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# SOS-ZEROPOL2030

# D4.1 Knowledge and outcomes from T4.1-T4.4 summarised in the 'integrated analysis' section of the individual case study pollutant template.

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## Part A: Per- and polyfluoroalkyl substances (PFAS)

Public

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# Disclaimer

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# 1. Executive Summary

The SOS-ZEROPOL2030 project aims to deliver a stakeholder-led European Seas zero-pollution framework to help achieve the European Union's long-term ambition of 'Zero Pollution' in European seas. The SOS-ZEROPOL2030 project focuses on marine pollution, where (i) per- and polyfluoroalkyl substances (PFAS) and (ii) tyre wear particles (TWPs) were selected as example pollutant case studies for 'chemical' and 'microplastic' pollution, respectively. It is important to note that these two very complex case study pollutants were intentionally chosen to allow the zero-pollution framework to be stress-tested under the most challenging scenarios. As a part of Work Package 4 (Integrated Case Study Pollutant Assessments) within the SOS-ZEROPOL2030 project, this deliverable report (D4.1. Part A) provides an integrated assessment for PFAS, while a separate report (D4.1 Part B) is available for TWPs. The integrated assessment comprises four primary components: (i) Mapping of primary emission sources along the value chain, (ii) Determination of environmental risk, (iii) Mapping of existing value chain and technological actions and strategies for TWP emission reduction, and (iv) Mapping of current governance strategies/efforts/arrangements for TWP pollution.

**Emission sources along the value chain:** Estimations indicate that point sources (without end-of-life emissions) are associated with about 5% of the total PFAS emission volume, diffuse sources account for the rest. The largest point emission sources of PFAS in Europe are PFAS production locations, with the majority of the direct emissions from PFAS production processes are to the air (~98%). Production locations are estimated to emit between 27 and 57 tonnes PFAS per annum to surface waters in Europe. Textiles, gases, medical devices, construction, and electronics are the five 'sectors' associated with the highest PFAS emissions. It is not currently possible to estimate end-of-life emissions (e.g. at incineration plants or landfill sites) due to a lack of data. As a result of their diverse and diffuse sources, estimates of PFAS emission volumes per environmental compartment are not currently reliable. Generally considered as inert during the use phase, fluoropolymers represent the largest mass of PFAS in end products, and may cause emissions of other, more harmful PFAS during production or end-of-life. Although regulations around fluorinated gases (F-gases) are strict, they, dominate the heating, ventilation, air conditioning and cooling application markets, and leakage cannot be prevented. Some of the most common F-gases metabolize into trifluoroacetic acid (TFA), a mobile and persistent PFAS which is increasing in concentration in natural environments. As PFAS are used in a wide range of industrial sectors and consumer products, banning the production, use, and import of PFAS in the EU is unlikely to result in a rapid decrease in emissions and pollution. Recommendations include:

(i) The PFAS restriction proposal could include derogations that allow time-limited use of specific PFAS for specific applications. With continued use comes continued production and/or import, as well as continued (but limited) emissions.

(ii) PFAS present in the environment may need to be removed from places where concentrations are high (e.g. airfields, military bases). Continued manufacturing, use, import and end-of-life treatment of PFAS requires continuous and stringent monitoring of PFAS in the environment.

(iii) A comprehensive sampling and analysis programme should ideally include various EU countries and types of landscapes, various environmental matrices, industrial sources and should investigate consumer products.

**Environmental risk:** The most marine environmental exposure data for PFOS, PFOA and novel PFAS is available for the Greater North Sea, Norwegian Sea, Barents Sea and Baltic Sea areas. Limited or no exposure data is available for Mediterranean and Black Sea. Sufficient toxicity data exists for PFOS and PFOA to conduct a hazard assessment, but sufficient toxicity data is only available for a minority of novel PFAS. A newly developed PFAS risk assessment tool indicated certain European sea regions have more than 25% of sampling stations with PFOS and PFOA levels above the toxicity threshold, while no European sea region had >14% of stations above the threshold for novel PFAS. Monitoring programmes sponsored by governmental bodies in which PFAS measurements are executed regularly and over a long time span are not yet in place in the EU. The combination of limited datapoints, constrained spatial and temporal coverage, and analytical limitations introduces significant uncertainty into the risk assessment of novel PFAS compounds. This uncertainty impacts not only the accuracy of current risk assessments but also the confidence with which environmental managers and policymakers can use these assessments to make decisions. Recommendations include:

(i) Expanded monitoring programmes that systematically include novel PFAS, with consistent sampling across a variety of geographic locations and matrices.

(ii) Improved analytical methodologies that increase the sensitivity, reliability, and comparability of PFAS measurements, especially for emerging compounds.

(iii) Long-term data collection to support trend analysis and better understand the persistence and accumulation of novel PFAS in various ecosystems.

**PFAS emission reduction measures:** Product chains in which PFAS play a role are often highly complex and not transparent in terms of which chemicals are used. The synthesis or end-of-life treatments of a material not classified in the existing REACH regulation categories may cause (significant) emissions of harmful PFAS. Some products will remain in which PFAS are considered essential. The incineration of fluoropolymers in rotary kiln ovens at standard conditions for municipal waste or for hazardous waste suffices to destroy almost all PFAS, reducing PFAS emissions compared to landfilling. Importantly, measures to significantly reduce PFAS emissions from production processes have been demonstrated to be implemented successfully. Where essential uses comprise fluorinated gases, measures should be taken to prevent leakage and to enable reuse. Recommendations include:

(i) An EU ban is required to force industries to move away from using PFAS in end products where possible. It is anticipated that safer alternatives can and will be found in a timespan of a few years for many products (by direct substitution with a safer chemical, redesign of a product, or finding a different product that fulfils the same function).

**Governance strategies/efforts/arrangements for PFAS pollution:** Governance analysis points to distinct regional differences in terms of political support (countries proposing the EU restriction all being in the Northeast Atlantic region, countries in the Black Sea region awaiting revisions of EU directives), levels of awareness (minimal awareness on the PFAS issue among stakeholders in the Black Sea region), institutional capacity (advanced research and monitoring programmes in the Northeast Atlantic, limited monitoring in the Black Sea). A disconnect appears to exist between the Bucharest Convention and EU-level governance of PFAS in the Black Sea, where EU-level regulatory developments happen rather independently from the regional sea convention. For the Northeast Atlantic there is more integration, where monitoring expertise at the OSPAR Convention is utilised in the updating of standards in EU legislation. Finally, there are **limited national/regional level initiatives independent from EU** level. The governance of pollutants of concern seems much stronger at the EU level than at the regional and national level. Recommendations include:

(i) The EU should support Member States in better monitoring of PFAS pollution from source-to-sea.
(ii) In parallel to the various policies, production restrictions and regulations being prepared at the EU level, the EU should encourage best practices already happening.
(iii) The EU should leverage and amplify the movement of PFAS-free alternatives, already rapidly growing, and seek synergies with industries such as recycling that can accelerate a transition to pollution-free and circular economy.

# 2. Introduction

## 2.1. General introduction to per- and polyfluoroalkyl substances (PFAS)

Per- and polyfluoroalkyl substances (PFAS) are classified as persistent environmental pollutants because microorganisms cannot mineralize them and sunlight cannot degrade them in the atmosphere below the ozone layer. The carbon-fluorine bond is so stable that it can only be broken by incineration at elevated temperatures (roughly in excess of 1000 °C for the most stable molecules)[1] or exposure to UV irradiation[2] as is present in the upper atmosphere. Some PFAS contain weak bonds such as ester or ether linkages, and these PFAS will typically degrade into smaller fragments.[3] As these smaller fragments are typically also classified as PFAS, this degradation process does not reduce the amount of PFAS, it only helps to disperse them further over the planet. For instance, some common refrigerants are so-called unsaturated hydrofluoroolefins (HFOs), which are photodegraded into trifluoroacetic acid (TFA) in the upper atmosphere. TFA subsequently undergoes wet and dry deposition into soils, rivers and the oceans.[4] TFA has been shown to accumulate in groundwater[5] and in surface water[6], with no half-life in the aqueous environment is currently known.[7] Concentrations have been shown to have increased over the last six decades in groundwater[5] and two decades in surface water[6]

Depending on physicochemical properties and end-of-life processing methods, PFAS are recycled, treated as solid waste, released into the air or discharged into groundwater or surface water. Only incineration will largely result in the destruction of PFAS, first to hydrofluoric acid (HF) and subsequently to calcium fluoride.[1, 8] All other end-of-life treatment processes that are currently used at large scale do not affect PFAS. As only 11% of the solid waste is incinerated globally[9], the net result is the accumulation of PFAS on the planet. Some types of discarded PFAS will accumulate in fixed locations, for example PFAS polymers in landfill sites[10], whereas small PFAS molecules in the aqueous compartment can “accumulate” in a far more dynamic manner. These small PFAS molecules can swiftly change their presence between different environmental compartments (e.g., sea, fish, humans, sea spray, ground water, plants, foods, etc.), causing a complicated equilibrium and quick proliferation of their presence in multiple organisms and environmental compartments.

With a higher rate of PFAS release into the environment than the rate of natural degradation, the concentration of PFAS is constantly increasing across all environmental compartments. PFAS have various negative impacts on the environment, which vary from greenhouse gas activity to ecotoxicity and adverse effects on the human health.[3] Some well-known PFAS, such as perfluorooctanesulphonic acid (PFOS) and perfluorooctanoic acid (PFOA), are also known to be carcinogenic. For these reasons, the manufacturing and use of these two PFAS (and a few others) is no longer allowed in the EU. Nevertheless, these two PFAS are already widely dispersed over the planet, still being released from products containing them and continue to be produced in some countries outside the EU. While the measured concentration may decrease at some highly polluted areas, the chemicals are still accumulating in the global environment. Only a global ban on the production and use of these chemicals can lead to a levelling off in their environmental accumulation. As there are large PFAS stocks currently residing in many consumer products and waste materials that will be released in the coming decades, this levelling off will only occur after many years. Therefore, even when these PFAS are banned and become a “legacy chemical”, they will remain with us for many years to come due to their persistence. That is the irony of PFAS; they have been promoted for their superior non-stick properties and will stick around with us for decades to come.

## 2.2. Background to WP4 of the SOS-ZEROPOL2030

As a part of Work Package 4 (WP4) within the SOS-ZEROPOL2030 project, this deliverable report document aims to provide both factual information and best-case risk assessment approaches to project partners and other work packages. This deliverable report (D4.1 Part A) focuses on one of the two case study pollutants (PFAS) within the SOS-ZEROPOL2030 project, with a separate report also available for tyre wear particles (TWPs).

This deliverable report document provides an overview of the findings in relation to emissions of per- and polyfluoroalkyl substances (PFAS) from:

i. Mapping of primary emission sources along the value chain (Section 3),
ii. Determination of environmental risk (Section 4),
iii. Mapping of existing value chain and technological actions and strategies (Section 5),
iv. Mapping of current governance strategies/efforts/arrangements (Section 6).

The deliverable report is specifically designed to be accessible to the intended end users within the project, as well as a diverse group of interested stakeholders. As such, the main report is a condensed summary of the findings and outcomes, while a detailed overview is presented in the accompanying Annexes for each of the 4 thematic areas described above. The main report contains brief summaries of the background and outcomes related to PFAS, as well as the main conclusions and recommendations for end users (research community, policy makers, value chain stakeholders). In-depth analysis of available and relevant information, descriptions of the used methodology, detailed data summaries and references to data sources can be found in the Annexes.

# 3. Assessment of primary PFAS emissions

## 3.1. Primary outcomes – PFAS emissions

Please refer to Annex A.1 for further information and in-depth analysis regarding the emission of PFAS.

### 3.1.1. Main point source emissions for PFAS in Europe

The largest point emission sources of PFAS in Europe are PFAS production locations, with emissions in the order of 400-4000 tonnes per annum.[3] The majority of the direct emissions from PFAS production processes are to the air (~98%), with only a small amount to surface waters. Production locations are estimated to emit between 27 and 57 tonnes PFAS per annum to surface waters in Europe.[3]

The second largest group of point source emissions are waste management facilities, such as wastewater treatment plants (WWTPs), waste incinerators, and landfill sites. These facilities process waste from all parts of the product chain, including part of the waste from PFAS manufacturing, waste from product usage in industry and by consumers, and from end-of-life products. PFAS emissions from these facilities could be to the air (volatile gases escaping from landfills[11, 12]), to surface water (WWTPs usually do not remove all PFAS from wastewater[13]), or to groundwater (landfill leachate could leak into the ground[14]).

Extrapolations of Flemish emission data suggest that the European emission of point sources to surface water is approximately 26 tonnes per annum.[15] These data relate to emissions from point sources to surface waters; industrial manufacturers, industrial and commercial PFAS users, and waste treatment facilities are all obliged to report on PFAS emissions.

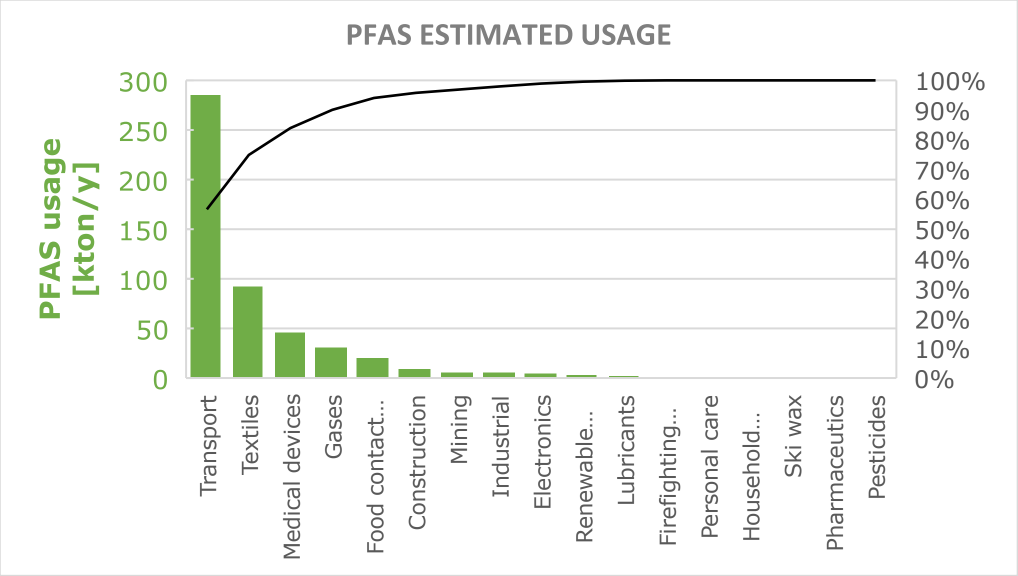
### 3.1.2. Most relevant diffuse sources of primary PFAS emissions in Europe

Diffuse emissions of PFAS occur predominantly in the use-phase, hence usage volumes likely relate quite closely to emissions. Figure 3.1-1 shows the usage volumes per sector. Emission volumes during use have been estimated in the restriction proposal,[16] which is based on a long list of defined assumptions and knowledge gained from stakeholder interviews. This estimation process indicated that applications within the TULAC (Textiles, Upholstery, Leather, Apparel, Carpets) domain cause the largest diffuse PFAS emissions (corresponding to approximately 10-35 kilotonnes per annum in the European Economic Area (EEA)), followed by emissions in the medical application sector (approximately 4-8 kilotonnes per annum). In addition, there are many other PFAS applications with emissions of <1 kilotonne per annum. Fluorinated gases (F-gases) have a direct emission volume of approximately 1.5 kilotonnes per annum for the amount introduced to the market in the same year. Taking into account stocks of F-gases that are not consumed upon use, the emission volume is estimated to be 31-38 kilotonnes per year. Figure 3.1-1 shows the contributions of all sectors.

Three general remarks are highlighted here:

- There is substantial data uncertainty in relation to the emissions of F-gases. It is inherently difficult to measure emissions related to the leakage of gases from diffuse sources and data about collection at end-of-life are scarce.
- Diffuse emissions are more important in terms of volumes than point source emissions.
- Although it is often challenging to relate specific PFAS use cases to emissions into specific environmental compartments, the largest diffuse emissions of PFAS

appear to be in the TULAC domain. These emissions relate both to air (dust particles) and to surface water (washing residues).



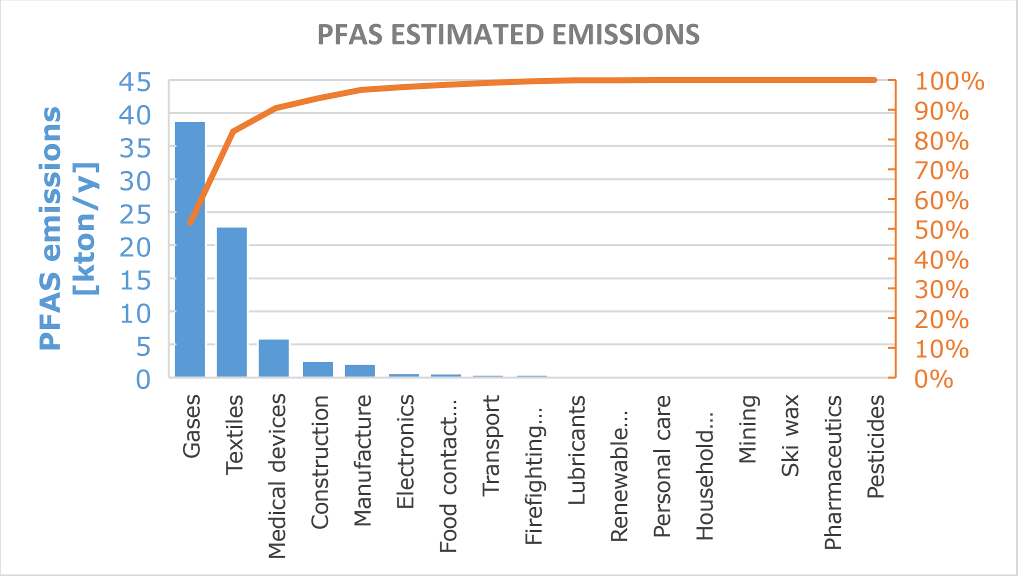


*Figure 3.1-1. Sectors with the highest estimated usage of PFAS in the EU (top) and highest estimated emissions of PFAS in the EU (bottom). Data and categorization of sectors are taken from the main document of the PFAS restriction proposal.*[17]

### 3.1.3. Largest contributors to overall PFAS emissions

Assuming that the stakeholder information used in the restriction proposal is the most accurate data that is available, it can be concluded that:

- A small number of application groups (gases, textiles/TULAC, medical devices, construction, manufacturing) are accountable for the largest share of diffuse PFAS emissions in the EEA.
- Diffuse PFAS emissions are likely to be higher in total volume than emissions from point sources. As measurements cannot be performed for all sources of diffuse PFAS

emissions, it is often very challenging to trace a specific chemical in the environment back to the original products or use cases.

- Some PFAS chemical manufacturing sites are currently important point sources for emissions into air and wastewater. They may also be the origin of a large share of PFAS emissions from chemical waste incinerators related to PFAS manufacturing.
- Usage of PFOS and PFOA was prohibited in the EU in 2009 and 2019. In 2022 however, they still form a significant share of PFAS volumes in Flemish wastewater. This may be related to the slow release of PFAS chemicals from firefighting foam or end-of-life consumer products, the continued import of products that still contain these chemicals into the EU, or degradation of other PFAS (e.g., the degradation of fluorotelomer alcohols which leads to the formation of PFOA[18]). These are classified as secondary emissions, and are therefore not taken into account in Figure 3.1-1.

Primary PFAS emissions are those where PFAS leak into a natural environment without undergoing any change in structure. Secondary emissions are those where (i) a non-PFAS undergoes a reaction in the environment and thereby forms a PFAS, and (ii) a PFAS is transformed in the environment into another PFAS. The estimation of primary emissions requires many assumptions and therefore estimated emission volumes often come with uncertainties of the same order of magnitude as the emission value.[17]

### 3.1.4. Most relevant PFAS chemicals in terms of their production/usage volumes

PFAS chemicals can be categorised in many ways. The PFAS restriction proposal is seen as the most comprehensive dataset, and this is therefore the main data source used herein. Production and emission volumes are not available per individual PFAS chemical and are primarily rough estimates for categories of PFAS chemicals. In this report we take the physical appearance, final environmental degradation products and transport pathways of PFAS emissions as leading arguments for the categorisation. We therefore consider the same main categories as in the restriction proposal:

- Perfluoroalkyl acids (PFAAs) and PFAA precursors: all small molecules (for example all molecules included in the risk assessment in this report), side chain fluorinated polymers (SCFPs, as they are PFAA precursors), but not including PFAS gases that are PFAA precursors;
- PFAS polymers, not including SCFPs;
- PFAS gases.

A comprehensive overview of physical properties and partitioning coefficients of low molecular weight PFAS is provided by the US Interstate Technology and Regulatory Council (ITRC)[19]. An overview of hazardous PFAS chemical categorization, likely emission scenarios and estimated production and emission volumes is presented in Table 3.1-1. Note that the total emission volumes shown in Table 3.1-1 do not closely match the estimations presented in Figure 3.1-1, which is mostly due to missing emission volume data and partially to categories of chemicals not covering all potential emissions. The significant difference in volumes shows the considerable uncertainty in the emission volume estimations.

