS may move into the environment, it is important to understand the environmental site settings and processes on site. This information can often be obtained from publicly accessible databases (such as the Geological Society of Ireland and EPA Maps), Annual Environmental Reports and Industrial Emissions Licences. The following are examples of the information that would help in building the CSM:

- Geographic location
- Geology – soil characteristics, depth to bedrock and type of bedrock
- Groundwater vulnerability
- Aquifer type
- Topography
- Surface water and stormwater drainage systems
- Surrounding land uses and abstractions
- On-site groundwater or surface water abstractions may mobilise PFAS compounds from on- or off-site sources
- Discharge locations

Table B - 2 gives examples of potential migration pathways that may be found at an industrial site and some questions that should be asked when conducting the Audit.

Table B - 2 Potential migration pathways that may be present on an industrial site

Number	Potential Source	Potential Migration Pathway	Source of information	Reference and further information
1	PFAS-containing aqueous film-forming foams and powders and contaminated firewater from historical fires and testing	If the AFFFs have been used or tested on an unsurfaced area (eg. For training), it is likely that PFAS will have entered the soil or the groundwater beneath the site. If the training was undertaken in a bunded area, the surface water drainage processes need to be assessed to determine whether the firewater will be treated prior to being discharged.	Firewater Risk Assessments Safety Data Sheets Historical fire incident reports	Kissa (2001)[19] Sweco (2020)[122] Figuiere et al (2025)[203]
3	Storage and use of chemicals and materials that may contain PFAS	Determine how the drainage system works if there are any spills from the storage tanks or areas. Determine how the drainage is treated, is it captured and treated as hazardous materials? Should it be tested for PFAS? Is it sent to a WWTP and if so, does the plant remove PFAS? Is there any pipework that is leaking that may contain PFAS containing substances?	Safety Data Sheets Industrial Emissions Licence Process flow diagrams	KEMI (2015)[33]
4	Groundwater abstraction	Any dewatering or abstraction on a site may mobilise and draw in potential plumes from on-site uses of PFAS which may have escaped to ground or surrounding land uses within the cone of depression of either or both: • Substations (AFFF storage, use or testing) • Stockpiling of material (such as municipal waste, recycled materials, soil or construction and demolition waste)	EPA Maps EPA LEAP Abstractions Portal Process flow diagrams	Glüge, J et al. (2020), An overview of the uses of per- and polyfluoroalkyl substances (PFAS)

Number	Potential Source	Potential Migration Pathway	Source of information	Reference and further information
		• Petrol stations or other bulk fuel storage locations (AFFF storage, use or testing) • Autobody repair shops, mechanics and car washes (car body waxes, windscreen wiper fluid, sealants, engine oil coolers and hydraulic fluid) • Farmland (herbicides, pesticides and biosolids obtained from wastewater treatment plants) How is this water discharged? Is it treated before being discharged? Is it tested for PFAS compounds?		
5	Combustion gases	Complete combustion of PFAS compounds is most likely in a two-stage process (primary combustion chamber and an afterburner). Recent research suggests that the incineration of materials >650°C will break PFAS bonds[90], however this is a subject of considerable study at present and has only been completed in laboratory trials However, research suggests that some compounds may remain in products of incomplete combustion.	Safety Data Sheets Industrial Emissions Licence Process flow diagrams	
6	Surface water and silt from silt traps	Stormwater could have traces of PFAS from fire-fighting training (if this has been carried out) or from other on-site sources references above and can be retained in concrete surfacing and leach[204]. Surface run-off from carpark areas or road surfaces are a known source of PFAS[46] and compounds may sorb to any silt particles in drainage or silt traps.	Safety Data Sheets Industrial Emissions Licence Process flow diagrams	
7	Industrial solid waste	Solid waste may consist of an accumulation of different PFAS containing materials.	Safety Data Sheets Industrial Emissions Licence Process flow diagrams	

2.3 Potential Receptors

Receptors may include environmental or human health receptors. These could include the following:

- Groundwater (eg. aquifers, springs)
- Surface water receptors (eg. Rivers, lakes and transitional waters)
- Soil
- Biota living in the above ecosystems
- Humans interacting with the above environmental media

3. Analysis and Preliminary Risk Based Assessment

After developing a site-specific diagrammatic or matrix CSM with all potential sources, pathways and receptors, determine whether there are any potentially complete linkages at the site that may need to be further assessed. A table can be used to complete this, such as the examples in Table B-3.