*Table 3.1-1. PFAS chemicals categorization, likely emission scenarios and estimated production and emission volumes. Data are reused from Annex A of the PFAS restriction proposal (Tables A.10, A.18, and A.19).[16] Related to the structure and (un)availability of the data, the volumes should be considered as rough indications.*

| Main category | Subcategory | Most likely emission scenarios | Production volume for manufacturing + end products [kton/y] | Est. emissions volume [kton/y] |
|---|---|---|---|---|
| PFAAs and PFAA precursors | Solids (majority of molecules) | Used in (manufacturing of) end products -> Dissolved in production process wastewater, discharged to surface or sewage.<br>Solidified and integrated into end products -> incineration, landfilling | 86+25 | 0.2 |
| | Liquids (PFBA, PFPeA, PFBS, 4:2-FTOH and 6:2-FTOH) | Mixed with water and other solvents (emissions mostly into various wet streams[*]) | | n.a. |
| | Side-chain fluorinated polymers (SCFP) | Used as coating, high chance for 'leakage' into environment during use. Transforms into PFAA, then gets dissolved in water. | 0+9[#] | n.a. |
| PFAS polymers | Fluoro-polymers [FP] | Solid waste -> incineration or landfilling | 75+125 | 0.03 |
| | Perfluoro-polyethers [PFPE] | Liquid material used as lubricant -> leakage or absorbed onto cleaning materials with subsequent incineration/landfilling | 0+2[##] | n.a. |
| Fluorinated gases | All F-gases[$] | Most are used to produce polymers. Emissions occur from production process, usage or leakage into atmosphere.[*] | 95+64 | 3.6 |

[*] If absorbents such as granular activated carbon[20] are used in a production process to prevent PFAS emissions from happening, emissions could quickly shift from gaseous or liquid to solid state. PFAS should subsequently be desorbed from absorbents and mineralized, while adsorbents should be regenerated.[21]

[#] This is the total for sectors where a volume has been estimated for SCFPs specifically (TULAC, medical, electronics, renewable energy and construction).

[##] Sectors include TULAC, electronics, renewable energy and lubricants). [$]Data for PFAS gases is not separately available, hence all F-gases are included.

## Key messages:

- **PFAS emission volumes cannot be reliably estimated with the available data.** There is no obligation to register the volume of PFAS emissions in companies or anywhere else, apart from some very specific situations. Hence, emission estimates of PFAS categories were made in the restriction proposal using 'rules of thumb'. Emission estimates of individual substances requires even more specific data, while less data are available than for groups.

- **Low molecular weight PFAS chemicals in the solid or liquid state are of the highest concern among all PFAS with regards to human health and environmental impacts**. These PFAS chemicals are among the PFAS most often detected in water, soil and biota samples, and typically also represent the highest relative volumes in both the EU and the US[22]. PFOA and PFOS, examples of PFAS in this category, are still among the most often detected PFAS in environmental studies[23, 24], even though their production and use have been restricted in the EEA. Their concentrations are more pronounced in areas with higher population density, thus suggesting that environmental degradation of other PFAS into these (in other words: secondary emissions) plays an important role in the total levels found in the environment.[25] Concentrations of PFOA and PFOS in water are expected to remain almost at the same level until 2050, as shown for the Elbe river.[26]
- Emissions of F-gases mainly occur into the air. In this environmental compartment**, F-gases partially decompose into gaseous PFAS**. Some of these are water-soluble and end up in aquatic systems (freshwater and marine). Although discussions about the implications of increasing concentrations of F-gases (e.g., TFA) are ongoing, researchers generally agree about the need to establish monitoring programmes for this PFAS in particular.[5, 27] Long-chain PFAS are, on the other hand, more often found in less populated areas (e.g., the Arctic), than in densely populated areas.[25] This observation suggests that atmospheric transport plays an important role in the spread of PFAS over the world.
- **Fluorinated polymers (FPs) by themselves are generally considered to be less of an environmental issue** than the processing aids used during the manufacture of FPs, which themselves are often also PFAS. This is related to the assumed inertness of the polymers and their classification as polymers of low concern (PLC).[28] However, the PLC concept does not take emissions during production and end-of-life into account. Emissions during production can currently be more effectively contained than a decade ago[29]. While emissions due to waste incineration are likely to be minimal[8], emissions from other end-of-life processes (e.g., land-filling) are, however, still largely unknown. Combined with the extreme persistence of FPs, it cannot be justified that FPs are of low concern for environmental and human health. [30]

### 3.1.5. Most likely emission points for PFAS along the value chain

Table 3.1-2 contains a compilation of the PFAS emission estimations provided in the PFAS restriction proposal, and are broken down by life stage and by the environmental compartments into which they are emitted.[17] There is currently a lack of data to allow for categorising the 'End product manufacturing' and 'Usage' stages. These stages are related to the highest emission volumes in a generalized value chain. On a sector level, however, it could be very different. Insufficient data is available to assess the emissions in different parts of the value chain for the indicated sectors.

*Table 3.1-2. Breakdown of emissions into stages and environmental compartments, data are from Annex B of the PFAS restriction proposal.*[3]

| **Stage** | **Emissions to compartment [mid estimate, kton in 2020]** | | | **Total emissions [kton in 2020]** | | |
|---|---|---|---|---|---|---|
| | **Air** | **Water** | **Soil** | Low | **Mid** | High |
| PFAS manufacturing | 3.7 | 0.06 | 0 | 0.4 | 2.1 | 3.7 |
| End product manufacturing | 74 | | | 56 | 74 | 92 |
| Usage | | | | | | |
| End-of-life | n.a. | | | 3.7 | n.a. | 7.3 |

### 3.1.6. Consumer products considered to be the primary sources of PFAS emissions

Certain consumer goods are manufactured by industries that use a range of PFAS. Reliable knowledge on the volumes of PFAS used in specific categories of consumer products could help consumers, procurement professionals and policy officers when making decisions. Quantitative and complete usage volumes data are, however, not publicly available. Although the data presented in Annex A of the PFAS restriction proposal[16] are only estimates, there appear to be no better estimates currently available. The top 3 consumer product categories per sector with the highest usage volumes of PFAS are presented in Table 3.1-3. Use volumes of PFAS in consumer products do not necessarily correlate with emissions during manufacturing and usage (as discussed in Section 3.1.4). It is challenging and outside the scope of this study to generalize the so-called emission factors for most product categories, as it depends on many aspects, including the behaviour of the distributor, seller and consumer. Some examples of emission factors are available for gases in air conditioning and refrigeration uses.[31]

*Table 3.1-3. Top 3 consumer product categories per sector with the highest usage volumes of PFAS.[16] Grey text indicates that no volumes are mentioned in the source data and therefore ranking the products in terms of usage volumes was not possible.*

| **Sector** | **Top 3 of (consumer) product groups per sector with highest estimated PFAS usage volumes** | | |
|---|---|---|---|
| **Textiles [Annex A]** | Consumer apparel (water-resistant clothes and shoes) | Home textiles (stain-resistant carpets and furniture) | Technical textiles (various coatings) |
| **Gases [Annex A]** | Air conditioning (stationary & mobile) | Refrigeration (commercial, industrial, transport) | Closed-cell foams (polyurethane, for insulation) |
| **Medical devices [2nd stakeholder consultation]** | Propellants in metered dose inhalers | Other propellants and ethanol suspensions for drug formulation | Anaesthetics |
| **Construction [Annex A]** | Architectural paints and coatings | Coil coating (metal parts, e.g. for facades) | Wind turbine and solar panel coatings |
| **Electronics & semiconductors *** | Wires and cables | Printed circuit boards | Capacitors |
| **Food contact materials [Annex A]** | Parts in industrial lines for food & feed production | Consumer cook & bakeware with anti-stick coatings | Beverage can coatings |

### 3.1.7. Most common transportation pathways

The pathways along which PFAS travel from the locations they are emitted via various environmental compartments to their accumulation zones, depends strongly on multiple factors:

- Ionic PFAS chemicals dissolve well in water and are therefore more likely to be transported in aqueous media than non-charged PFAS chemicals.
- PFAS gases and fluorotelomer alcohols (FTOHs) are gaseous or volatile, which makes atmospheric transport the most likely transportation route.
- Long-chain PFAS molecules ($>C_8$) tend to adhere more strongly to sediment, soil, and other solids than short-chain analogues.
- Amphiphilic PFAS molecules, such as PFOS and PFOA, tend to accumulate on surfaces and boundary layers, for instance on sediment particles and in sea foam.

Most research has focused on the transportation of PFAS chemicals from known polluted areas like airports, military bases and firefighting training sites into sediments and aqueous systems. Known polluted areas typically attract more attention than areas which are more remote or considered more pristine. Significant amounts of PFAS are transported through the air, as they are found consistently in remote areas.[32, 33] Passive sampling has been used to demonstrate that the import and export flows of the most common PFAS are of a similar magnitude, thereby indicating that water is still a more important transport medium than air for PFAS in general[34]. In marine environments, both horizontal and vertical transportation mechanisms affect further distribution. There are also indications that co-transport with particles (sediment, microplastics, etc.) can play a significant role in environmental transport of PFASs in aqueous matrices, especially for the more hydrophobic PFAS. [32]

### 3.1.8. Marine environmental compartments are considered primary accumulation zones for PFAS.

Coastal waters, especially when close to estuaries or rivers with high PFAS concentrations, typically show the highest concentrations of PFAS in measurements of seawater samples.[24, 35, 36] This indicates that a steady state has not yet been reached, with the input mass per time unit of ∑PFAS (all PFAS taken into account in a specific study) being higher than the mineralized mass of ∑PFAS. Furthermore, surface water typically contains higher concentrations of PFAS than deeper water[24, 37]. As with other chemicals, the interchange of pollutants between surface water and deeper water depends strongly on the circumstances (higher exchange in the North Sea, little in the Black Sea). The concentration gradient slowly drives water-soluble PFAS chemicals to deep seas and oceans. Due to the large volume of deep water compared to surface water, deep water is considered to be the main final sink for these chemicals even though concentrations at the surface are usually significantly higher than in deeper water. [38, 39]

# 4. Assessment of PFAS risks

## 4.1. PFAS risk assessment approaches

Please refer to Annex A.2 for further information and in-depth analysis regarding risk assessment of PFAS.

This section describes the development of a risk assessment framework(s) that incorporated the following components:

- An exposure assessment of PFAS based on reported exposure concentrations across different regional seas and key EU regions, which is subsequently used to identify current data gaps.
- A toxicological assessment of PFAS based on database and literature data, which is subsequently used to identify current data gaps.
- A method to integrate this exposure and toxicological data into the most comprehensive environmental risk assessment for the specific case study pollutants, reflecting the current capability to evaluate the risks associated with this complex and emerging pollutant.

For the purposes of this study, the group of PFAS chemicals is divided into older/legacy PFAS (PFOS and PFOA) and novel/emerging PFAS. The methodology used for conducting the exposure assessment of PFAS is presented in Section A.2.1 and Section A.2.2, while the limitations with existing PFAS data are discussed in Section A.2.3. The methodology used for conducting the hazard assessment of PFAS is presented in Section A.2.4. Finally, the methodology used to develop the PFAS risk assessment is presented in Section A.2.6.

### 4.1.1. SOS-ZEROPOL2030 risk assessment framework

The scenario-based risk assessment concept that has been developed in WP4 of SOS-ZEROPOL2030 reflects the fact that the chosen case study pollutants were already expected in advance to have insufficient exposure and toxicity (hazard) data associated with them. In an ideal situation (**Scenario 1**), there is already sufficient empirical exposure and hazard data available on which to base or conduct a robust risk assessment (Figure 4.1-1). Such situations are mostly applicable to single legacy chemical pollutants that have been studied extensively over many years. However, for some pollutants, especially those which are (i) complex (e.g. mixtures or a combination of particles and chemicals), (ii) difficult to measure in the environment, and/or (iii) classified as emerging contaminants, it is rare that there is either sufficient exposure and or hazard data to enable a robust risk assessment. In such cases, there is potential to utilise modelling approaches to 'fill in the gaps'. Within SOS-ZEROPOL2030, **Scenario 2a** is defined as a situation where there is sufficient exposure data available for a risk assessment to be conducted, but insufficient hazard data. In this scenario, any risk assessment would need to rely upon the use of models to generate the necessary hazard input data. Similarly, **Scenario 2b** is defined as a situation where there is sufficient hazard data available for a risk assessment to be conducted, but insufficient exposure data. In this scenario, any risk assessment would need to reply upon the use of models to generate the necessary exposure input data. For Scenarios 2a and 2b the robustness of the risk assessment for the selected pollutant is considerably reduced, although the overall robustness is strongly influenced by the quality of the modelled data. In the final and 'worst case' situation (**Scenario 3**), there is insufficient empirical exposure data and insufficient empirical hazard data. In this scenario, any risk assessment of a specific pollutant would need to rely upon the use of models to generate the necessary exposure and hazard input data. For Scenario 3 the robustness of the risk assessment for the selected pollutant is most likely to be the lowest in terms of robustness, although the ability to generate high quality modelled data could potentially mitigate some of the uncertainty.

It is important to highlight that the goal of this work in SOS-ZEROPOL2030 is not to generate a final or complete risk assessment for either of the case study pollutants. Rather, PFAS and TWPs were selected as two of the most complex emerging pollutants from a European (and global) perspective, and the goal is to develop a risk assessment framework that forms an important and integrated component of the overall SOS-ZEROPOL2030 pollution mitigation framework and road map. In a sense, we use PFAS and TWPs as 'worst case' pollutants from a risk assessment perspective, to identify if it would be possible to conduct a meaningful and robust risk assessment were sufficient real/empirical exposure and hazard data available. By applying the scenario-based risk assessment framework to the two case studies, we also demonstrate how it can be used to (i) identify current knowledge and data gaps for these pollutants, and (ii) how modelling approaches can be utilised to (at least partially) fill in these knowledge gaps until the necessary empirical data can be generated.

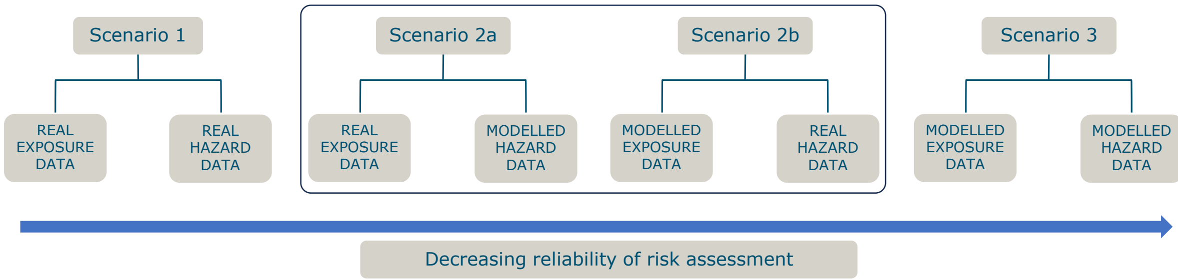


*Figure 4.1-1. Overview of the 3 risk assessment scenarios developed and utilised within SOS-ZEROPOL2030. Each scenario reflects the availability of empirical exposure and hazard data for a specific pollutant, and indicates when modelled data needs to be utilised. It also demonstrates how the reliability of the risk assessment decreases with an increasing reliance upon modelled data. Importantly, this can be used as a basis for identifying knowledge and data gaps that need to be addressed before a robust risk assessment can be achieved.*

### 4.1.2. PFAS Risk Assessment Tool – the PFAS RAT

To support environmental risk management and decision-making, we have developed a comprehensive risk assessment tool (RAT) that enables users to explore the risk associated with reported concentrations of PFOS, PFOA, and various novel PFAS compounds across European regional seas. The tool aggregates PFAS data from validated sources, including governmental and non-governmental environmental monitoring programmes (OSPAR, Le Monde and a scientific literature review), ensuring high data quality. Assessment Factors (AFs) are applied to compounds with known toxicological thresholds based on peer-reviewed literature and regulatory guidelines. For compounds without specific thresholds, the tool enables flexible application of alternative factors based on best available data and expert input. The PFAS RAT has the potential to aid in ongoing PFAS risk management efforts, informing both regulatory frameworks and pollution mitigation strategies tailored to Europe's diverse marine ecosystems.

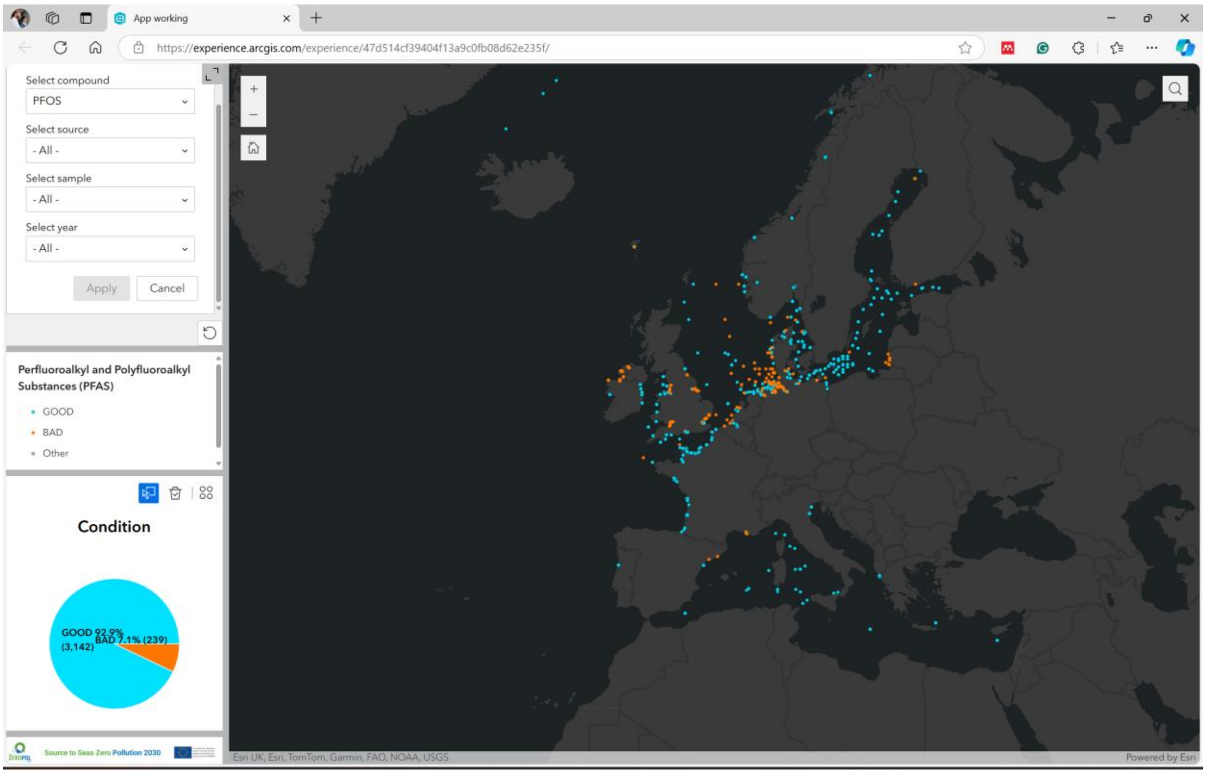
A link to the interactive PFAS RAT is provided here:
https://experience.arcgis.com/experience/47d514cf39404f13a9c0fb08d62e235f/

This RAT represents a powerful resource for environmental scientists, regulators, and policymakers working to manage PFAS contamination in European regional seas. By offering a multifaceted approach that includes compound, dataset, matrix, and temporal filters, the tool allows users to generate targeted risk assessments. The integration of AFs provides context on the ecological risks posed by these compounds, supporting science-based decision-making and contributing to the ongoing protection of European marine environments from PFAS pollution. More detail regarding the development and functionality of the PFAS RAT is provided in Section A.2.5 (Annex A).

## 4.2. Primary outcomes – PFAS risk assessment

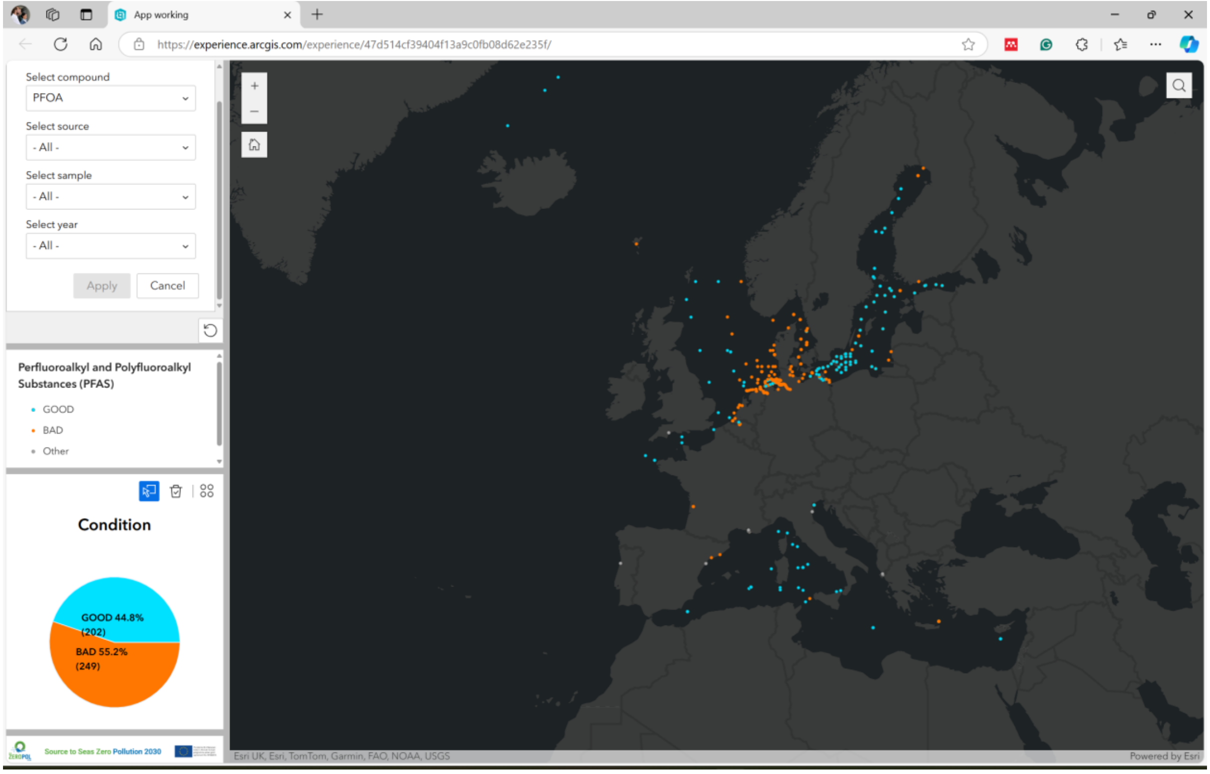
### 4.2.1. PFOS and PFOA exposure in the (marine) environment

Currently, the most exposure data for PFOS and PFOA is available for the Greater North Sea, Norwegian Sea, Barents Sea and Baltic Sea areas, all of which have >100 data points over multiple years. Limited or (in the worst case) no PFOS or PFOA exposure data is available for the other European sea areas, such as the Mediterranean Sea and Black Sea. An overview of the currently available PFOS and PFOA exposure concentration datapoints across European Seas is presented in Figure 4.2-1 (PFOS) and Figure 4.2-2 (PFOA). The source data comes from a combination of multiple databases and scientific literature, and covers water, sediment and biota matrices, as well as multiple years.



Select compound: PFOS
Select source: - All -
Select sample: - All -
Select year: - All -

*Figure 4.2-1. All currently available PFOS exposure concentration datapoints across European Seas. Source data comes from multiple databases and scientific literature, covering water, sediment and biota matrices, as well as multiple years.*



Select compound: PFOA

Select source: - All -

Select sample: - All -

Select year: - All -

*Figure 4.2-2. All currently available PFOA exposure concentration datapoints across European Seas. Source data comes from multiple databases and scientific literature, covering water, sediment and biota matrices, as well as multiple years.*

### 4.2.2. PFOS and PFOA hazard assessment in the (marine) environment

A detailed summary of the current knowledge regarding PFAS hazards in the aquatic environment and the AF-based hazard assessment approach selected for use in the current study is presented in Section A.2.4 (Annex A). Despite a reasonable amount of toxicity data being available for the legacy PFAS chemicals (PFOS and PFOA), there is insufficient aquatic ecotoxicity data available in the ECOTOXicity Knowledgebase to construct species sensitivity distributions (SSDs) and so the AF approach was implemented. This means that there is also insufficient ecotoxicity data to provide region- or community-specific hazard and risk assessment for PFOS and PFOA across the different seas in the EU. Using all available ecotoxicity data for seawater and freshwater, the AF approach provided predicted no effect concentrations (PNECs) of 0.4 and 0.3 ng/L for PFOS and PFOA, respectively. There were no observed effect concentration (NOEC) data available for three trophic levels meaning an AF of 10 could be used, which is the lowest AF that can be used when sufficient data is available. These PNEC values are low, indicating that the toxicity threshold is low in aquatic environments.

### 4.2.3. PFOS and PFOA risk assessment

Based on the availability of marine environmental exposure data and hazard data, the risk assessment of PFOS and PFOA in the marine environment are classified as Scenario 1 in our SOS-ZEROPOL20230 risk assessment framework (Figure 4.2-3). However, the use of

AFs to conduct the hazard assessment means that it could also be considered as Scenario 2a (modelling of available toxicity data). It should be noted that the amount of exposure and hazard data for PFOS and PFOA is sufficient for risk assessment in some of the European seas (Northeast Atlantic and Baltic Sea), but insufficient for others (Mediterranean Sea and Black Sea). The insufficient exposure data currently available for the Mediterranean Sea and Black Sea and would be considered Scenario 2b. As such, generation of additional exposure and toxicity data for PFOA and PFOS would be beneficial. To determine a good or bad status, the risk assessment utilised the thresholds defined in Section A.2.6 (Annex A). Based on the available exposure and hazard data for PFOS, normalised by the number of observations, the risk assessment identified the Adriatic Sea, the Celtic Sea and the Western Mediterranean as the European sea regions with the highest risk from PFOS exposure, with 25% or more of the sampling stations above the threshold (Table 4.2-1). Based on the available exposure and hazard data for PFOA, normalised by the number of observations, the risk assessment identified the Adriatic Sea, Aegean-Levantine Sea, Baltic Sea, Barents Sea, Bay of Biscay and the Iberian Coast, and the Greater North Sea, incl. the Kattegat and the English Channel as the European sea regions with the highest risk from PFOA exposure, with 25% or more stations above the threshold. Only 7% of PFOS datapoints across all European sea regions were estimated to be above the threshold, while 55% of PFOA datapoints across all European sea regions were above the threshold.

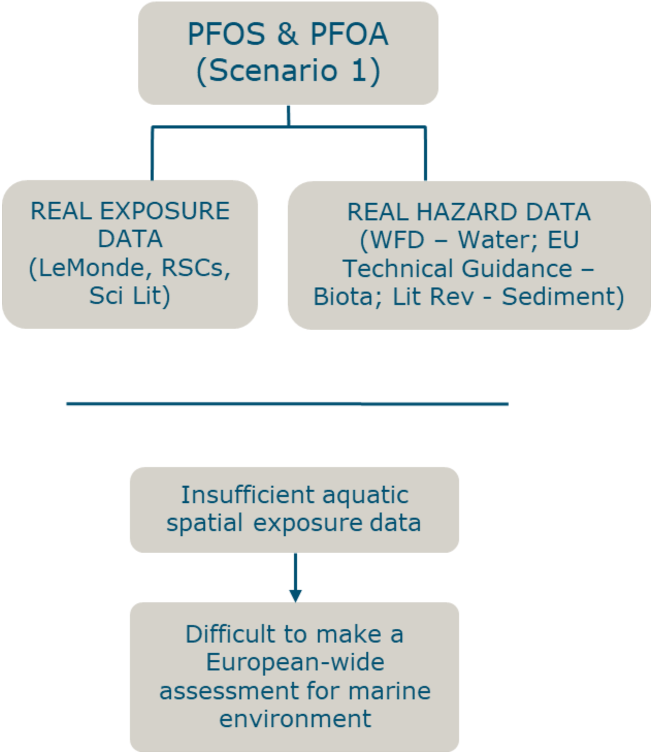


*Figure 4.2-3. Assessment of the available PFAS data indicated that there was currently sufficient empirical exposure and empirical hazard data for a robust risk assessment to be conducted to the specific PFAS chemicals PFOS and PFOA. As a result, PFOS and PFOA can be considered as 'Scenario 1' pollutants.*

*Table 4.2-1. PFOS and PFOA risk assessment indicating the number PFOS and PFOA datapoints (across all years) in each of the European sea regions and the percentage of datapoints that are above (BAD) and below (GOOD) the hazard assessment threshold. A total European risk assessment for PFOS and PFOA is presented at the bottom of the table.*

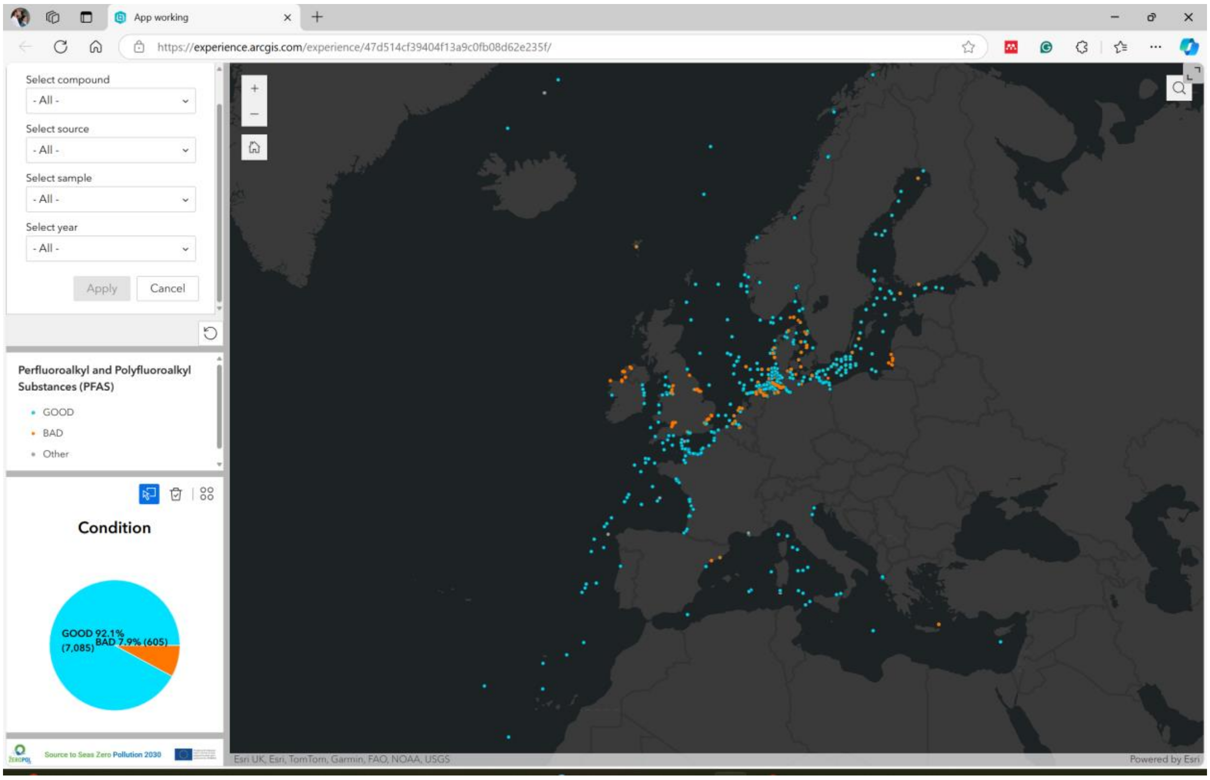
| **European Sea Region** | **# PFOS Datapoints** | **Percentage +/- threshold** | **# PFOA Datapoints** | **Percentage +/- threshold** |
|---|---|---|---|---|
| **Adriatic Sea*** | **14** | | 8 | |
| BAD | 4 | 28.57 | 6 | 75.00 |
| GOOD | 10 | 71.43 | 2 | 25.00 |
| **Aegean-Levantine Sea*** | **12** | | **12** | |
| BAD | 0 | 0.00 | 3 | 25.00 |
| GOOD | 12 | 100.00 | 9 | 75.00 |
| **Atlantic** | **0** | | **0** | |
| BAD | 0 | 0.00 | 0 | 0 |
| GOOD | 0 | 0.00 | 0 | 0 |
| **Baltic Sea*** | **163** | | **163** | |
| BAD | 16 | 9.82 | 84 | 51.53 |
| GOOD | 147 | 90.18 | 79 | 48.47 |
| **Barents Sea*** | **309** | | **8** | |
| BAD | 0 | 0.00 | 2 | 25.00 |
| GOOD | 309 | 100.00 | 6 | 75.00 |
| **Bay of Biscay and the Iberian Coast*** | **26** | | **2** | |
| BAD | 0 | 0.00 | 2 | 100.00 |
| GOOD | 26 | 100.00 | 0 | 0.00 |
| **Celtic Seas*** | **149** | | **3** | |
| BAD | 40 | 26.85 | 0 | 0.00 |
| GOOD | 109 | 73.15 | 3 | 100.00 |
| **Greater North Sea, incl. Kattegat and English Channel*** | **2165** | | **172** | |
| BAD | 163 | 7.53 | 146 | 84.88 |
| GOOD | 2002 | 92.47 | 26 | 15.12 |
| **Greenland Sea** | **27** | | **27** | |
| BAD | 0 | 0.00 | 0 | 0.00 |
| GOOD | 27 | 100.00 | 27 | 100.00 |
| **Iceland Sea** | **1** | | **1** | |
| BAD | 0 | 0.00 | 0 | 0.00 |
| GOOD | 1 | 100.00 | 1 | 100.00 |
| **Ionian Sea and the Central Mediterranean Sea** | **15** | | **6** | |
| BAD | 0 | 0.00 | 0 | 0.00 |
| GOOD | 15 | 100.00 | 6 | 100.00 |
| **Macaronesia** | **0** | | **0** | |
| BAD | 0 | 0.00 | 0 | 0 |
| GOOD | 0 | 0.00 | 0 | 0 |
| **North Atlantic** | **11** | | **1** | |
| BAD | 1 | 9.09 | 1 | 0.00 |
| GOOD | 10 | 90.91 | 0 | 100.00 |
| **Norwegian Sea** | **429** | | **9** | |
| BAD | **0** | 0.00 | 0 | 0.00 |

| | | | | |
|---|---|---|---|---|
| GOOD | 429 | 100 | 9 | 100.00 |
| **Western Mediterranean Sea*** | **60** | | **39** | |
| BAD | 15 | 25 | 5 | 12.82 |
| GOOD | 45 | 75 | 34 | 87.18 |
| **TOTAL** | **3381** | | **451** | |
| BAD | 239 | 7.07 | 249 | 55.21 |
| GOOD | 3142 | 92.93 | 202 | 44.79 |

*Sea basins with 25% or more stations exhibiting PFOS or PFOA levels higher than the threshold determined in the hazard assessment.

### 4.2.4. Novel PFAS exposure in the (marine) environment

Currently, the most exposure data for novel PFAS is available for the Greater North Sea, Norwegian Sea and Baltic Sea areas, all of which have >100 data points over multiple years. Limited or (in the worst case) no novel PFAS data is available for other European sea areas, such as the Mediterranean Sea and Black Sea. An overview of the currently available novel PFAS exposure concentration datapoints across European Seas are presented in Figure 4.2-4. The source data comes from a combination of multiple databases and scientific literature, and covers water, sediment and biota matrices, as well as multiple years.


https://experience.arcgis.com/experience/47d514cf39404f13a9c0fb08d62e235f/

Select compound: - All -
Select source: - All -
Select sample: - All -
Select year: - All -

*Figure 4.2-4. All currently available PFAS exposure concentration datapoints across European Seas (including novel PFAS as well as PFOS and PFOA). Source data comes from multiple databases and scientific literature, covering water, sediment and biota matrices, as well as multiple years.*

### 4.2.5. Novel PFAS hazard in the (marine) environment

A detailed summary of the current knowledge regarding the availability of novel PFAS toxicity data and hazard assessment in the European marine environment and other environmental matrices is presented in Section A.2.4 (Annex A). There are some aquatic ecotoxicity data available for 35 of the 48 PFAS chemicals (not including PFOS and PFOA) for which there is existing marine environmental exposure data. The amount of toxicity data ranged considerably for the different novel PFAS (see Table 7.4-2 in Section A.2.4 of Annex A). There was sufficient toxicity data (one or more data points) for these 35 novel PFAS for PNEC calculations using the AF approach for hazard assessment to be conducted. However, there is currently insufficient toxicity data for key marine species regarding novel PFAS to calculate region- or community-specific PNECs across the different seas in the EU. Using all available ecotoxicity data for seawater and freshwater, the AF approach provided PNECs that ranged from 0.4 ng/L (PFNA; most toxic) to 108 µg/L (FRD-902; least toxic). The amount of toxicity data available for each individual novel PFAS chemical varied significantly, meaning that AFs of 10-1000 were applied for individual chemicals. For example, 13 of the novel PFAS had only acute toxicity data and no long-term NOEC data, meaning that an AF of 1000 had to be applied. The resulting PNEC values span multiple orders of magnitude, indicating that the risk of effects from individual novel PFAS can vary significantly.

### 4.2.6. Novel PFAS risk assessment

Based on the availability of marine environmental exposure data and hazard, risk assessment of PFAS in the marine environment is classified as Scenario 2a in our SOS-ZEROPOL20230 risk assessment framework (Figure 4.2-5). This is primarily due to the need for using AFs to conduct the novel PFAS hazard assessment and that toxicity data is only available for a relatively small number of novel PFAS compounds. It should be noted that the amount of exposure and hazard data for novel PFAS is sufficient for risk assessment in some of the European seas (Northeast Atlantic and Baltic Sea), but insufficient for others (Mediterranean Sea and Black Sea). The insufficient exposure data currently available for the Mediterranean Sea and Black Sea and would be considered Scenario 2b (or even Scenario 3). As such, generation of additional exposure and toxicity data for novel PFAS (including those for which there is currently no exposure and/or toxicity data) would be beneficial. To determine a good or bad status, the risk assessment utilised the thresholds defined in Section A.2.6 (Annex A). For novel/emerging PFAS substances with limited data, the risk assessment indicates that the Adriatic, Greater North Sea, Baltic Sea and North Atlantic are the most at risk, with 10% or more of their datapoints over the thresholds. None of the European seas have more than 14% of stations above the threshold (Table 4.2-2) and only 8.5% of novel PFAS datapoints across all European sea regions were estimated to be above the threshold.

There are substantial limitations to conducting comprehensive risk assessments for novel PFAS due to a combination of limited data availability, restricted spatial and temporal coverage, and analytical challenges. One of the primary challenges in risk assessment for novel PFAS is the scarcity of datapoints. Compared to legacy PFAS (PFOS and PFOA), novel PFAS compounds have only recently been included in environmental monitoring programs, leading to a much smaller data pool. This scarcity restricts our ability to characterize the environmental presence, behaviour, and risks of these compounds with confidence. With fewer datapoints, it becomes difficult to conduct statistically robust analyses or to extrapolate findings across larger geographic regions or time periods. The lack of data is especially problematic for compounds with unknown or poorly understood toxicological profiles, for which environmental threshold values, such as PNECs, may not yet be established. Without reliable data on concentration levels and toxicological effects, uncertainty remains high in risk assessments. This limitation underscores the need for expanded PFAS monitoring initiatives that include a more comprehensive array of compounds, particularly in areas where data gaps are most pronounced.

The restricted spatial and temporal coverage of available PFAS data further complicates risk assessment for novel PFAS. Current datasets are often concentrated in specific regions, typically near industrial areas or known contamination hotspots, while vast portions of European marine and freshwater environments remain unmonitored. This uneven spatial distribution hampers our ability to draw meaningful conclusions about PFAS presence and behaviour across broader geographic scales, especially in remote or ecologically sensitive areas where PFAS contamination may also be occurring. Temporal limitations also impact the assessment. Many monitoring efforts only began relatively recently, particularly for novel PFAS compounds, resulting in a lack of temporal data necessary to evaluate trends over time. Consequently, there is limited information on the persistence, accumulation, or seasonal variation of these compounds in the environment. This temporal gap hinders our understanding of the long-term risks associated with novel PFAS, which are often as persistent, if not more so, than legacy PFAS compounds.

Accurate risk assessment of novel PFAS is constrained by analytical limitations that affect data reliability and comparability. Many novel PFAS are challenging to detect and quantify due to their diverse chemical structures, which often require specialized analytical methods. Standardized methods have been developed for some legacy PFAS (e.g., PFOS and PFOA), but novel PFAS frequently require non-standardized or experimental techniques, resulting in variability between datasets and potential inaccuracies. Analytical challenges also include the limits of detection and quantification for novel PFAS in different matrices (e.g., water, sediment, biota). For example, trace concentrations of PFAS in complex matrices such as sediment or biota may fall below detection thresholds, leading to underestimation of true environmental levels. Furthermore, cross-contamination during sample collection and processing is a known issue in PFAS analysis, which can lead to false positives or inflated concentration levels. These factors introduce uncertainty into the datasets, and by extension, into the resulting risk assessments.

*Table 4.2-2. Novel PFAS risk assessment indicating the number datapoints (across all years) in each of the European sea regions and the percentage of datapoints that are above (BAD) and below (GOOD) the hazard assessment threshold. A total European risk assessment for novel PFAS is presented at the bottom of the table.*

| European Sea Region | # Novel PFAS Datapoints | Percentage +/- threshold |
|---|---|---|
| **Adriatic Sea** | **86** | |
| BAD | 6 | 6.98 |
| GOOD | 80 | 1333.33 |
| **Aegean-Levantine Sea** | **189** | |
| BAD | 3 | 1.59 |
| GOOD | 186 | 6200.00 |
| **Atlantic** | **36** | |
| BAD | 0 | 0.00 |
| GOOD | 36 | 100.00 |
| **Baltic Sea** | **1158** | |
| BAD | 162 | 13.99 |
| GOOD | 996 | 86.01 |
| **Barents Sea** | **56** | |
| BAD | 2 | 3.57 |
| GOOD | 54 | 96.43 |
| **Bay of Biscay and the Iberian Coast** | **157** | |
| BAD | 2 | 1.27 |
| GOOD | 155 | 98.73 |
| **Celtic Seas** | **83** | 53.55 |
| BAD | 0 | 0.00 |
| GOOD | 83 | 100.00 |
| **Greater North Sea, incl. the Kattegat and the English Channel** | **1739** | |
| BAD | 184 | 10.58 |
| GOOD | 1555 | 89.42 |
| **Greenland Sea** | **222** | |
| BAD | 0 | 0.00 |
| GOOD | 222 | 100.00 |
| **Iceland Sea** | **5** | |
| BAD | 0 | 0.00 |
| GOOD | 5 | 100.00 |
| **Ionian Sea and the Central Mediterranean Sea** | **102** | |
| BAD | 0 | 0.00 |
| GOOD | 102 | 100.00 |
| **Macaronesia** | **12** | |
| BAD | 0 | 0.00 |
| GOOD | 12 | 100.00 |
| **North Atlantic** | **9** | |
| BAD | 1 | 11.11 |
| GOOD | 8 | 88.89 |
| **Norwegian Sea** | **78** | |
| BAD | 0 | 0.00 |
| GOOD | 78 | 100.00 |

| | | |
|---|---|---|
| **Western Mediterranean Sea** | **377** | |
| BAD | 6 | 1.59 |
| GOOD | 371 | 98.41 |
| **TOTAL** | **4309** | |
| BAD | 366 | 8.49 |
| GOOD | 3943 | 91.51 |

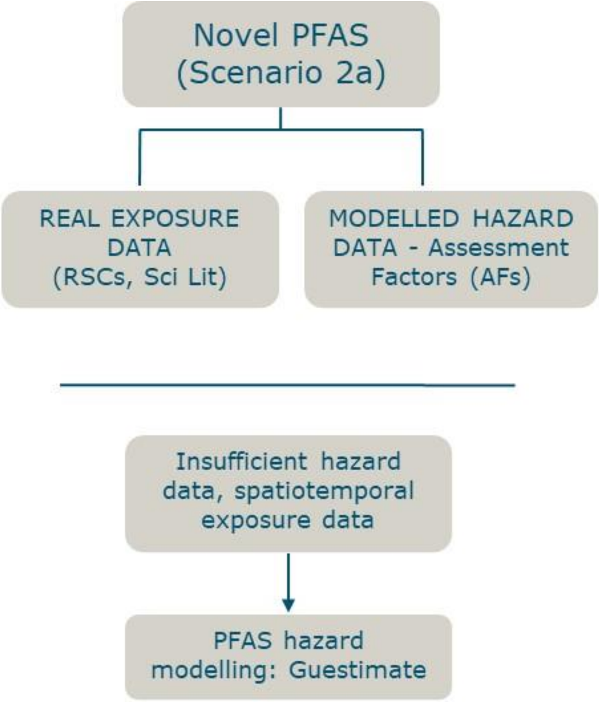


*Figure 4.2-5. Assessment of the available PFAS data indicated that there was currently sufficient empirical exposure data for a robust Scenario 1 level risk assessment to be conducted for the new generation of novel PFAS chemicals. However, there is insufficient empirical hazard data available and so modelling is required to generate predicted hazard data for use in the risk assessment. As a result, novel PFAS can be considered as 'Scenario 2a' pollutants. Assessment of the available data indicated an insufficient amount of aquatic species hazard data, as well as an insufficient amount of spatiotemporal exposure data, is currently available to allow a European-wide assessment for the marine environment. In particular, modelling of PFAS hazard is currently considered to be only able of generating low quality data.*