Table B - 3 Potential source, pathway and receptor linkages that may be found on industrial sites

Number	Potential Source	Potential Pathways	Potential Receptor	Linkage
1	Contaminated firewater from historical fires and testing Soil and/or groundwater containing PFAS from fire suppression used on historical fires or in tests	Groundwater (unsealed ground) Stormwater drains (concrete or asphalt surfaces)	Bedrock aquifers Surface water bodies where industrial effluent or stormwater drains are discharged	Potentially complete linkage
2	Contaminated firewater from historical fires or in tests PFAS-containing fire suppression systems stored on site	Stormwater drains	Surface water bodies where industrial effluent or stormwater drains are discharged	Linkage may be incomplete if the area is bunded and tested prior to being disposed of appropriately off-site. However, it is important to note that PFAS can be absorbed onto concrete surfaces. If clean surface run off or rainwater from contaminated areas are washed into bunds, it could contain trace concentrations of PFAS. If this is then discharged to a stormwater drain, then this could be a viable SPR Linkage.

If the preliminary risk assessment highlights that there are sources of PFAS at the site and several possible linkages with surface and groundwater bodies in particular, these linkages may need to be further assessed. This may involve testing the effluent for PFAS compounds.

Considering the increase in regulation of PFAS in Europe and globally, regulation could focus on sites and industries that may have PFAS present and where it may be in discharges. Should any PFAS be found in the effluent, it will be useful to determine any obvious sources, whether the concentration exceeds a human health or environmental quality standard and what measures might be required to minimise or prevent further discharges.

4. Supplementary Information

This section provides a summary on PFAS and regulations relevant to industrial sites and can be provided to site managers to give context to the Audit.

4.1 PFAS Context

PFAS are a group of approximately 14,000 recorded synthetic compounds[1] with waterproof, oilproof and fireproof properties. Due to these desirable characteristics, they are widely used in commercial and industrial products in a variety of industries. They have also been proven to be highly persistent in the environment, bio-accumulative and have negative effects on human health. Due to widespread use of these compounds globally, and in Ireland[4], concerns about legacy contamination are being raised and the compounds are becoming heavily regulated and banned.

The main pathway for PFAS compounds to impact humans is through drinking water and ingestion of contaminated food products[147]. Many studies have correlated potential relationships between elevated levels of PFAS in blood and adverse health impacts[147] such as:

- Increased cholesterol levels
- Alterations in liver enzymes

- Reduced immune response to vaccines in children
- Increased risk of high blood pressure and/or preeclampsia in pregnant women
- Small reduction in infant birth rates; and
- Increased risk of kidney or testicular cancer.

Ecological receptors, such as aquatic species, are more sensitive to PFAS exposure as they reside in or depend on water and may not be able avoid PFAS compounds, if their environment is impacted. Some studies have shown links between PFAS exposure and developmental reproductive effects in fauna and reduced fertility[133].

4.2 Regulatory Context

From a regulatory point of view most notable PFAS compounds are:

- PFOS (e.g. used in textile treatment, aqueous film forming foams [AFFFs], semi-conductor devices, chrome plating, hydraulic lubricant);
- PFOA (e.g. Teflon/non-stick coatings, AFFFs, street runoff); and
- PFHxS (e.g. AFFFs, textile treatment, pesticides, electronics, coatings).

These are currently all either restricted or regulated under the Stockholm Convention, which is ratified in EU Law, and consequently in Ireland. The Convention requires parties to reduce, or where feasible, to eliminate the release of persistent organic pollutants (POPs), of which these three PFAS are classified. Notwithstanding the three listed above, the EU are actively increasing the list of PFAS compounds that are regulated and plan in the future to regulate them as a group[205].