# 5. Assessment of PFAS emission reduction potential

## 5.1. Primary outcomes – Existing product chain and technological actions for emission reduction of PFAS

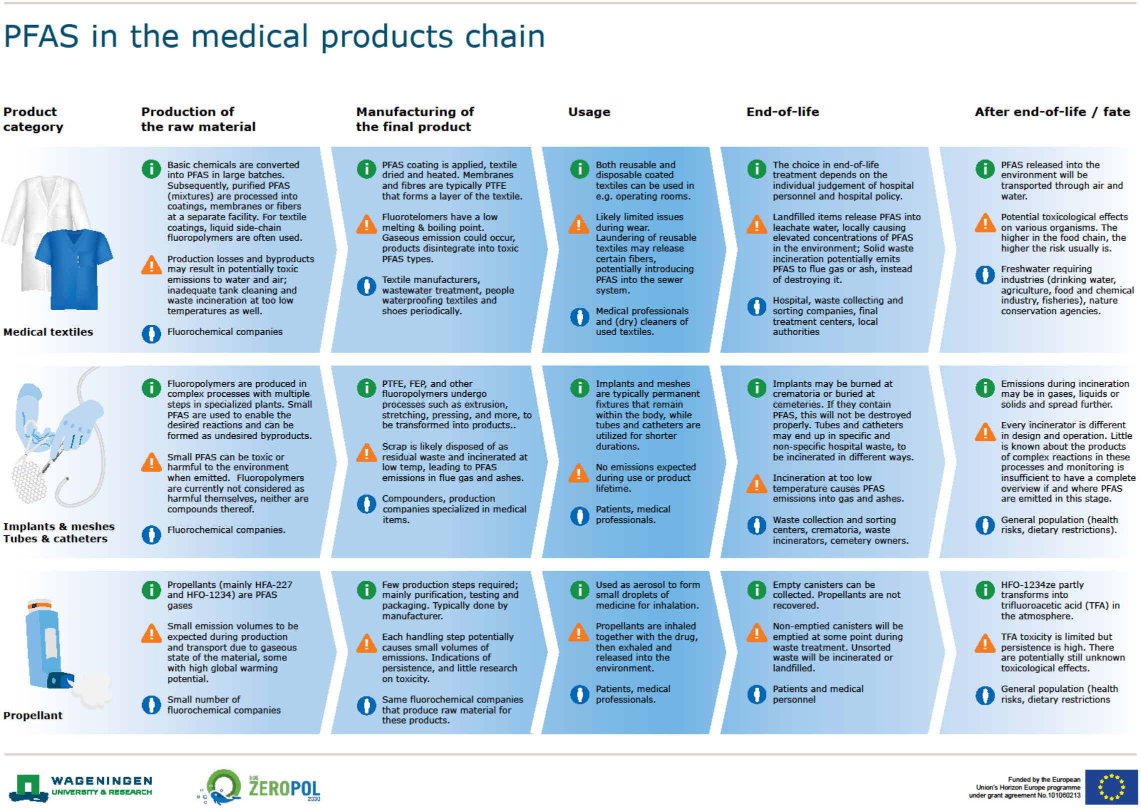
Please refer to Annex A.3 for further information and in-depth analysis regarding the reduction of PFAS emissions.

This section mainly focuses on the reduction potential for PFAS emissions from the medical sector. The motivation for choosing this sector consists of a few elements:

- PFAS emissions are generally the highest in the use phase and are thus strongly correlated to the product function and use modes. The ZeroPM project (https://zeropm.eu/) considered the 'chemical function, end-use function, and function as a service' when designing a database with potential alternatives for PFAS.[40]
- We anticipate that replacing PFAS by alternative materials in the medical sector will be perceived by stakeholders as more challenging than in most other sectors.
- The medical sector is associated with a significant contribution in emission volumes.
- The first Living Lab organized within the context of the SOS-ZEROPOL2030 project focused on the medical sector.

### 5.1.1. Visual representation of PFAS in medical products chain(s)

Figure 5.1-1 shows how PFAS are integrated into three different medical product chains. It also describes briefly what emissions are to be expected and into which environmental compartments they may be released. Emissions may occur throughout the product chain for most of the product types. Furthermore, a product containing a specific type of PFAS may cause emissions of various other types, especially during manufacturing and end-of-life stages. Further complexity in assessing potential emission volumes is caused by the fact that the majority of medical devices that contain PFAS are imported into the EU.[16] This introduces additional complexity for the EU in overseeing PFAS emissions in product chains.



## PFAS in the medical products chain

| Product category | Production of the raw material | Manufacturing of the final product | Usage | End-of-life | After end-of-life / fate |
|---|---|---|---|---|---|
| **Medical textiles** | ⓘ Basic chemicals are converted into PFAS in large batches. Subsequently, purified PFAS (mixtures) are processed into coatings, membranes or fibers at a separate facility. For textile coatings, liquid side-chain fluoropolymers are often used.<br>⚠ Production losses and byproducts may result in potentially toxic emissions to water and air; inadequate tank cleaning and waste incineration at too low temperatures as well.<br>👤 Fluorochemical companies | ⓘ PFAS coating is applied, textile dried and heated. Membranes and fibres are typically PTFE that forms a layer of the textile.<br>⚠ Fluorotelomers have a low melting & boiling point. Gaseous emission could occur, products disintegrate into toxic PFAS types.<br>👤 Textile manufacturers, wastewater treatment, people waterproofing textiles and shoes periodically. | ⓘ Both reusable and disposable coated textiles can be used in e.g. operating rooms.<br>⚠ Likely limited issues during wear. Laundering of reusable textiles may release certain fibers, potentially introducing PFAS into the sewer system.<br>👤 Medical professionals and (dry) cleaners of used textiles. | ⓘ The choice in end-of-life treatment depends on the individual judgement of hospital personnel and hospital policy.<br>⚠ Landfilled items release PFAS into leachate water, locally causing elevated concentrations of PFAS in the environment; Solid waste incineration potentially emits PFAS to flue gas or ash, instead of destroying it.<br>👤 Hospital, waste collecting and sorting companies, final treatment centers, local authorities | ⓘ PFAS released into the environment will be transported through air and water.<br>⚠ Potential toxicological effects on various organisms. The higher in the food chain, the higher the risk usually is.<br>👤 Freshwater requiring industries (drinking water, agriculture, food and chemical industry, fisheries), nature conservation agencies. |
| **Implants & meshes Tubes & catheters** | ⓘ Fluoropolymers are produced in complex processes with multiple steps in specialized plants. Small PFAS are used to enable the desired reactions and can be formed as undesired byproducts.<br>⚠ Small PFAS can be toxic or harmful to the environment when emitted. Fluoropolymers are currently not considered as harmful themselves, neither are compounds thereof.<br>👤 Fluorochemical companies. | ⓘ PTFE, FEP, and other fluoropolymers undergo processes such as extrusion, stretching, pressing, and more, to be transformed into products..<br>⚠ Scrap is likely disposed of as residual waste and incinerated at low temp, leading to PFAS emissions in flue gas and ashes.<br>👤 Compounders, production companies specialized in medical items. | ⓘ Implants and meshes are typically permanent fixtures that remain within the body, while tubes and catheters are utilized for shorter durations.<br>⚠ No emissions expected during use or product lifetime.<br>👤 Patients, medical professionals. | ⓘ Implants may be burned at crematoria or buried at cemeteries. If they contain PFAS, this will not be destroyed properly. Tubes and catheters may end up in specific and non-specific hospital waste, to be incinerated in different ways.<br>⚠ Incineration at too low temperature causes PFAS emissions into gas and ashes.<br>👤 Waste collection and sorting centers, crematoria, waste incinerators, cemetery owners. | ⓘ Emissions during incineration may be in gases, liquids or solids and spread further.<br>⚠ Every incinerator is different in design and operation. Little is known about the products of complex reactions in these processes and monitoring is insufficient to have a complete overview if and where PFAS are emitted in this stage.<br>👤 General population (health risks, dietary restrictions). |
| **Propellant** | ⓘ Propellants (mainly HFA-227 and HFO-1234) are PFAS gases<br>⚠ Small emission volumes to be expected during production and transport due to gaseous state of the material, some with high global warming potential.<br>👤 Small number of fluorochemical companies | ⓘ Few production steps required; mainly purification, testing and packaging. Typically done by manufacturer.<br>⚠ Each handling step potentially causes small volumes of emissions. Indications of persistence, and little research on toxicity.<br>👤 Same fluorochemical companies that produce raw material for these products. | ⓘ Used as aerosol to form small droplets of medicine for inhalation.<br>⚠ Propellants are inhaled together with the drug, then exhaled and released into the environment.<br>👤 Patients, medical professionals. | ⓘ Empty canisters can be collected. Propellants are not recovered.<br>⚠ Non-emptied canisters will be emptied at some point during waste treatment. Unsorted waste will be incinerated or landfilled.<br>👤 Patients and medical personnel | ⓘ HFO-1234ze partly transforms into trifluoroacetic acid (TFA) in the atmosphere.<br>⚠ TFA toxicity is limited but persistence is high. There are potentially still unknown toxicological effects.<br>👤 General population (health risks, dietary restrictions |

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*Figure 5.1-1. Visual representation of PFAS in three medical product chains. The text gives information about the role of PFAS in the different parts of the chain, the expected emissions, and the groups of people that are directly affected by the emissions. This factsheet was used for the first Living Lab in the Northeast Atlantic and is available as a separate pdf from https://edepot.wur.nl/659708.*

### 5.1.2. The product chain of PFAS in medical devices

Medical devices are categorized based on the risk associated with their use, as governed by EU regulation 2017/745 and shown schematically in Figure 5.1-2. The higher the risk, the more comprehensive the (technical) documentation of the item must be according to this regulation. Manufacturers of such items typically disclose only very limited technical documentation on the product website or in documents that come with the product. Neither can it be guaranteed that all materials used in a device are mentioned in the documents, as this is currently not obliged by law. Hence, it is impossible for the general public to know exactly what materials are used in what product. Hereafter follows a description of parts of the product chains for medical products that are known to use PFAS, to demonstrate how PFAS are incorporated into these products and what emissions this could engender.

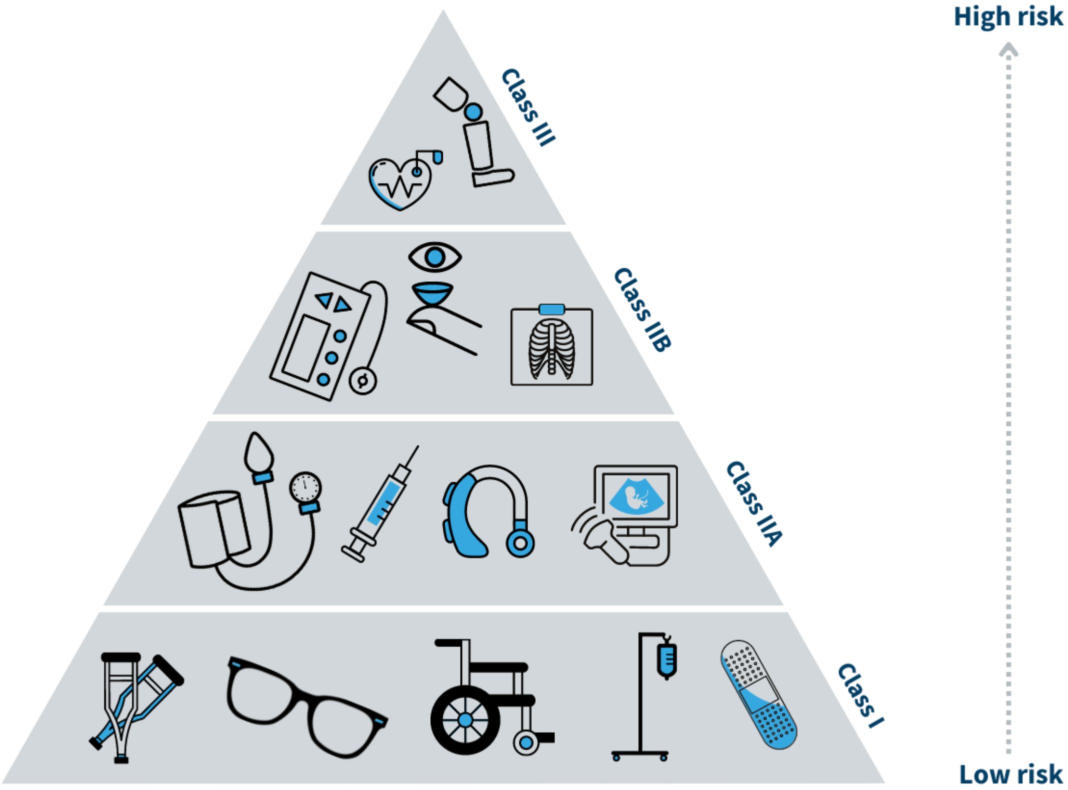

*Figure 5.1-2. Categorization of medical devices in the EU. Reproduced from the Danish Medicines Agency.*[41]

## Plastic products

Plastic products are typically produced by melting a resin of the polymer of choice, followed by casting, blowing, or shaping the molten polymer. The melt viscosity of polytetrafluoroethylene (PTFE) is too high to enable processing by these methods[42], but polyvinylidene fluoride (PVDF) and fluorinated ethylene propylene (FEP) can be processed in this way. In such melt-based processes, production losses ("scrap") potentially occur in various steps. Starting up or shutting down a process, cleaning a machine, reshaping products after manufacturing and products that don't match the set requirements could all lead to material losses. While it is economically attractive for a manufacturer to minimize scrap volumes, often the formation of scrap can't be avoided completely. Some clean PFAS-polymer scrap is recycled within the premises of production facilities, for example by producing PTFE micropowders.[30] Other PFAS-polymer scrap is not separately collected and recycled, since the volumes of plastic-waste generated are too small to be attractive for sorting and recycling facilities to handle. These materials are either landfilled or incinerated at a municipal waste incineration facility, where only the latter will result in near-complete mineralization of fluoropolymers.[43]

PTFE can be converted into final products by processes that are similar to those used for ceramics. Tubes can be made by ram extrusion[44], while tubes, sheets and tapes can be made by paste extrusion, and more complex shapes can be made by compression moulding. [45] In all of these processes, a subsequent sintering step (or, more correctly, interdiffusion) is performed.[45] In this process, PTFE molecules interpenetrate and crystallize, leading to the final material structure. Without having a comprehensive set of data available, it could be expected that the largest material losses in these process occur during handling of fine powders when filling the machines, or again by faulty end products that do not meet the required specifications. This will add to the production of scrap (as described in the previous section), or the production of microplastics that have a high potential to leak into the environment.

### Medical textiles

Liagkouridis *et al*. investigated the presence of fluoropolymer coatings in a surgical drape, four surgical gowns and one ambulance jacket.[46] While the analytical technique used needs refinement for quantification of the retrieved chemicals, the results suggest that all products had been coated with side-chain fluorinated polymers. Various SCFPs can be mixed; the mixture is typically applied as a durable water repellent (DWR) coating onto a garment. Such a DWR coating is applied by contacting the textile with an aqueous emulsion, removing the excess liquid and drying.[47] Various chemical companies mention that they produce and market such coating materials. Examples of ready-to-use products can be found in the AsahiGuard E-series[48] and Daikin Unidyne[49] ranges. Such coatings are applied to provide the garment with a liquid-tight layer, without compromising comfort.[50] According to the PFAS restriction proposal, PTFE is also often used as a coating material for medical textiles. The application process is not described in this text and is likely to be evolving quickly with the development of new technologies.[51]

Emissions are unlikely to happen in significant amounts while wearing or using the coated textiles, as the coating is typically covalently bound to the textile and designed to stay there.[47] Some emissions might occur into water water when washing the textiles; these will most likely be released together with loose fibres into the sewerage system. SCFPs can degrade into FTOHs and perfluoroalkyl carboxylates (PFCAs) with the same carbon chain length.[52] Depending on the product lifespan and the half-life in the environment in which it has ended up, degradation of the chemicals may take between a few days and many years.[52] Separate collection systems for waste fractions in hospitals are not necessarily standardized – based on personal communication, it was concluded that nurses and other personnel often have to decide how to dispose of waste based on their own knowledge. Textiles used in the Operating Room (OR) may have been in contact with bodily fluids and are therefore likely disposed of as specific hospital waste. In the Netherlands, this is treated in the same way as other hazardous waste; by incineration at a specialized plant (ZAVIN). This type of plant operates at significantly higher temperatures than municipal waste incinerators (>1200 °C) and its process is designed for full combustion. No continuous monitoring is in place for PFAS, but a recent scientific publication suggests that PTFE (as an example of a more difficult to incinerate PFAS polymer) is almost completely mineralised in such a waste incinerator.[8]

### Implants, meshes, catheters and tubes

Grouping of these products is logical from the perspective of materials. Preliminary investigations were done in which information was retrieved from the PFAS restriction proposal[16] and from websites of companies that manufacture such products. This information shows that implants, meshes, catheters and tubes commonly contain PTFE as one of its components. In a few products, typically when only some of the benign properties of a fluoropolymer are required, PVDF or FEP are used. All products in this category contain solid PFAS and are designed to be non-absorbable (resist enzymatic degradation). Some are designed to remain inside the body after the surgery and are able to keep providing their function for many years.[53] After death, degradation of PTFE is expected to happen on such a long timescale that it is considered inert[54], so PTFE in buried corpses will remain there. Conditions in the oven of a crematory are at least similar to those of municipal waste incinerators or  (secondary combustion chamber >850 °C, residence time >2 s)[55] and are therefore likely are likely to result in full mineralisation of PFAS polymers.

### Metered Dose Inhalers

Aerosol devices for the inhalation of medicines can be classified in four categories: (i) Nebulizers, (ii) Metered Dose Inhalers (MDI), (iii) Dry Powder Inhalers (DPI), and (iv) Soft Mist Inhalers (SMI). MDIs are the most widely used type of device, likely owing to reasons of usage comfort (multiple doses are carried, the device is portable), as well as effectivity of drug delivery.[56] These devices rely on fluor-containing gases as propellant. Traditionally, chlorofluorocarbon (CFC) gases were used as propellant.[57] Dichlorodifluoromethane (CFC-12) was used as the main ingredient and trichlorofluoromethane (CFC-11) and dichlorotetrafluoroethane (CFC-114) were blended into the mixture to modify the vapor pressure. These gases are also used to produce PTFE (see Section A.3.5), improving the ease of logistics and production efficiency. Due to their high Global Warming Potential (GWP), CFCs were phased out. Norflurane (HFA-134a) and apaflurane (HFA-227ea) are currently the main gases used as propellants in MDIs.[58] They have a significantly lower GWP than the CFCs, but both are a PFAS. While HFA-134a creates TFA as an environmental degradation product[59], HFA-227ea has an atmospheric lifetime of centuries[60]. Hydrofluoroolefins, of which the main material of interest is HFO-1234ze, again have a lower GWP than CFCs and HFCs[61], but most are still classified as PFAS. Canisters contain the drug to be inhaled. To prevent interaction between the drug and the canister material, the inside of the canister is often coated with PTFE, both for MDIs and DPIs[58]. Empty canisters can typically be brought back to the pharmacy, in which case they are disposed of as hazardous solid waste and incinerated in a dedicated facility. Collection rates are not measured and are therefore unknown, hence a share of these canisters will probably end-up in mixed municipal solid waste (MSW) and either be incinerated or land-filled. Research has shown that large differences exist between countries in the sales and usage of MDIs and PDIs, while average patient needs are considered to be equal.[62] This suggests that significant PFAS emissions in the medical sector can be avoided by prescribing PDIs more often when feasible for the patient.

## End of life

The SOS-ZEROPOL Living Lab in Utrecht concentrated on PFAS in medical items (textiles, implants, meshes, tubes, catheters and propellants). In preparation for the workshop, we performed a literature search to investigate which products in these categories that are regularly used are expected to contain PFAS. Figure 5.1-3 shows a product chain of PFAS in the medical sector, with a specific focus on waste management, end-of-life, emissions and fate. After use, PFAS containing objects are discarded in different waste types. Figure 5.1-3 shows a few streams, including MSW, non-specific medical waste (NSMW), and specific medical waste (SMW). Liquids are discharged in the waste water treatment system, while gases are mostly emitted into the air during the use phase.

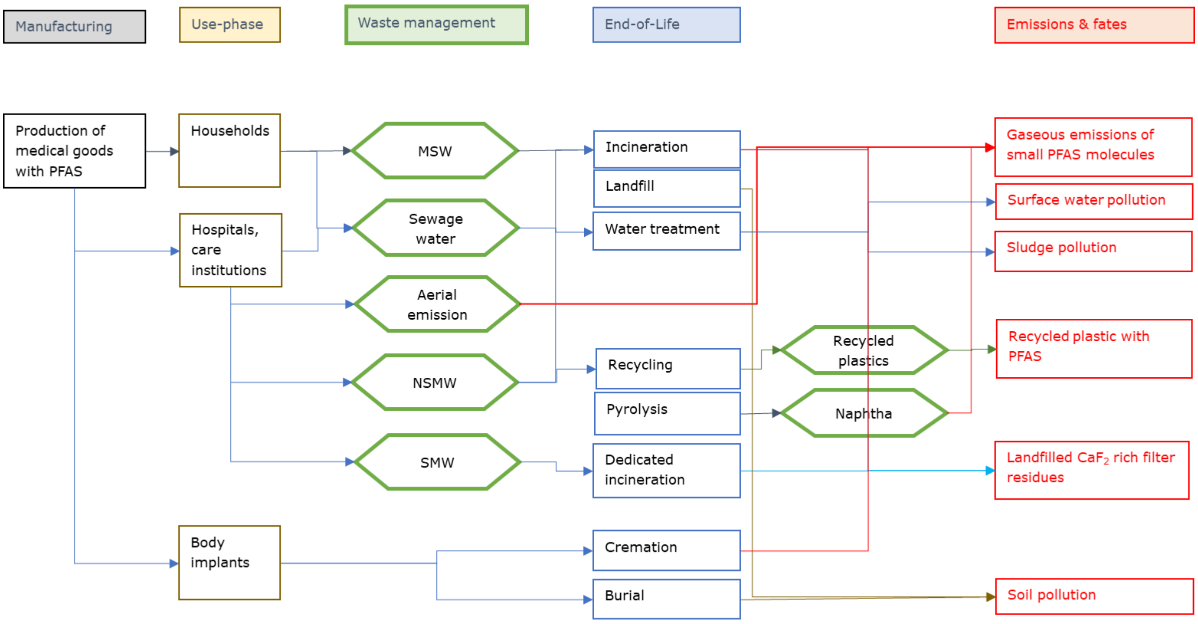

*Figure 5.1-3. Simplified scheme showing the product chain of PFAS containing medical objects with a specific focus on waste management, end-of-life and emissions.*

Body implants will normally remain in the body after the person deceases. Via various waste management systems, PFAS is emitted into various environmental compartments. PFAS and PFAS-containing objects that have been sorted into the specific medical waste stream are incinerated at elevated temperatures (referred to as 'Dedicated incineration' in the scheme shown in Figure 5.1-3), which will ensure near-complete mineralization to calcium fluoride.

MSW and NSMW can both be processed by landfills and municipal waste incinerators. Small amounts of the waste fractions (high-value mono-material plastics, such as PVC) may be taken out for recycling. In landfills, most PFAS will slowly but surely break down into smaller molecules that partly are PFAS themselves. Through leachate and gases, the landfill disperses PFAS molecules further into the environment. Conventional waste incineration will result in the partial mineralisation of PFAS molecules. Much is still unknown about the final fates of PFAS molecules entering the incinerator, as this is very difficult to study.[8] Solid PFAS polymers, like PTFE, will probably completely mineralise in conventional European waste incinerators.[8] The fate of smaller PFAS molecules have not been studied at larger scale. Fluoropolymers could degrade into smaller gaseous molecules, with some of these fractions still being PFAS. Some of these smaller PFAS molecules require higher temperatures to fully mineralise them and their partial reaction products could therefore potentially end-up in fly ashes (which are typically land-filled) and in exhaust gases which are released in the atmosphere.

### 5.1.3. Overview of the current technological actions and strategies to limit PFAS emissions

The overview of technological actions and strategies to limit PFAS emissions is generalized as much as possible. However, to assess the feasibility of phasing out PFAS in a certain part of a product chain, a detailed analysis will need to be performed. The potential success rate of an action or strategy depends on factors such as the performance of alternatives, the (negative) effects that are related to usage of alternatives, and readiness of technologies to be used at an industrial scale. Moreover, social factors such as societal awareness, product pricing, and the acceptance of products with lower convenience also play an important role in the success rate of such measures. Hereafter follows a list of technological actions that can currently be taken and considerations on the potential effects of these actions.

#### Replacing PFAS in a product by another material.

Glüge *et al*[63] show in an extensive overview that many products contain PFAS and that they are used to provide a large variety of properties. In many cases, not all of those properties are required for a product to perform as desired. This needs to be assessed on a case-by-case basis. In Section 5.1.5 this is done for items in two specific categories (medical devices and heating, ventilation, refrigeration and air conditioning). Further examples of sectors in which PFAS chemicals have been successfully replaced by less harmful and non-persistent chemicals are given in the Annex (Section A.3.8)

#### Minimising emissions in PFAS production plants

Although diffuse emissions have been shown to represent a significantly larger volume, emissions from PFAS production are still important. Even if the usage of PFAS will be restricted in the EU, most likely derogations will be created. Product groups for which PFAS usage will still be allowed will sustain the demand for PFAS production, therefore it is useful to investigate technologies that result in cleaner production of PFAS. Chemours have shared the measures they're taking at the Dordrecht and Fayetteville sites with the broader public. [29, 64] These include the use of activated carbon filters, flue gas cleaning or thermal oxidation of flue gases combined with advanced stack monitoring, together with changes in the process layouts. Reverse osmosis treatments of wastewater are applied to reduce emissions into aqueous phases. Although these strategies may not be perfect, the effects are likely significant. This was demonstrated by a reduction in the permitted emission of PFAS into wastewater by 99% compared to the previous permit in Dordrecht. [29]

### Fluorosurfactant-free production of fluoropolymers

As briefly mentioned in Section A.3.5 and A.3.6, emulsion polymerization processes are employed to produce various fluoropolymers at industrial scale. Processing aids used in these processes (among others PFOA, HFPO-DA, and ADONA) are required to obtain a polymer with a high molecular weight – which is essential to attain the intended properties. The pollution caused by these low-molecular weight PFAS has received significant attention from media, researchers, NGO's and governmental bodies.[30, 65, 66] The same is true for the health risks of these molecules, which has been investigated in more detail than for most other PFAS.[67]

Scientific research towards alternative processing aids for fluoropolymer synthesis is limited but promising.[68] Meanwhile, some of the large industrial manufacturers have announced they will stop using PFAS as processing aids in the manufacturing of PTFE, PVDF, and PFA, among others.[69] Together with the technical efforts to minimize emissions from PFAS production and potentially decrease the volumes of PFAS produced in the EU, the use of alternative processing aids may help to minimize PFAS emissions from PFAS manufacturing processes. It is important to note, however, that some alternative processes do not *add* PFAS surfactants but create them *in-situ.* Depending on the level of process control and mixing efficiency, this strategy may slightly decrease the required amount of surfactant in a reactor but will not contribute significantly towards fluorosurfactant-free production of fluoropolymers.

### Reliable, affordable and quick analysis methods for various matrices

To sustain other efforts to reduce PFAS, it is important for companies, researchers and governmental organisations to have access to reliable, affordable and quick analysis methods that accurately detect and quantify PFAS. Currently available methods typically rely on gas chromatography combined with mass spectroscopy (GC-MS). While it is reliable, the equipment is expensive, analysis can be complex and can take a long time. Faster and cheaper screening would help to identify emission sources at more locations and timpe points. Combustion Ion Chromatography (CIC) may play a role here, but method development towards a "Total Per- and Polyfluoroalkyl Substances" parameter is still ongoing.[70]

### Waste management optimization

Optimisation of waste management practises is a relatively effective method to reduce PFAS emissions. Effective measures include optimized landfill design to prevent leakage of PFAS-containing leachate into groundwater, moving away from using WWTP or septic tank sludge as fertilizer/biosolid towards combustion in waste, monitoring of industrial wastewater for various PFAS (as in currently done in Flanders), and installing absorption plants at PFAS-using industrial sites. However, a change in waste management practises will typically also cause challenges for incumbents, as the options are more expensive or require separate collection and processing of waste fractions, etc. Therefore, the success of such mitigation measures depend on effective legislation, coordination and enforcement by governments.

### 5.1.4. Potential and future technological actions and strategies to limit PFAS emissions into the environment and decrease existing pollution

Many different technological actions can be envisioned to limit PFAS emissions into the environment, varying from relatively simple (redesigning a PFAS-containing product using existing and accepted alternatives for the PFAS, as demonstrated in e.g. ski wax, paper coatings, and refrigeration applications) to highly complicated (essential uses). Recently, research into environmental pollutant removal technologies focusing on PFAS has also shown promising results. A number of potential actions and strategies for emission and current pollution reduction are listed below and commented on:

- **Efficient industrial use of F-gases and after use capturing to limit emissions during the use phase.** The US Environmental Protection Agency collaborated with producers of aluminium, magnesium and the semiconductor industry to find ways to reduce F-gas emissions from these manufacturing processes.[71]
- **Optimized technology and procedures for the reuse of anaesthetic gases.** Devices and processes to capture anaesthetic gases such as desflurane, sevoflurane and isoflurane exist, but many details may need further optimization.[72]
- **Fluoropolymer recycling.** Dyneon, a daughter company of 3M, reported the operation of a pilot scale pyrolysis process in which fluoropolymers have been converted into their respective monomers.[72] Apart from this example, no references were found that describe experimenting with or using this technology anywhere else.
- **WWTP advancements targeted at removing residues of medicines from wastewater that oftentimes also remove PFAS.** Incineration of PFAS-containing sewage sludge in a WWTP with an internal fluidized bed incinerator under standard conditions only enabled the conversion of approximately 50% of the PFAS input mass into non-PFAS.[73] Processes such as adsorption using ion exchange resins, electrochemical degradation, and nanofiltration are more effective in removing PFAS than conventional processes (~95–100% removal is reported in some cases).[74] These processes, however, greatly increase the resources that WWTPs need. It was argued in the SOS-ZEROPOL2030 Living Labs in both the Netherlands and in Bulgaria that it is very unattractive to remove PFAS from wastewater in WWTPs from a cost perspective. It is expected that it is even less attractive to remove some of the most harmful PFAS from the environment.
- **The low concentration of PFAS in aqueous matrices makes removal expensive.** High volumes of water need to be processed to remove small amounts of PFAS . The EU-funded SCENARIOS project aims to develop a foam-based fractionation-technique to collect PFAS from surface or groundwater into a concentrate of a few litres, and subsequently destruct this highly contaminated residue. Using the tendency of most PFAS to be surface-active, this technology could be a promising way towards PFAS removal from matrices with low concentrations. A supramolecular chemistry approach has recently shown a similar potential (concentration of PFAAs by a factor

106).[75] Such concentration technologies could help PFAS removal from natural waters to become technically and economically feasible.

- **Waste sorting processes that separate out PFAS-containing objects into concentrates, with the intention to recycle or incinerate the concentrate.**
- **Optimization of incinerator design and operations based on in silico experimental data.** A recent study showed that mineralisation of a relevant mixture of fluoropolymers can be >99.99% in a well-designed and operated incineration facility.[8] While >90% of the incinerators in Europe use a moving grate design[76], this study used a rotary kiln design. This difference will potentially impact the mineralisation efficiency of PFAS in solid waste, as moving grate incinerators are more likely to have zones with insufficient oxygen pressure (6 vol% of hot gas is the minimum[76]). Ideally, a similar study should be performed in a moving grate based incineration plant, which is more representative, to have even more insight into the PFAS emissions from solid waste incineration. Technological actions to reduce emissions from solid waste treatment could include optimization of incinerator design and operation, and improved waste sorting (solid waste with significant fluorine content could be incinerated instead of landfilled, if a country operates both practices).

### 5.1.5. PFAS replacement by alternative chemicals for two primary PFAS applications.

#### Medical devices

Medical devices often consist of multiple components, which in turn contain many materials. Material selection tools used to design these components primarily focus on the patient health & well-being and hence aim to minimise the chance of medical complications. A recent review suggested that expanded PTFE (e-PTFE) meshes can lead to significantly fewer complications than meshes made of other materials (e.g. polyester vascular grafts, bioabsorbable polymers for tissue regeneration or nitinol for stents) in some cases, but more often no significant benefit was reported for the e-PTFE device in terms of success rates.[77]. Furthermore, the review showed that in many of these devices, the biggest improvement in surgical performance is made by well-designed functionalisation with specific molecules (such as drugs) rather than by tuning the base material.

The production, usage and end-of-life treatment of PTFE objects likely causes more severe pollution than that of similar objects made from, for example, polypropylene (PP). The additional pollution is a potential cause for illness in new patients to which the use of PTFE in surgery may contribute. In the Netherlands, the Green Deal on Sustainable Healthcare directly links pollution to health and therefore aims to reduce pollution caused by the healthcare sector.[78] If this vision becomes the standard for medical procurement, a significant reduction in the use of PFAS-containing medical devices could be achieved. Deciding which use of a PFAS in a medical device is essential, following the essential use criteria, has also been suggested in this context.[79]

Powder inhalers instead of MDIs have been shown in Sweden to be suitable for ~90% of inhaler users.[80] Many countries see much higher MDI use, hence a considerable (but not quantified) potential exists for reducing both greenhouse gas and PFAS gas emissions by reconsidering the use of other types of inhalers. In other use cases (medical lasers are mentioned specifically), it is not clear what volumes and types of PFAS are used for which purposes in medical devices; therefore it is impossible to assess which chemicals could replace PFAS and to which extent.

#### Heating, Refrigeration, Ventilation and Airconditioning (HRVAC) systems

Until the 1980s, chlorofluorohydrocarbons were the most commonly used coolants and refrigerants in refrigerators and air-conditioning equipment. Due to their large negative impact on the ozone layer these have been replaced since then with various hydrofluorocarbons (HFCs). These gases are, however, very potent greenhouse gases and contribute to global warming. The F-gas regulation of the European Union[81] describes in detail which gases and gas mixtures can be used for which application. The prescribed alternative gases vary from unsaturated fluorohydrocarbons (HFO) such as tetrafluoro-propenes, to hydrocarbons (cyclopentane, isobutane, etc.), to carbon dioxide, ammonia, etc.[82] Changing from one coolant to another could require a redesign of the hardware (heat exchangers, fans, etc.), due to differences in physical properties of the coolants. With an estimated service life of HRVAC equipment in the order of 15-20 years[82] and a continued need to refill existing systems, it could be expected that PFAS in HRVAC applications can only be phased out slowly.

While in some sectors large opportunities are offered by drop-in replacement of PFAS with other coatings (DWR coatings, ski wax, pans; see Section 5.1.3), other sectors may provide more examples where the intrinsic properties of the used PFAS are currently irreplaceable by drop-in alternative chemicals or mixtures. Some examples are elaborated in Section A.3.8. In many of these cases, it could be possible to avoid the use of PFAS when a system change would happen. The impact of system changes may be more significant than the impact of replacing PFAS chemicals in individual products by alternative chemicals.

### 5.1.6. What will happen if PFAS are replaced with alternative chemicals?

In this section, we look at both (i) the impacts on primary PFAS emissions, and (ii) possible technological and environmental side effects that could occur if PFAS are replaced with alternative chemicals.

- Replacement of PFAS by alternative chemicals would logically lead to lower amounts of PFAS being manufactured and used in end products. In general, production and usage volumes scale with primary PFAS emission volumes, hence lower production and use will generally cause lower emission volumes. It will likely take a number of years before an effect could be measured, considering that the largest share of emissions is due to product use and durable products can have long lifespans.

- In the longer term, replacement of PFAS by safer alternatives will also decrease secondary emissions (related to degradation of PFAS towards their most stable variants, PFAAs).
- A potential side effect is that neglect of the risks associated with the replacement chemicals could lead to 'regrettable substitutions'. In this case, the hazard caused by the replacement outweighs the hazard caused by the PFAS – a situation that should be prevented.
- Should the PFAS restriction proposal be put in effect, the replacement of a PFAS by another chemical in a specific application could affect competitors that have not switched to another material. Time-limited derogations are to be expected for the use of PFAS in a specific application. When the derogation needs to be re-evaluated the existence of a non-harmful PFAS alternative will likely affect a potential prolongation of the derogation.
- F-gases caused 2.3% of the greenhouse gas (GHG) emissions in the EU in 2019. Replacement of PFAS gases by alternatives (e.g. for refrigerants) will likely result in a decrease in GHG emissions.

### 5.1.7. Perspective on the reduction potential for PFAS in key applications

The most effective option to prevent PFAS emissions is to avoid using PFAS in end products and in manufacturing processes. This should be evaluated on a product level, as considerations for material choices are different for each product, each usage and each company. PFAS can technically be phased out in a significant number of use cases. This is shown in scientific literature, in material from NGOs such as ChemSec[83], and by large retailers that stopped selling PFAS-containing products.[84] In some cases, however, the use of PFAS will remain unavoidable for some more time.[84, 85] This is reflected by the concept of 'essential use': an application that is necessary for health or safety, critical for the functioning of the society and for which no acceptable alternative exists. Essentiality will need to be evaluated for each individual use, which will cause challenges for implementation. For the products and use cases where PFAS will remain essential, emissions need to be minimised mainly by the following two measures:

- Limit emissions from production by implementing measures in chemical plants and processing facilities that produce or use PFAS. Such measures are currently being taken by PFAS producers (improved wastewater treatment, flue gas scrubbing, thermal oxidation of byproducts and flue gases, etc.), showing that at least some of the required technology exists. Regulatory and financial drivers will be required to accelerate the implementation of the technological measures.
- Limit emissions from end-of-life by ensuring full mineralization of PFAS in waste treatment. Recognition of PFAS in sorting processes is required, as well as the availability of sufficient capacity at destruction facilities and a price mechanism to encourage destruction.

At the post-consumer side, efforts to minimize PFAS emissions are currently limited. This leaves much room for improvement in many aspects (governance, citizen and professional behaviour, technological measures).

# 6. Overview of PFAS governance strategies

This section gives an overview of current and emerging governance efforts to reduce and mitigate PFAS at the regional, European and national level. We zoom in on two of the EU's regional seas as case studies: the Northeast Atlantic and Black Sea regions, with examples taken from individual EU Member States. More information on the underlying rationale and methodologies can be found in the Annex A.4. A full deliverable report on PFAS regional, European and national governance strategies will be published in November 2024 (D4.2).

## 6.1. Primary outcomes – Emerging PFAS governance in the Northeast Atlantic and Black Sea

### 6.1.1. Governance strategies by the EU, OSPAR Convention and the Bucharest Convention

The EU has implemented various regulations and directives to address the production, use, and environmental impact of PFAS. These policies aim to set thresholds, control production, and mitigate the negative effects of some PFAS throughout their lifecycle. Much is currently in motion as the EU **Chemicals Strategy for Sustainability**[86] is starting to be implemented, to help achieve the aims of the zero pollution ambition for a toxic-free environment of the European Green Deal.[87]

The most prominent actions flowing from the chemicals strategy are a **PFAS restriction proposal under REACH.**[18] The REACH regulation lists substances of very high concern, which include the PFAS GenX. Several PFAS have already been banned, and in addition to the universal restriction proposal, REACH is processing restrictions on PFHxA and firefighting foam.

The EU implements a **regulation on persistent organic pollutants,** transposing restrictions under the Stockholm convention, including PFOS (since 2009), PFOA (since 2020) and PFHxS (since 2022). The **Water Framework Directive (WFD),** the **Marine Strategy Framework Directive (MSFD),** and the **Environmental Quality Standards Directive (EQSD)** set standards for ground-, surface- and seawater levels of priority substances, which include some PFAS. This has implications for the monitoring of water and biota at the national level and initiating actions when thresholds are passed. The **European Food Safety Authority (EFSA)** has set the threshold for Tolerable Weekly Intake for a group of PFAS that accumulate in the body to 4.4 ng per kilogram of body weight. Most EU citizens are exposed to more than this. The **Drinking Water Directive (DWD)** includes thresholds for the 'sum of PFAS' of 0.1 µg/L for a group of 20 PFAS, or a 'PFAS total' of 0.5 µg/L for all PFAS, which will come into force in 2026. Finally, the **Industrial Emissions Directive (IED)** will – following an ongoing revision – regulate PFOA and PFHxS.

A comprehensive policy overview can be found in SOS-ZEROPOL2030 Deliverable Report D2.1 (Devriese et al., 2023)[88], and an in-depth governance analysis of the PFAS restriction proposal process in D2.2 (van Leeuwen et al., 2023)[89]. For the Northeast Atlantic Sea, the **OSPAR Convention** brings together 15 contracting parties (including both EU and non-EU countries), as well as representatives of the European Commission, in working towards a better environmental quality of the Northeast Atlantic Sea. The latest Quality Status Report from 2023 barely mentions PFAS and primarily focuses on other pressures on the marine environment. Under OSPAR, PFOS has been monitored since 2023 in water and since 2018 in fish and biota. In 2022, PFAS have been added to the list of chemicals for priority action to reduce concentration levels by the OSPAR committee on hazardous substances. This list has recently been aligned with the priority substances lists under REACH and the WFD. For the OSPAR monitoring programme, measurement of 24 PFAS will be prioritised in line with the EQSD.

For the Black Sea, the **Bucharest Convention** brings together 6 contracting parties (including both EU and non-EU countries) to prevent, reduce and control the pollution in the Black Sea, in order to achieve a good environmental status. In recent decades, the Bucharest Convention parties have focused funding and human resources on actions around minimising eutrophication. While there is a protocol on the Protection of the Black Sea Marine Environment Against Pollution from land-based sources and activities, it currently does not list PFAS as hazardous substances. Due to the ongoing war, the Black Sea commission is practically on hold. Regarding PFAS there is only very limited awareness and, since most nations are not part of the EU, there is no full alignment with EU monitoring methodologies and thresholds.

### 6.1.2. National level examples of governance strategies

At the national level we take examples from France and Netherlands for the Northeast Atlantic Sea region, and from Bulgaria and Romania for the Black Sea region.

The **French parliament** has voted for a ban on the manufacture, import and sale of any cosmetic product, wax product (for skis) or clothing textile product containing PFAS substances from 2030, with the exception of protective clothing for safety and civil security professionals. Kitchen utensils, which were initially included in the ban, were removed from the list after MPs cited manufacturers' arguments over risks to employment.[90]

In **The Netherlands**, the ministry for infrastructure and water led a multi-stakeholder process in 2021 that resulted in the ‘action framework for PFAS-containing soil’, which establishes the principle that ground can only be moved to other locations, e.g. for construction work, if it will not increase levels of PFAS in the receiving location. In 2024, the ministry of Health, Wellbeing and Sports is exploring avenues for a more rapid transition to PFAS alternatives specifically in medical applications, in response to an accepted motion in parliament. Besides these sector-specific examples, much direct regulation of chemical producers and industrial users is happening through emission permits at council and province level. This process has come under increased scrutiny following the discovery of worrying levels of PFAS near the Chemours factory in Dordrecht.

In sharp contrast, our exploration of PFAS governance strategies in **Bulgaria** and **Romania** did not reveal any clear existing governance initiatives. All of our interviews point to a limited awareness on the issue of PFAS in both countries and the absence of monitoring of PFAS. The mainstream media is not reporting about PFAS and even environmental NGOs are only recently beginning to engage on the issue. The implementation of new EU regulations would likely be challenging, for example the DWD with requirements for monitoring and reducing PFAS levels in tap water from 2026.