4.2.1 POPs Regulation (2020)

In the EU, the POPs Regulation (2020) implements the Stockholm Convention and aims to protect human health and the environment with specific control measures to manage the restriction of PFAS compounds[5]. The POPs Regulation is enacted in Ireland through the EU (Persistent Organic Pollutants) Regulations 2020 - S.I. No. 1 46/2020[102]. The POPs Regulation requires the following of its member states:

- By 4th July 2025, the use of PFOA-containing AFFFs in all forms will be banned. This includes PFOA, its salts and related compounds.
- Stockpiles containing PFOA or related substances present on site that are greater than 50kg and above the threshold concentrations of >0.025mg/kg for PFOA and its salts and >1mg/kg for any individual PFOA-related compounds or combination of PFOA-related compounds) need to be reported to the EPA and the PFOA disposed of as a waste. Currently, there are no facilities licensed to accept PFAS waste. At the time of writing this thesis, this waste is required to be shipped offshore.
- Limit of 10mg/kg of PFOS and its derivatives to be allowed in waste material (including soil).

4.2.2 European Registration, Authorisation and Restriction of Chemicals (2021) (EU REACH) Regulation

EU REACH Regulation regulate the registration, evaluation, authorisation and restriction of chemicals manufactured, imported and used within the EU and is constantly being revised. Currently, the manufacture and use of several PFAS compounds are being restricted under REACH. Perfluorinated carboxylic acids (C9-C14 PFCAs) their salts and precursors, which includes PFOA, have been restricted in the EU since February 2023. Several other compounds are being reviewed for potential restrictions and/or are on the candidate list of substances of very high concern.

4.2.3 Water Framework Directive

The European Water Framework Directive and its daughter Directives are transposed in Ireland through the Environmental Objectives (Surface Waters) Regulations[7] and Groundwater regulations [206]. It is the only current 'in-force' legislation that is relevant to environmental protection against PFAS contamination in Ireland. This defines PFOS and its derivatives as a "priority hazardous substance" and has regulatory environmental quality standards (including annual average and maximum allowable concentrations). The limits in the Surface Water Regulation apply to public authorities. However, the EPA have a responsibility under the

Regulations to eliminate PFOS where it can, such as through water discharges regulated by Industrial Emissions Licences (as outlined below in Section 2.5).

Currently there are no standards for PFAS compounds in groundwater. However, PFOS is defined as a hazardous substance in relation to groundwater, hence it should not be recorded above its detection limit down gradient of a groundwater discharge.

The European Commission has proposed to set environmental quality standards for the sum of 24 PFAS in surface waters. It is unknown as to when these standards will be implemented.[207] It was reported by the European Commission that groundwater standards are likely to be aligned with the Drinking Water Quality Standards (see below) which includes 20 PFAS[9].

4.2.4 Drinking Water Directive

The Drinking Water Directive is enacted in Ireland through the EU (Drinking Water) Regulations 2023 - S.I. No. 99/2023[8] and sets out the water quality standards for water intended for human consumption. From 11 January 2026, a "Sum of twenty PFAS" compounds must be analysed for and compliant with a standard of 100ng/L (0.1µg/l). The regulations require water providers, such as Uisce Éireann to carry out risk assessments for abstractions intended for human consumption and highlight sites that could be a source of PFAS.

4.2.5 Industrial Emissions Directive

In the context of the Industrial Emissions Directive (2010/75/EU), there are no current industrial emissions requirements for PFAS compounds in wastewater. However, the European Council and Parliament have recently discussed a revision on the Directive and the establishment of an Industrial Emissions Portal (IEP) to replace the existing E-PRTR regulation. The co-legislators have proposed to add PFOA and PFHxS to the substances listed in Annex II, with regulations potentially being enacted by 2028. The verdict should be issued by 2026[9].