### 6.1.3. Industry approaches and initiatives

In this section we turn to industry approaches and initiatives in response to the emerging concern over PFAS emissions.

Industry stakeholders, ranging from producers of base chemicals, compounders involving fluoropolymers, industrial users and manufacturers, are actively lobbying in the EU. This happens bilaterally, through public consultations and through sector groups. They are primarily highlighting the benefits of continued PFAS use, the technical difficulty of transitioning to alternatives, and the required time for developing alternatives. Industry narratives often state that PFAS is a societal issue to be addressed, but prefer end-of-life remediation options over alternative production options.

In the medical sector in the Northeast Atlantic case study, there is a merger of interest between the powerful petrochemical industry and pharmaceutical industry lobbies, both at national, EU and global scales. Their position papers have in common an argument for the essentiality of medical applications as a basis for derogations and continued or expanded PFAS applications. Both industries appear reluctant to take a leading role in any transition away from PFAS.

For public-facing brands and companies, however, there is an increasing marketing incentive to remove PFAS from some of their products. Indeed, an increasing number of these brands are making commitments to going or being PFAS free, which is increasingly sought-after by consumers and can still provide a competitive advantage (see Figure 6.1-1).

*Figure 6.1-1. Members of the PFAS Movement, illustrating the increasing commitments from public-facing companies to 'go PFAS-free'. Image from Chemsec https://chemsec.org/pfas/#members-of-pfas-movement).*

Other industry stakeholders in the medical sector, like hospitals, recycling companies, waste treatment organisations, are more actively exploring circular and PFAS-free alternative product chains. In the PFAS product chain, the interests of producers of PFAS-free and more generally toxic-free products have the potential to align with those of the recycling industry. Both benefit from clear end-of-waste criteria, which are possible if waste products do not contain chemicals of concern.

The most intensive pockets of producing industry in the Black Sea areas are along the Danube river, most of which are foreign registered companies. There are few consistent data sets on PFAS pollution levels attributable to specific industries. There is also not much known about industry approaches towards PFAS emission reduction actions, with company environmental policies only stating general commitments to 'protect nature' and 'comply with laws and regulations' (see e.g. Maceplast[91]).

# 7. Conclusion and recommendations

## 7.1. PFAS emissions

### 7.1.1. Conclusions

- Estimations indicate that point sources (taking PFAS manufacturing plants into account but not taking end-of-life emissions into account) are associated with about 5% of the total PFAS emission volume. Diffuse sources (including industrial use of PFAS to manufacture products and final usage of the products) account for the rest.

- End-of-life emissions could not be estimated due to a lack of data (monitoring data are not available from either incineration or landfill sites).
- Both publicly available data and emission models do not currently allow a reliable estimation of PFAS emission volumes per environmental compartment. This is due to the dominance of emissions from diverse and diffuse sources.
- Fluoropolymers represent the largest mass of PFAS in end products. Fluoropolymers are generally considered as inert during the use phase, but may cause emissions of other, more harmful PFAS during production or end-of-life.
- F-gases dominate the market for heating, ventilation, air conditioning and cooling applications and are used in other sectors as well. Regulations around F-gases are strict, but leakage cannot be prevented. Some of the most commonly used F-gases eventually metabolize into TFA, a mobile and persistent PFAS of which concentrations in natural environments have been shown to increase during the last six decades. Toxicological effects of this molecule are thus far shown to be limited, but as concentrations keep increasing, a tipping point could eventually be reached.
- Textiles, gases, medical devices, construction, and electronics are the five ‘sectors’ with the highest PFAS emissions in the estimations provided in the PFAS restriction proposal.
- Given that PFAS chemicals are used in a wide range of industrial sectors and even more different end products, banning the production, use, and import of PFAS in the EU is considered unlikely to lead to a rapid decrease in emissions and pollution on a global scale.

### 7.1.2. Recommendations

Recommendations for PFAS restriction proposal and environmental management:

- Time-limited derogations for specific applications: The PFAS restriction proposal could consider granting time-limited exemptions for certain PFAS applications. This would allow for continued but regulated use, which would also mean continued production or import and limited emissions.
- Management of diffuse and point sources: Recognise that diffuse sources of PFAS contribute the largest emission volumes, typically at low concentrations, while point sources (e.g., legacy and ongoing industrial discharges) cause localised pollution with potentially high concentrations. Both diffuse and point sources can be harmful, considering most PFAS are either persistent and mobile or persistent and bioaccumulative.
- Addressing existing environmental contamination: Independent of the potential ban, high concentrations of PFAS already present in certain areas (e.g., airfields, military bases, and sites with firefighting foam usage) may require targeted remediation to reduce environmental and health risks.

- Continuous and stringent monitoring: Continued PFAS production, import, use, and disposal must be paired with ongoing and rigorous monitoring of environmental PFAS levels.
- Comprehensive sampling and analysis programme: A robust programme should include sampling across multiple EU countries and landscape types (urban, rural, natural, water-based) and cover various environmental matrices (surface water, sediment, deep marine water, biota, air).
- Inclusion of industrial and waste sources: Monitoring should also encompass key industrial and urban sources, including wastewater, landfill leachate, and emissions from end-of-life treatments.
- Regular assessment of consumer products: To track potential PFAS release and exposure, a regular investigation of PFAS presence in various consumer products should be conducted.

## 7.2. PFAS risks

### 7.2.1. Conclusions

- The most exposure data for PFOS, PFOA and novel PFAS is available for the Greater North Sea, Norwegian Sea, Barents Sea and Baltic Sea areas, all of which have datapoints covering multiple locations and over multiple years. Limited or (in the worst case) no PFOS, PFOA and novel PFAS exposure data is available for Mediterranean and Black Sea.
- Although a reasonable amount of toxicity data is available for the legacy PFAS chemicals (PFOS and PFOA), there is insufficient aquatic ecotoxicity data available in the ECOTOXicity Knowledgebase to construct SSDs and so the AF approach was implemented to derive PNECs for use in risk assessment.
- While the amount of toxicity data varied considerably for individual novel PFAS, there was sufficient toxicity data available to derive PNECs for 35 novel PFAS using the AF approach for hazard assessment. As the amount of toxicity data available for each of the 35 novel PFAS chemical varied significantly, AFs of 10-1000 were applied for individual chemicals.
- Based on the available exposure and hazard data for PFOS, normalised by the number of observations, the risk assessment identified the Adriatic Sea, the Celtic Sea and the Western Mediterranean as the regions with the highest risk from PFOS exposure, with 25% or more stations above the threshold (Table 4.2-1).
- Based on the available exposure and hazard data for PFOA, normalised by the number of observations, the risk assessment identified Adriatic Sea, Aegean-Levantine Sea, Baltic Sea, Barents Sea, Bay of Biscay and the Iberian Coast, and the Greater North Sea, incl. the Kattegat and the English Channel as the regions with the highest risk from PFOA exposure, with 25% or more stations above the threshold.

- For novel/emerging PFAS substances with limited data, the risk assessment indicates that the Adriatic, Greater North Sea, Baltic Sea and North Atlantic are the most at risk with 10% or more of their datapoints over the thresholds (A.2.6), although none of the European seas have more than 14% of stations above the threshold.
- In various studies, concentrations of novel PFAS in environmental matrices have been measured at various locations and in some cases temporal trends have been investigated. Monitoring programmes sponsored by governmental bodies in which measurements are executed regularly and over a long time span are not yet in place in the EU.
- The analytical capacity required to quantify concentrations of a high number of different PFAS molecules at many locations, in multiple matrices, and with an appropriate temporal spread is enormous. The likelihood of increasing the data availability to a level that it becomes sufficient for generalized toxicological research is very low.
- The combination of limited datapoints, constrained spatial and temporal coverage, and analytical limitations introduces significant uncertainty into the risk assessment of novel PFAS compounds. This uncertainty impacts not only the accuracy of current risk assessments but also the confidence with which environmental managers and policymakers can use these assessments to make decisions.

### 7.2.2. Recommendations

- One of the main recommendations is the generation of robust exposure and toxicity data for more novel PFAS chemicals that is added to relevant monitoring and ecotoxicity databases (e.g. ECOTOXicology Knowledgebase). Importantly, such data should not be ‘lost’ in the grey literature.
- $EC_{50}$ data for PFAS should be considered in the future for use in hazard assessment, as this will enrich the toxicity datasets and improve the assessment approach selected. Conversion of acute SSDs to chronic SSDs through AFs is an option that can be considered.
- Expanded monitoring programmes that systematically include novel PFAS, with consistent sampling across a variety of geographic locations and matrices.
- Improved analytical methodologies that increase the sensitivity, reliability, and comparability of PFAS measurements, especially for emerging compounds.
- Long-term data collection to support trend analysis and better understand the persistence and accumulation of novel PFAS in various ecosystems.
- Addressing limitations with the size of monitoring programmes, long-term data collection and current analytical methodologies will require coordinated efforts among regulatory bodies, research institutions, and industry stakeholders to enhance the data quality and coverage necessary for comprehensive risk assessments. Only with these advancements can we more confidently evaluate and

mitigate the potential environmental risks posed by novel PFAS compounds in European and global aquatic environments.

- Artificial intelligence (AI) approaches should be developed and implemented for automated processing, quality assurance and harvesting of data from extensive toxicity data sources such as databases (e.g., ECOTOXicology Knowledgebase) and scientific literature.
- Due to the extremely high number of PFAS chemicals, it is recommended that PFAS-specific predictive toxicity modelling tools are developed, as experimental toxicity data generation for all PFAS, for both acute and chronic endpoints, is not feasible.
- In addition, the similar physicochemical properties of many PFAS chemicals could open the way for grouping and read across approaches to be developed and implemented for PFAS risk assessment.

## 7.3. PFAS emission reduction measures

### 7.3.1. Conclusions

- Product chains in which PFAS play a role are often highly complex (as shown by some examples for medical devices) and not transparent in terms of which chemicals are used. Products that contain a substance of very high concern (SVHC), are classified as persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB) above 0.1 weight percent have to indicate that to the users of such a product in accordance with the REACH regulation. As there are many PFAS that do not fall in these categories, the end user might therefore not be informed. The synthesis or end-of-life treatments of a material not classified in the above-mentioned categories may cause (significant) emissions of harmful PFAS.
- Recent research shows that incineration of fluoropolymers in rotary kiln ovens at standard conditions for municipal waste or for hazardous waste suffices to destroy almost all fluoropolymers. While most incineration facilities in the EU are moving grate designs and results may not be fully transferable, the results indicate that incineration likely causes fewer emissions from PFAS-containing products than landfilling.
- A few PFAS production locations have shown that measures to significantly reduce PFAS emissions from production processes can be implemented successfully. Where essential uses comprise F-gases, measures should be taken to prevent leakage and to enable reuse.
- Wastewater treatment plants are not usually designed to remove persistent organic pollutants (of which PFAS are an example) from wastewater. Technologies to concentrate PFAS into smaller volumes (e.g. using foam fractionation) are currently being piloted and may lead to significantly lower costs for removing PFAS from wastewater.

### 7.3.2. Recommendations

An EU ban is required to force industries to move away from using PFAS in end products where possible. It is anticipated that safer alternatives can and will be found in a timespan of a few years for many products (by direct substitution with a safer chemical, redesign of a product, or finding a different product that fulfils the same function), based on alternatives that have popped up in the past few years (ceramic coatings for pans, polyester membranes for clothing, alternative formulations of textile coatings, alternative engineering plastics, and etc.). The existence of a safer alternative will decrease the demand for PFAS products and therefore of emissions in all stages of the product chain. Safer alternatives could also inspire producers in non-EU countries to incorporate a non-PFAS strategy.

## 7.4. PFAS governance strategies

### 7.4.1. Conclusions

Preliminary conclusions of our governance analysis point to **distinct regional and national differences** between both PFAS case studies. Differences can be seen in (i) political support (countries submitting the EU PFAS restriction proposal all being in the Northeast Atlantic region, countries in the Black Sea region awaiting revisions of EU directives), (ii) levels of awareness (minimal awareness on the PFAS issue among stakeholders in the Black Sea region), and (iii) institutional capacity (advanced research and monitoring programmes in the Northeast Atlantic, limited monitoring in the Black Sea). This is partly explained by the higher proportion of non-EU Contracting Parties in the Bucharest Convention in comparison with the OSPAR convention. Furthermore, the ongoing war in Ukraine has heightened tensions in the Black Sea region, resulting in pollution issues being deprioritized on the political agenda.

We also find **overlaps and disconnects** in PFAS governance. For the Northeast Atlantic there is some governance integration, where monitoring expertise at the OSPAR Convention level is utilised to update concentration levels and threshold in EU regulations. There is also emerging integration between monitoring marine pollution and addressing land-based sources of marine pollution via the contracting OSPAR parties. Between the Bucharest Convention and EU-level governance of PFAS in the Black Sea there are more disconnects, which are also due to the aforementioned reasons. The PFAS restriction adopted by the French parliament can be seen as an example of governance overlap, considering that an EU restriction is currently being discussed. As PFAS governance is emerging at many levels simultaneously, the likelihood of overlaps can be anticipated.

Finally, we find **a range of industry approaches and initiatives.** Industry is a very diverse stakeholder group. The more organised primary production components of the product chain are lobbying strongly against regulation and trying to maintain PFAS production unaffected by putting emphasis on remediation solutions. A growing number of primarily public-facing industries and brands are trying to move away from PFAS in their products, since many alternatives already exist.

### 7.4.2. Recommendations

The EU should support Member States in better monitoring of PFAS pollution from source-to-sea. In the Black Sea Region in particular, there is a need to enhance capacity to monitor and raise awareness around PFAS. This could include cooperation across regional sea conventions, as OSPAR already has more experience in monitoring and addressing land-based sources of pollution.

In parallel to the various policies, production restrictions and regulations being prepared at the EU level, the EU should encourage the best practices that are already happening. The example of France shows that Member States can become frontrunners in restricting certain applications of PFAS. The EU should also leverage and amplify the movement of PFAS-free alternatives, already rapidly growing, and seek synergies with industries such as recycling that can accelerate a transition to pollution-free and circular economy.

# A Annexes

## A.1. Assessment of primary PFAS emissions

### A.1.1. Data availability and data quality

Although much knowledge on PFAS pollution has been gathered over the last decades, the knowledge is still fragmented and incomplete. ECHA is required by the REACH regulation "to publish information it holds on registered substances (whether on their own, in mixtures or in articles) free of charge on the internet." Companies that produce or import a chemical need to register this under REACH when the volume is above 1 t/y. The ECHA CHEM website shows a tonnage band for an individual chemical, based on all registration dossiers. This tonnage band covers an order of magnitude (e.g. 1,000 – 10,000 t/y).

Data on production volumes within the EEA are assessed as relatively reliable compared to data on import, export and usage, as production takes place at a limited number of companies. Data on the export and import of PFAS is much less reliable, as often products that contain PFAS are not registered as such. PFAS concentrations in seawater, surface water, soils and air are often measured only at a few locations for a limited time. Furthermore, many studies use different analytical techniques and focus on a different selection of PFAS chemicals, making a meaningful comparison of data sets challenging. Moreover, the available data shows that measured concentrations of PFAS in the environment vary substantially, both spatially and temporally, and these variations are not always understood.

In this document, we aim to answer the technical questions raised in relation to the emission of PFAS into the environment. As the SOS-ZEROPOL2030 project focuses on the marine environment, we will aim to address these questions both in relation to the total emissions and the emissions entering the marine environment. Nevertheless, most of the questions on PFAS emissions can only be answered with approximations and extrapolations given the paucity and fragmented nature of the data available.

Environmental agencies from five EU countries (Denmark, Germany, the Netherlands, Norway, and Sweden) collaborated on a document proposing to restrict the manufacture, placing on the market and use of PFAS in the EU. It was published online at the ECHA website in March 2023.[17] In this report we will refer to this document as the 'PFAS restriction proposal'. This document and its Annexes were used as the main data source for this report, owing to its useful overviews, comprehensive data, and information from stakeholder surveys that is not available elsewhere. Where possible, information was cross-checked with other data sources.

### A.1.2. Main point source emissions of PFAS in Europe

Emissions can occur at known and well-defined places (point sources) or at places without a single point of origin or not introduced into a receiving stream from a specific outlet (diffuse sources). Point source emissions are better suited for emission monitoring, therefore we focus on those first, following two different approaches.

Firstly, point source emission volumes and an estimated share of emissions into surface water are listed in the PFAS restriction proposal[16]. Using this information, the total point source emissions to the surface water can be estimated. Secondly, the Flemish database of point source emissions to the surface water in Flanders can be extrapolated to the European level. Comparison between the two datasets gives insight in the quality of the data.

### A.1.3. First approach: using data of the restriction proposal

The prime point sources of PFAS emissions in Europe are production locations of PFAS with emissions ranging between 400 and 4000 tonnes per annum.[3] At the PFAS production locations the majority of emissions are released into the air compartment and only a small fraction to the surface water compartment. Secondary point emission sources are waste management facilities, such as waste water treatment plants (WWTPs, emitting mostly to the surface water) and landfill site leachates that contain PFAS (emitting into surface water and groundwater, some of which is treated by WWTPs).

The total direct emissions of the 20 PFAS manufacturing locations in the EEA is estimated to be between 400 and 4000 tonnes per annum[3] [Annex XV restriction report, Annex B, section B9.2.2], of which the direct emissions to air are dominant (~98%) while the direct emissions to surface water are considerably lower (~2%). This would imply that roughly between 8 and 80 tonnes PFAS per annum is directly discharged to the surface water in the EEA at the manufacturing sites. The indirect emissions of PFAS manufacturing sites via solid waste (treated at third parties) are substantial[66], but accounted for in emission volumes of the waste management sites.

The total PFAS emission volume from European landfill sites for solid wastes via leachate to the water compartment is crudely estimated to be 1-5 tonnes per annum[3] [Annex XV restriction report, Annex B, B9.18.2.3]. Actual PFAS emission volumes at waste incinerators cannot be estimated accurately, as no monitoring is in place. Recent research shows that incineration of fluoropolymers (0.3 wt% of total input) under standard conditions for municipal waste or hazardous waste incineration in a rotary kiln type oven both give high destruction efficiencies (>99.99%).[8] Since moving grate designs dominate in municipal waste incineration facilities[92], the average PFAS destruction efficiency may be different in reality. PFAS emissions into bottom ashes of a few incinerators have been analysed. Extrapolation of the found concentrations indicates that European bottom ashes contain approximately 26 kg PFAS per annum and 46 kg per annum in the fly ashes [3] [Annex XV restriction report, Annex B, B9.18.2.4]. These ashes are typically landfilled. In most European countries the landfill sites are well-managed and leachates are collected for treatment at WWTPs. Wastewater containing PFAS likely cannot be treated effectively, as most municipal WWTPs are not equipped with the necessary technology. Once discharged into surface waters, this wastewater can lead to indirect emissions of PFAS[3] [Annex XV restriction report, Annex B.4.5.8]. Furthermore, it should be noted that the gaseous emissions of small PFAS molecules to the air, can indirectly cause emissions to the aqueous compartment. Due to photochemical degradation in the stratosphere some of these PFAS molecules are converted into TFA that will precipitate into the rivers and the seas. These emissions cannot be approximated yet.

The total PFAS emission at waste water treatment facilities in the EU is estimated to be 5-10 tonnes per annum via the effluent and approximately 0.5 tonnes per annum via the sludge[3] [Annex XV restriction report, Annex B, section B9.18.2.5]. A second estimation was made by extrapolating the Dutch data of waste water treatment facilities[93] over the entire EU using the population (17.5m in NL and 745m in EU in 2021) as weighing factor. In this way, we estimate that 5 tonne per annum of PFAS are discharged with the effluent and 1.3 tonnes per annum in the sludge.

### A.1.4. Second approach: using the Flemish data of point source emissions to surface water

The Flemish database of point-source emissions to the surface water is particularly detailed. It shows that in the time period of 2007 to 2020 8 tonnes of PFAS have been discharged in Flanders to surface water (both direct and indirect). The lion share of the emissions (66%) occurred at manufacturing sites, followed by 32% at various waste treatment facilities and 1% from a long list of miscellaneous point sources. Extrapolating this data to the entire European Union using the gross domestic product (GDP) as weighing factor suggests that 26 tonnes of PFAS are discharged to the surface water in the EU per annum. The data treatment and calculations behind this number can be found in the Excel file ‘Flanders reported PFAS discharge loads into wastewater’, part of a publicly available dataset.[15] This would imply 17 tonnes from manufacturing sites and 9 tonnes from waste treatment facilities. The 17 tonnes per annum discharged at manufacturing facilities to the surface water aligns reasonably well with the estimation in the restriction proposal: between 8 and 80 tonnes per annum. Moreover, the 9 tonnes at waste treatment facilities compares reasonably well with the numbers estimated in the restriction proposal (between 6 and 16 tonnes annum).

### A.1.5. Main diffuse sources of PFAS emissions in Europe

Diffuse emissions, which are those that enter the atmosphere from non-point sources, occur predominantly in the use phase. The emissions during use have been estimated in the restriction proposal relying on a long list of assumptions. This renders the picture that applications within the textile (TULAC) domain are dominant and emit 10-35 kilotonnes per annum in the EEA, followed by emissions in the medical application sector which account for roughly 4-8 kilotonnes per annum, emissions due to construction products (1.5-3.5 kilotonnes per annum), fluorinated gases with an emission of roughly 1.5 kilotonne per annum and then many applications with less than 1 kilotonne per annum. The emission of the fluorinated gases is clouded by a large uncertainty as the stock levels of these gases is much larger, crudely estimated 39 kilotonnes, hence the actual emissions can be much larger.

Diffuse emissions thus represent much larger volumes than point emissions, the uncertainty in the volumes is larger, and it is more challenging to implement well-functioning monitoring systems for diffuse emissions than for point source emissions. This implies that the PFAS restriction proposal can only be effective if not only production of PFAS chemicals but also import thereof and usage of products that contain PFAS are covered, as is the case in the current proposal.[17]

### A.1.6. Emissions in the PFAS value chain

PFAS emissions stem from

- Production of base (PFAS) chemicals;
- (industrial) Usage of the chemicals in end product manufacturing;
- Usage of PFAS-containing end products;
- End-of-life treatment of discarded objects containing PFAS.

The most comprehensive and reliable data source for PFAS emissions in the EU is the overview in the restriction proposal for PFAS under REACH and its Annexes.[3, 16, 17, 94] This proposal estimates emissions to all environmental compartments and considers many different angles.

Since most EU countries do not obligate companies to measure and register of PFAS emissions, no dataset offers a reliable overview of the real emissions based on monitoring data. The best available dataset concerning PFAS emissions in the EU contains information about PFAS loads in Flemish wastewater, which is publicly accessible.[95] The number of chemicals that need to be registered and the concentration limit above which reporting is obligatory have been made more strict over the years in which registration has taken place (from 2007 onwards). Nevertheless, the registered volume of emissions accounted for less than 0.1% of the emissions in 2021 which could be expected to occur in Flanders, based on the average emissions in the EU mentioned in the restriction proposal.

Potential PFAS point sources encompass manufacturing sites of PFAS (20 in EEA), industrial processing and application sites (>100 000 facilities in EEA where such activities may take place has been estimated[17]) and waste treatment facilities (~500 incinerators, ~30000 waste water treatment sites and ~300.000 landfill sites in EU). In many of these facilities, it is unknown which types and quantities of PFAS emissions occur and to which environmental compartment. It could be argued that these should instead be considered as diffuse sources. The combined emissions from PFAS application and the use of end products represent about 90% of the total PFAS emissions, as shown in Table 3.1-2.

Large volumes of PFAS surfactants are used in the production of fluoropolymers. For certain fluoropolymers all manufacturing processes make use of PFAS surfactants. Some other fluoropolymers can be manufactured without using surfactants, but these processes typically generate PFAS impurities that are ultimately still emitted. [96]

- Yearly loads of PFAS in emissions from government-owned wastewater treatment plants (WWTPs) to surface water in Flanders have shown strong fluctuations[95];

without further investigation the reason for this fluctuation remains unknown. Temporal fluctuations in emissions from the 3M plant in Zwijndrecht dominate the input of PFAS into wastewater in Flanders, as indicated in Figure 7.4-1. Emission volumes from diffuse sources do not depend on production schemes or treatment plant efficiencies and hence are expected to provide a stable baseline of emissions into water. The role of WWTPs in PFAS transportation varies with, among others, region, plant layout and wastewater input composition. Industrial wastewater may, in some cases, be directly discharged into surface water. Some WWTPs concentrate most of the PFAS in the influent into the sludge, while in others the total PFAS concentration in the effluent water is higher than in the influent. WWTPs and waste incinerators are interconnected, sludge from WWTPs is often incinerated.

- In Romania, a recent study shows that PFAS emissions from WWTPs into surface water represent a small fraction of the total presence of PFAS in riverine water. The authors conclude that the largest share of PFAS in surface water could be linked to improper disposal of PFAS-containing products or the use of firefighting foam.[97]
- In Italy it was observed that the concentration of PFAS in effluent water can often be higher than in influent.[13] In WWTPs exhibiting this phenomena, biotransformation processes such as the formation of PFAS molecules from precursors produce more PFAS than the amount that is removed by the sludge in the same period of time. A review article suggests that this is the case for the majority of WWTPs globally.[98]
- The effluent of an industrial wastewater treatment plant close to Leverkusen was in 2010 found to be the main point source for PFAS emissions into the Rhine. Mitigation actions have been taken and were found to reduce the emissions of the plant to a level that is indistinguishable from that of the river sections just before the plant. [99]

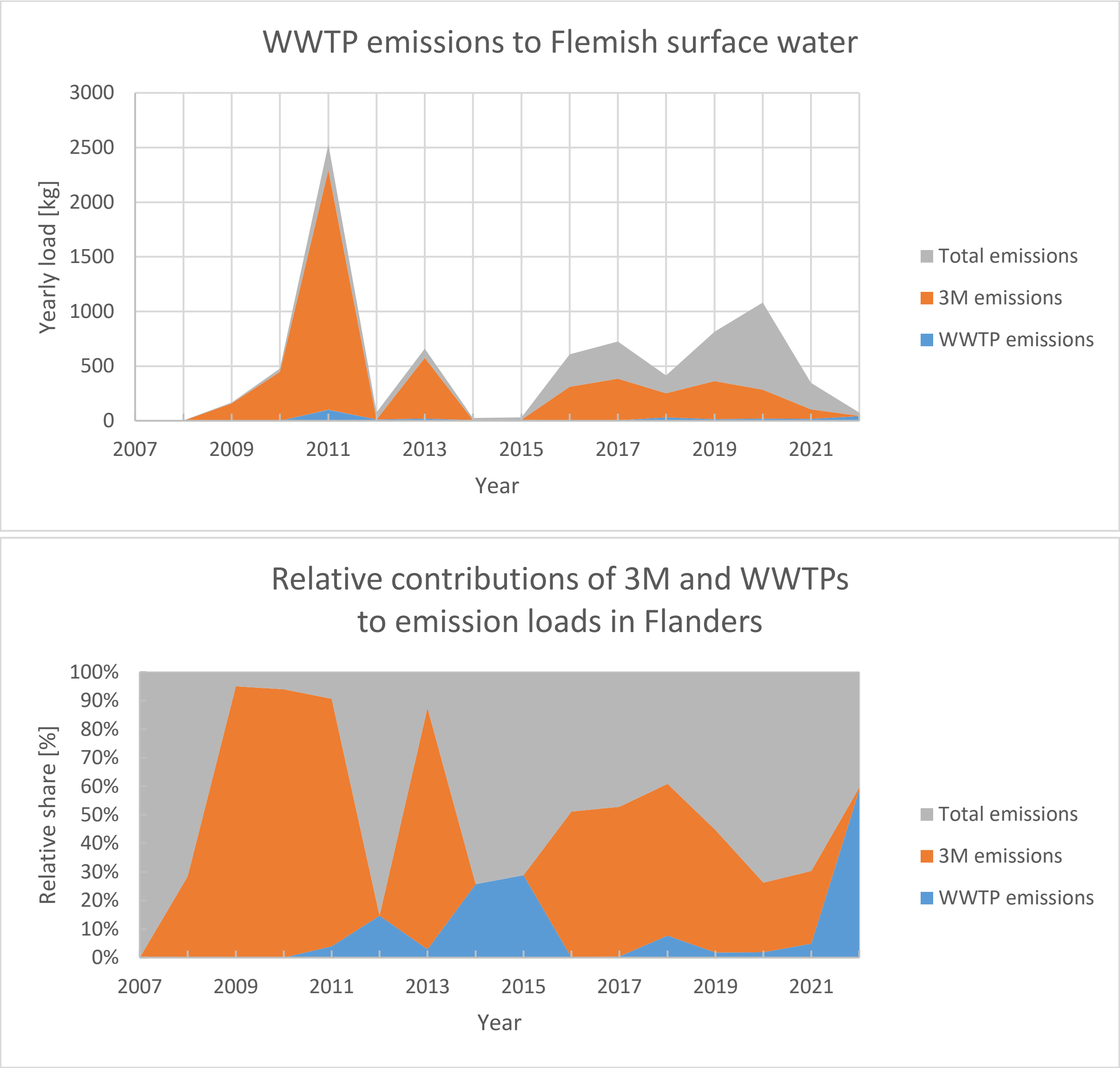

*Figure 7.4-1. Yearly loads of PFAS emissions into Flemish wastewater and relative contributions of the 3M manufacturing plant in Zwijndrecht and that of all Flemish wastewater treatment plants to the total yearly loads, in the period 2007-2022. Data were retrieved from a publicly available database[95]; categorization and data analysis has been performed for the current report.*

Estimations in Table 3.1-2 thus show that the largest volumes of emissions are related to the industrial use of PFAS for end product manufacturing and the use of end products. This fact indicates that the amounts of PFAS emissions generated in the EU would only decrease significantly if a restriction on PFAS would not be limited to manufacturing of these chemicals. A comprehensive regulation that considers industrial use, consumer use of PFAS-containing products, and both import and export activities is necessary to significantly mitigate emissions.

### A.1.7. PFAS emissions in relation to consumer products

In the PFAS restriction proposal, end product manufacturing and product usage together govern the PFAS emission volumes. Emissions from PFAS chemical production and product end-of-life treatments are not taken into account. While it should theoretically be possible to estimate PFAS emissions from all lifecycle stages for single products, in practice this is not common practice. This implies that products with high emissions during PFAs chemicals manufacturing or during end-of-life are likely underrepresented in this overview. Some examples include emissions from the use of PFAS to prevent mist formation during metal plating, the use of PFAS as lubricant in plastic processing, and the use of fluorinated gases as solvent for cleaning in semiconductor manufacturing. Nevertheless, the emission volumes of these applications are estimated to be negligible in comparison to the amounts of fluorinated gases produced and the amounts used in TULAC.

Figure 3.1-1 shows estimates of PFAS usage and emissions per sector; the relation to consumer products is discussed in the next section. Data for these graphs were taken from the main document of the PFAS restriction proposal.[17] Two sectors clearly stand out: 'Textiles', which includes Textiles, Upholstery, Leather, Apparel and Carpets (TULAC) and 'Gases', which relates to the application of fluorinated gases and includes the usage in other sectors. Emissions from medical devices are expected to grow significantly and it is likely that this sector will receive derogations that allow continued PFAS use. Other sectors that emit >500 t/y of PFAS include construction, PFAS chemicals manufacturing, electronics & semiconductors, and food contact materials. Consumer products within these sectors were estimated to cause the highest emission volumes are listed in Table 3.1-3.

Where possible, the selection of products in Table 3.1-3 was based on direct emissions from a product category. Data for attributing emissions to consumer product groups were taken from Annex A of the restriction proposal.[16] For the 'medical devices' and 'electronics and semiconductors', no quantification was found and therefore the text is shown in grey. For these sectors, the top three of products was selected based on information from other sources, of which references are provided in the table.

### A.1.8. Environmental fate and transport of PFAS

Environmental fate and transportation pathways are strongly dependent on physicochemical properties of the chemical and the environmental compartment into which the emission has occured.[100] Several schemes have been drawn that provide a visual representation as an answer to this question, although reality is always more complex. A good example is shown in Figure 7.4-2, as cited from Panieri *et al.*[101]. In this scheme, the volumes of the streams are not taken into account. An important remark is that long-range atmospheric transport is not depicted in this figure, while it is known to be an important pathway in the distribution of certain PFAS.[102, 103] Furthermore, this scheme suggests that uptake into aquatic and terrestrial ecosystems and humans mainly takes place from sediment. Whereas this is true for aquatic plants[104], the general consensus is that the uptake of PFAS by the general populations is mainly through drinking water and dietary exposure, although many potential exposure routes have not been investigated in detail.[100] Another scheme, designed by Evich et al.[103], is shown in Figure 7.4-3. This scheme clearly points out that emissions occur in each of the stages in the PFAS lifecycle. Similar to Figure 7.4-2, many more emission and transportation routes exist in reality.

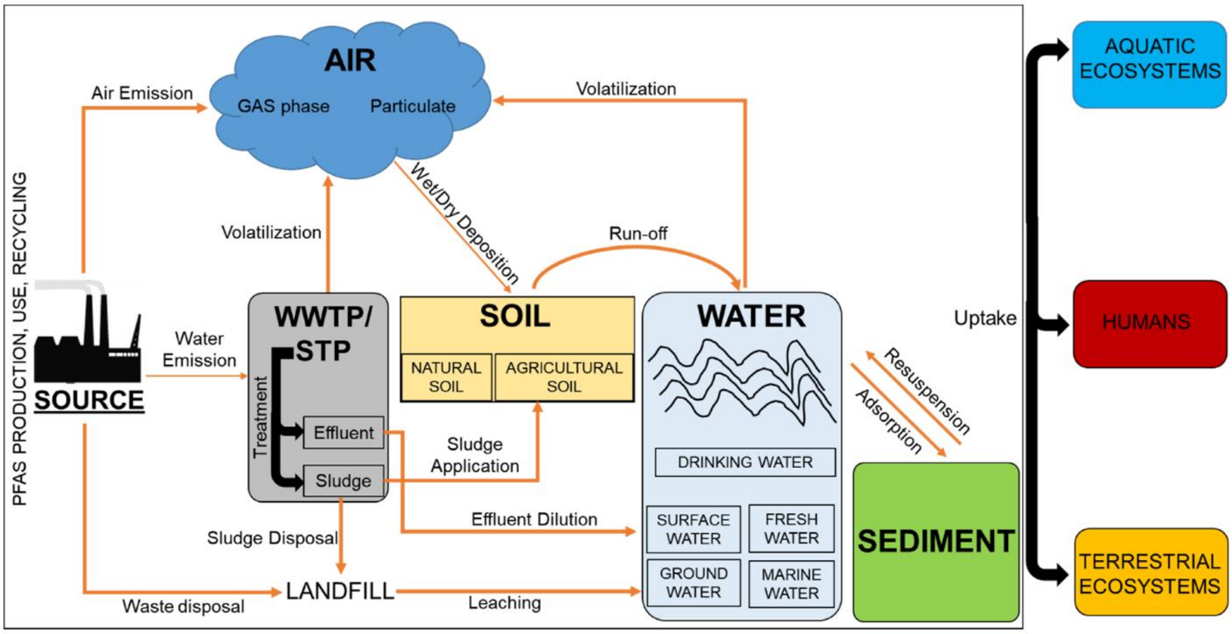

*Figure 7.4-2. Schematic overview of transportation routes for PFAS after primary emission has occurred, reused from Panieri et al[101]. Note that the blocks represent potential accumulation zones and the arrows represent transportation pathways.*

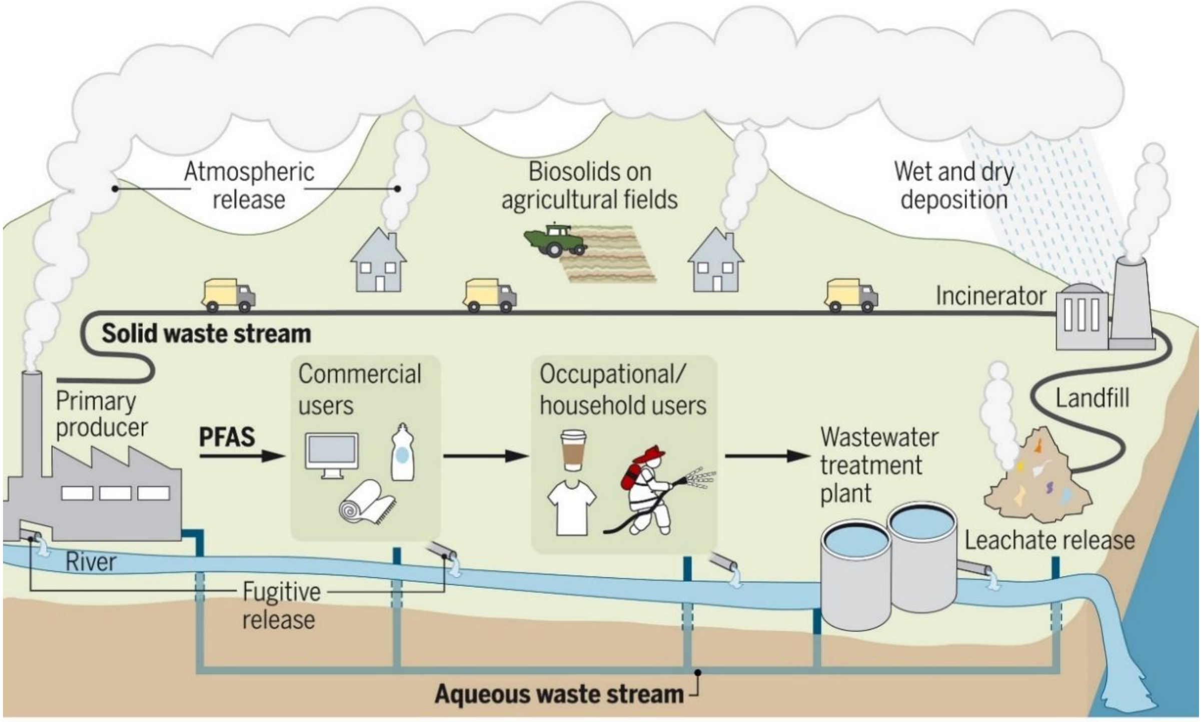

*Figure 7.4-3. PFAS lifecycle and emissions from each of the steps, reused from Evich et al..[103]*

### Water

PFAS emissions to water occur at many locations; both point sources and diffuse sources contribute significantly. Many PFAS molecules are salts, giving rise to a significantly higher water solubility than structurally similar non-charged molecules have. Dissolved PFAS will accumulate in surface water, groundwater and marine water.[102] Transportation towards an accumulation zone may be severely slowed down due to interaction with sediments or soil, especially for cationic and zwitterionic chemicals.[103]

The fate of PFAS emitted into water bodies varies widely, depending on factors such as partition coefficients, chemical structure of the molecule, presence of currents and flow, water temperatures and ionic strength, presence of objects in the water to which PFAs can absorb, and etc. Considering that diffuse sources are the most relevant primary source of PFAS emissions into water (see Section A.1.6), the transportation routes with highest estimated volumes are shown in Figure 7.4-4.

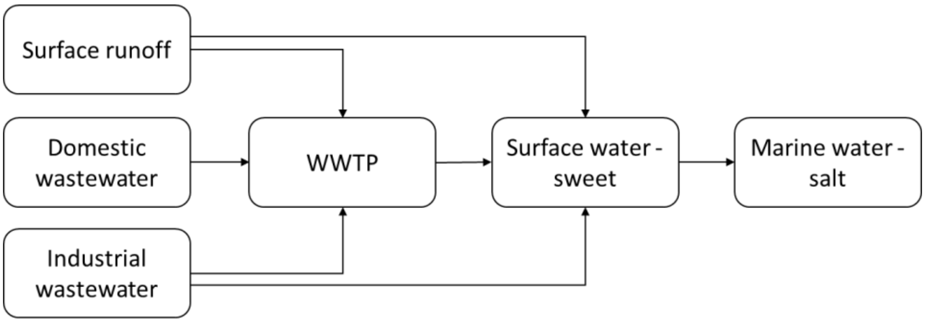

*Figure 7.4-4. Scheme indicating the PFAS transportation routes in water with likely the largest PFAS fluxes*.

Some remarks concerning emissions of PFAS and subsequent transportation processes:

- Sectors and products for which emission volumes are estimated to be the highest, as discussed in Sections 3.1.6 and A.1.6, are not directly associated with the marine environment. PFAS emitted from these products or from associated processes could move into marine compartments in various other ways. Water and sediment in rivers bring soluble and absorbed PFAS to the sea, gases (potentially after some molecular transformations under the influence of UV light) are taken up in precipitation.
- Direct emissions of PFAS into seawater (for example from the use of aqueous film forming foam (AFFF) or in naval coatings) likely represent relatively small emission volumes compared to emissions from terrestrial sources, but may be impactful in or close to navy harbours or in warzones.[105]
- Surface runoff is associated with PFAS present on terrestrial grounds, typically in areas where a PFAS spillage has occurred and in urban areas. After solubilization by precipitation, the PFAS chemicals typically flow into surface water.[106] The EU proposed to introduce new regulations for the treatment of wastewater in 2022, which still have to be agreed upon. These regulations would oblige to treat

rainwater from urban areas in WWTPs, in order to decrease direct emissions of pollutants into surface water.

- High concentrations of various PFAS molecules have been found in various environmental compartments close to airports, military sites and fire stations.[35, 107] These are likely related to the use of aqueous film-forming foam (AFFF). According to literature, currently available models are not able to accurately predict the transportation routes of PFAS chemicals in such a real-world contamination site or require more diverse and specific input values than what is typically available.[108]

Once PFAS arrived in a sea or ocean, the high persistence of PFAS chemicals allow for distribution across the water body, mainly driven by currents. This aspect is further discussed in Section 3.1.8.

### Air

A significant share of emissions from the manufacturing of PFAS chemicals is into the air compartment. The most likely transportation route is the following:

PFAS chemical production facility -> deposition to soil and dust at a concentration level decreasing with distance to the source -> dissolution in water phases related to precipitation -> surface water & sea.

Depending on the products and processes used in the production facility, the chemical profiles in the emissions can vary.[109, 110] In the Chemours plant in Fayetteville, North Carolina, a thermal oxidizer was installed and operations began in 2019. A sampling campaign took place in the immediate vicinity of this plant before and after its commissioning. The significantly lower emissions of emerging PFAS after commissioning may indicate that effective measures to mitigate emissions to air can be designed.[109] Fluorotelomer alcohols form an example of a group of PFAS chemicals that are volatile, ubiquitous, have a long enough lifetime (20 days) to enable long-range transport, and are known to degrade in the atmosphere.[111]

Further important mechanisms related to emissions into the air compartment are:

- Certain hydrofluorocarbons and hydrofluoroolefins in the atmosphere are known to degrade into TFA. This molecule is miscible with water and does not adsorb onto sediment nor bioaccumulate significantly.[112] Once present in the atmosphere, TFA will partition entirely into water droplets, leading to wet deposition[113]. Together with direct TFA emissions into water, the molecule will flow towards the lowest point. Oceans, seas and lakes are the likely accumulation zones for TFA.[114, 115]
- Several industrial end product manufacturing processes are known to generate PFAS emissions into air. Examples include the thermal application of fluoropolymer dispersions on fabrics[116], the use of volatile PFAS as surfactants in semiconductor manufacturing, and the application of paints[117]
- A long list can be composed of end products that directly emit PFAS into the air. Some examples include propellants in inhalers and aerosols in the field of

cosmetics[63], sulphur hexafluoride ($SF_6$) used as dielectric gas in the power industry[118], and certain cleaning agents[63].
- The formation of sea spray aerosols (SSAs) from surfactants in surface seawater causes PFAS deposition from the sea onto terrestrial grounds.[119] In Europe, this effect is the strongest in countries that are close to the Atlantic Ocean and often have relatively high wind speeds (most notably Ireland, Iceland, Norway, Great-Britain, the north-western part of Spain and the western part of France). This process demonstrates that the marine environment should not be seen as a sink for all PFAS chemicals. It is, however, an important accumulation zone for long-chain PFAS.

### Sediment and suspended particulate matter

The continuous interaction between water and sediment and the fact that PFAS can be present in or on both matrices contribute to the role of sediment in fate and transport of PFAS chemicals. In rivers and estuaries it was found that concentrations of PFAS in water were higher than those in beach sand and sediment in the water.[120-123] Higher concentrations of PFAS in sediment than in the corresponding water body have however also been reported.[123, 124] This is likely related to the molecular structure of the PFAS (the longer the chain and the more hydrophobic the molecule, the stronger the partitioning towards sediment and suspended particles[122, 123]). A trend of substituting long-chain PFAS chemicals for short-chain analogues is ongoing[125], hence it could be expected that in the near future the concentration of PFAS in water environments will increase compared to the concentration adhered onto particles. The magnitude of PFAS transport via particles in water has not been quantified in the literature. In rivers, suspended particulate matter can be up to 36 kg $m^{-3}$.[126] It could therefore be considered as a minor transport route.

More specifically for Europe, in Austrian and Hungarian sections of the Danube, it has been shown that the sediment mostly consists out of sand and has a low carbon content. As expected, PFAS adsorption to this type of sediment is minor and transport of PFAS is expected to occur mainly through the water phase.[127] The same conclusion was drawn for the Rhine.[128] The opposite situation, in which sediment brings along major amounts of PFAS and contributes significantly to pollution levels, has been reported in rivers that flow into the Great Lakes.[129]

PFAS transportation in marine environments can also take place through adsorption of the chemicals onto particulate matter. This can be either sediment or biological matter.[38, 130] For most PFAS chemicals, transport in the water phase (advective transport) is a more important mechanism. However, for perfluorodecanoic acid (PFDA) and precursor compounds of perfluorooctane sulfonate (PFOS), transport via particles was found to be responsible for 35% and up to 86% of the chemicals' vertical flux, respectively.[131]

### Man-made environments

Microplastics have been shown to preferentially adsorb certain PFAS chemicals[39], hence they could act as PFAS carriers (transport) and concentrators (accumulation). The scale at which this mechanism takes place and affects the distribution of PFAS in surface water and seawater seems to be largely unknown to date.

Landfills are a known accumulation zone for PFAS-containing products.[103] In the US it was estimated that most of these products are from municipal solid waste and biosolids (sewage sludge), and that the annual PFAS outflow is around 16% of the PFAS mass.[14]

### A.1.9. PFAS sinks in the marine environment

Literature does not provide an exhaustive overview of PFAS volumes that are accumulated or will accumulate in certain environmental compartments. A review paper from 2006, written by Prevedouros *et al.*[132], is one of the few that explore the concept of environmental inventories with regards to PFAS in detail (Table 7.4-1). The inventories calculated in this paper are limited to the Norther Hemisphere, due to limits in data availability. The spread in the estimations is too large to draw solid conclusions on the magnitude of accumulation zones or environmental sinks. For as far as we have found, more recent literature does not provide better estimations.

*Table 7.4-1. Estimated inventory of PFCAs in the Northern Hemisphere, listed per environmental compartment. Data was retrieved from Prevedouros et al[132].*

| **Environmental compartment** | **Estimated inventory [tonnes]** |
|---|---|
| Sea & ocean | 110 – 10 000 |
| Freshwater | 4 - 800 |
| Sediments | 3 – 340 |
| Air | n.a. |
| Other media | n.a. |

Marine waters are in the scientific literature considered to be the main sink for water-soluble PFAS.[38, 132] Examples of PFAS that are water-soluble and thought to accumulate in marine environments are perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), which are two of the most extensively researched PFAS molecules in literature. In the Arctic seas it was shown that although the concentration of PFOS decreases with decreasing depth, the total mass of PFAS stored in deep layers is significantly higher than that in superficial and intermediate waters. Furthermore, the concentration of PFOS is predicted to increase in deep water and to decrease in more superficial water at least until 2038.[133]

Lakes have also been shown to accumulate perfluoroalkyl acids (PFAAs)[115]. Lakes which are not connected to an open sea are however scarce and are likely of minor importance for the total environmental inventory.

### Effect of currents and vertical mixing

In general, concentrations of water-soluble PFAS are higher in marine surface waters than in deeper waters.[133-135] The main horizontal transportation in seas and oceans takes place via large-scale currents. Figure 7.4-5 shows the system of currents in the North Sea. Grey arrows indicate the inflow from the Atlantic Ocean, black arrows relate to the more superficial currents that bring water back to the ocean. The width of the arrows relates to the volume of the current. PFAS substances from rivers such as the Scheldt and Rhine have been shown to be transported towards Germany and Denmark, likely due to these currents.[36, 99] Effects like the outflow of PFAS from the North Sea into the Atlantic Ocean and the partitioning between seawater and sediment have not been studied, for as far as we know.

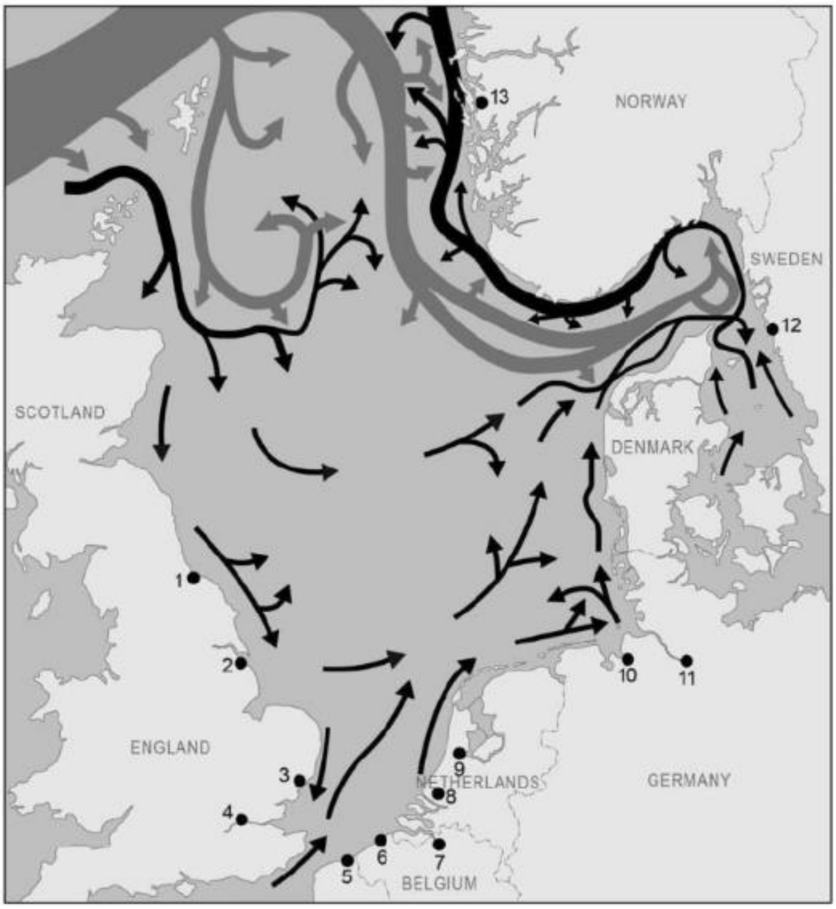

*Figure 7.4-5. General circulation pattern in the North Sea, image taken from[136]. The width of the arrows is a broad indication for the volume of the currents.*

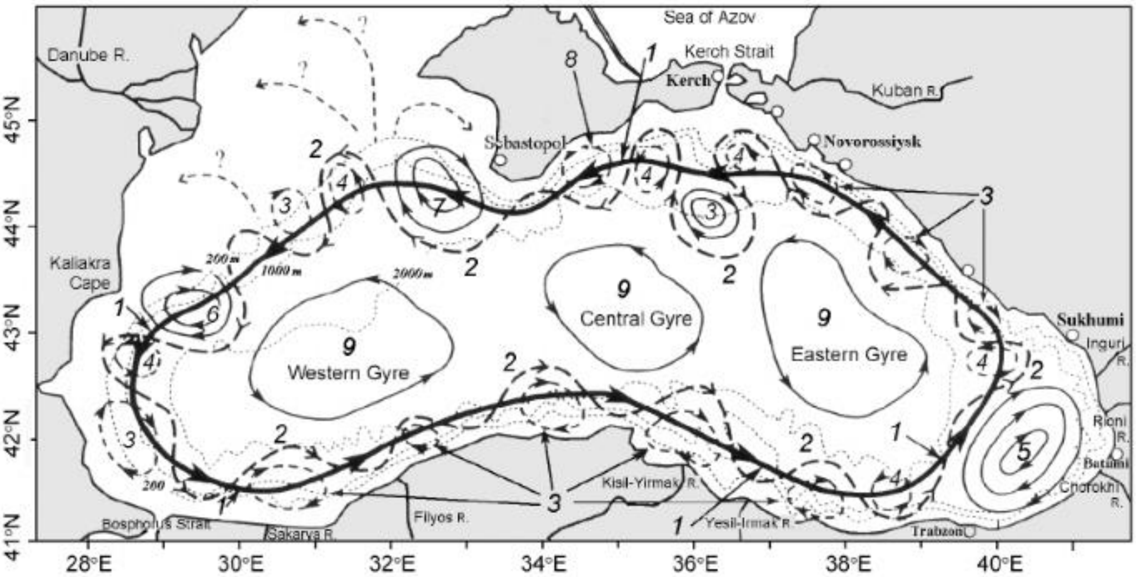

*Figure 7.46. General circulation pattern in the Black Sea, image taken from Korotenko et al. -*

In the Black Sea, a main cyclonic circulation (known as the Rim Current) exists, which is surrounded by smaller vortices ('coastal eddies') which flow in the opposite direction (Figure 7.46). These were considered important for transportation of oil spills from the coastal areas onto the open sea[137]; the same argument might be used for PFAS surfactants since their concentration is also highest at the air-water interface. The almost complete absence of vertical mixing is a particular feature of the Black Sea. In oceans, vertical mixing is an important driving force for redistribution of PFAS. [38] Considering the patterns in the Black Sea, it could be imagined that most of the PFAS will remain relatively close to its surface.

### Surface enrichment

Sea spray and aerosols play an important role in long-range transportation of PFAS with surfactant properties.[119] Transport of PFAS from the sea to terrestrial grounds affects the bigger picture: seas and oceans are not only a sink for PFAS but can also act as pathway towards other environmental compartments.

### Coastal areas vs mid-ocean

Several papers have reported that concentrations of PFAS in seawater generally decrease with increasing distance to the coast.[99, 121, 132] This could well be a temporal effect, the high persistence of typical PFAS chemicals would allow further distribution into deeper water and oceans.

### Soil

Soil is an important sink for long-chain PFCAs, especially if the soil is carbon-rich.[103, 138] Short-chain PFAS molecules and especially surfactants are more likely to remain in the water phase and end up in surface water or groundwater than fluoropolymers and long-chain PFAS. It has been shown that PFOS and PFOA can migrate with precipitation into underlying aquifer systems, although the topmost few meters of soil typically contains the highest concentration of PFAS.[103]

### Sediment and suspended particulate matter

Alike in soil, partition coefficients mainly relate to the carbon content of the solid and the molecular structure of the pollutant. In riverine systems, partition of pollutants can take place between water, sediment, and suspended particulate matter. The dynamics of such exchange processes can vary significantly among different PFAS chemicals.

### Macro and microplastics

Many plastics derived from fossil feedstocks have a density lower than that of seawater. This causes plastic particles to accumulate preferentially at the sea surface and in ocean gyres. Microplastics were however also shown to be present at high concentrations in deeper water layers.[139] This effect may also be present for PFAS, which could either become microplastics themselves or be present in or at other plastics that become microplastics. It should be noted that:

- Fluoropolymers such as PTFE, ETFE, and FKM rubbers have significantly higher densities than non-fluorine containing polymers or than seawater, in the range of 1700 – 2200 kg $m^{-3}$.[140] This could increase the sinking velocity compared to other particles of similar size and shape. Studies focusing on PFAS typically analyse low molecular weight PFAS and disregard fluoropolymers, potentially overlooking the deposition of fluoropolymer PFAS at the bottom of seas and oceans.
- Concentrations of PFAAs in the Northern Atlantic Subtropical Gyre were shown to be higher than in surrounding seawater[135], indicating that there may be similarities between the fate of microplastics and that of PFAS in marine environments.

The input of microplastics input to the Black Sea is known to be dominated by riverine input. The three largest rivers – Danube, Dnieper and Don – are responsible for over 50% of the current microplastics input into the Black Sea.[141] Considering the limited exchange between the Black Sea and the Mediterranean Sea, together with the fact that eddies are a typical sink for microplastics, one could expect that these eddies are also a sink for certain PFAS. Quantification of the volume of PFAS concerned with this mechanism is yet to be reported.

### Biota

Uptake of PFAS into plants happens mostly through the roots and is typically faster with short-chain PFAS.[110, 142] The application of contaminated sludge as fertilizer (‘biosolids’) is one of the main drivers for the concentration of PFAS chemicals on agricultural land. Both agricultural soils and the plants on top are currently not considered as a main reservoir for PFAS in the literature. Literature research shows that higher levels of PFAS are typically observed in tissues in species higher in the trophic level, but also that a large bandwidth exists. Figure 7.4-7 (adapted from Khan *et al.*[143]) graphically represents this trend.

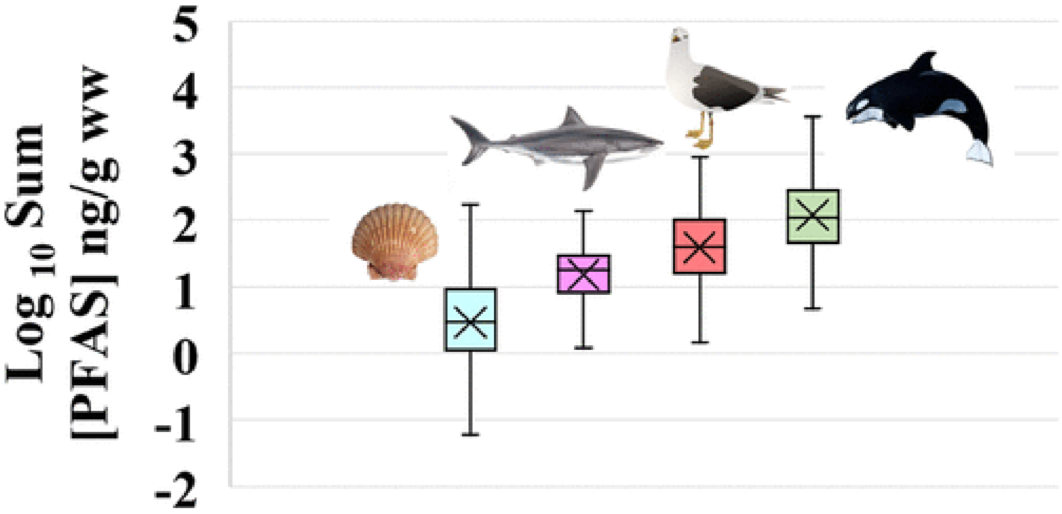

*Figure 7.4-7. PFAS concentration levels in invertebrates, fish, birds, and mammals; adapted from[143].*

## A.2. Environmental risk

### A.2.1. Methodology for PFAS exposure assessment

Three different types of data were mapped to define the exposure of PFAS in European seas. The first dataset is the Forever Pollution Map, developed by Le Monde and 17 partners as part of the cross-border Forever Pollution Project, revealing the scale of Europe's contamination by per- and polyfluoroalkyl substances (PFAS) in water and sediments. The second dataset is derived from OSPAR, where PFAS monitoring is carried out within OSPAR's Coordinated Environmental Monitoring Programme (CEMP) in sediment (primary matrix), biota and seawater (secondary matrices). Finally, an extensive scientific literature review was conducted within the scope of SOS-ZEROPOL2030 to gather additional exposure data on PFAS substances. This additional data review was conducted as the existing databases were not expected to contain all of the available PFAS exposure data.

As the risk assessment focused on European seas, only exposure data within marine areas was retained for that purpose. As a result, the following matrices were retained from each dataset:

OSPAR = Water + biota

LEMonde = Water + sediment

SOS-ZEROPOL2030 dataset = Water + Sediment

### A.2.2. SOS-ZEROPOL2030 PFAS exposure data review approach

The literature search was performed using Google Scholar and Web of Science to obtain a comprehensive list of scientific papers in which measurement data have been reported for the concentration of ‘novel’ PFAS in European marine waters, sediment and biota. Except for PFOS, PFOA, long-chain (>C8) PFCA's and PFSAs, and PFHxA and PFHxS, we considered all small molecules as novel PFAS for this assessment. Fluoropolymers were excluded from the investigation. The search for environmental concentration measurement data was performed between January 1 and April 30, 2024 and included various combinations of the keywords PFAS, novel, environmental concentration, seawater, marine, biota, sediment. Relevant data (sampling location, chemical, measured concentration, used analysis method, analytical limitations) were extracted from the main body and/or the supplementary information file(s) belonging to the paper. After homogenization of the units, all datapoints were gathered in a single list.

The 78 papers and databases retrieved in the literature search described in the previous section were filtered for the sampling region (this study only includes samples taken in the Mediterranean Sea, North Sea, Black Sea, and the European portions of the Atlantic Ocean and Arctic Ocean), leading to a final selection of 32 papers and 3 databases. A full overview of the sources used for this investigation is given in the data file ‘PFAS environmental concentrations for T4-2.xlsx’, which can be retrieved from the Marine Data Archive.[144] This file shows which PFAS chemicals have been assessed in all 78 papers and databases. Next to that, it contains the 39298 relevant and georeferenced datapoints used for the risk assessment of ‘novel’ PFAS in marine environmental matrices, with novel defined as described in the previous section.

### A.2.3. Limitations with existing PFAS exposure data

Recent insights [145] show that substances such as fluorotelomer alcohols, which have been used abundantly in consumer products, have been taken along in environmental sampling and measuring campaigns very sparsely. So-called ‘arrowhead’ compounds, PFAS such as perfluoroalkyl acids (PFAAs) that are the endpoints of environmental degradation processes, are typically included in environmental monitoring campaigns and may give some indications for the presence of the original molecules. Many of the original molecules can degrade into the same arrowhead compound, therefor it is often impossible to trace back what (amount of) the original component has been present in the environment when just monitoring a selection of compounds. Analytical chemistry methods still don’t allow for a reliable quantification of all individual PFAS in complex mixtures, such as in samples from a natural environment.[145] Hence, even if many environmental monitoring campaigns are performed, the reported concentration data of individual molecules are expected to represent only a small fraction of the total PFAS presence in any of the matrices of interest.[146] The presence of other chemicals in a sample, such as unknown PFAS or other molecules that interact with the PFAS of interest, may greatly affect the toxicological profile of the sample. In conclusion, there is an important discourse between the available exposure data and the data that an ideal risk assessment would need.

### A.2.4. Methodology and results for hazard assessment

Within SOS-ZEROPOL2023, we have assessed approaches to establish Predicted No Effect Concentrations (PNEC) for PFAS and TWP chemicals. The aim was to develop PNECs to be used in environmental risk assessment for these chemicals for communities inhabiting the Northeast Atlantic Ocean, Mediterranean Sea, and the Black Sea. The environmental risk is generally considered acceptable when the PNEC is lower than the predicted environmental concentration (PEC)[1]. If the concentration of a given chemical in the environment is known (measured or modelled), a risk quotient (RQ) can be estimated by dividing the PEC with the PNEC (SSD-generated or AF generated)[1,7]. Given that different chemicals display additive toxicity, the RQs can be summarized for multiple chemicals.

Water quality benchmarks, here called PNECs, represent the concentration of a chemical expected to cause no or negligible impacts for a given ecosystem. Derivation of PNECs rely heavily on laboratory data from ecotoxicity testing of the chemicals. In ecotoxicity testing, biological variables (most often survival, reproduction, or growth) responsive to chemical exposure are measured in individual species. Endpoints typically collected from ecotoxicity testing are $LC_x$ (lethal concentration for x% of the test organisms), $EC_x$ (effective concentration causing a biological response in x% of the test organisms) and NOEC (no observed effect concentration) from acute, chronic, and sub-lethal ecotoxicity tests.

For robust PNEC determination for use in assessing the environmental risk of specific chemicals in specific ecosystems, there are some important aspects that need to be considered[7]. **The data set(s) used to perform hazard assessment need to be of high quality, transparent, and publicly available.** For input data collection, the source and underlying data sets should be available. The **quality criteria** used for data filtration should be clear and transparent. Filtration of data from large ecotoxicity databases may be necessary to ensure data used are relevant in terms of endpoints and that they are comparable. The **chosen endpoint should have ecological relevance**, typically acute or chronic effects on survival, growth, and reproduction. As toxicity occurs as a function of exposure time as well as exposure concentration, **exposure time** used in the ecotoxicity tests should be considered. Acute aquatic toxicity tests are generally 4 days or less, and chronic aquatic toxicity tests can be weeks to years, depending on the life span of the species and the biological response monitored[8]. An example of criteria for ecotoxicity data to be regarded as chronic for various species is Postuma et al.,[4] where >12 h for algae and bacteria, >24 h for unicellular organisms, >48 h for crustaceans and >7 days for molluscs, worms and fish were classified as chronic ecotoxicity data.

PNECs can be derived in different manners: a deterministic approach based on the use of coefficients called assessment factors (AFs) and a statistical approach based on the so-called species sensitivity distribution (SSD)[1–3]. The most common method involves using assessment factors (AFs), where threshold exposure concentrations determined in laboratory tests for individual species are adjusted to apply to populations in real-world ecosystems. PNEC are derived by dividing the lowest concentration available from ecotoxicity data by an appropriate AF (ranging from 10 to 1,000), which is based on the quantity and quality of available toxicity data, namely the number of taxa tested and what tests are performed (acute or chronic tests)[1].

When larger amounts of ecotoxicity data are available for multiple species, PNECs can be derived using Species Sensitivity Distribution (SSD)[2]. SSD is a cumulative probability distribution applied to a set of toxicity thresholds for individual species, based on the assumption that acceptable effect levels follow a specific distribution pattern relative to chemical concentration and that the tested species represent a random sample of the community. SSDs estimates either the concentration of a chemical that is toxic to no more than x% of all species (the $HC_x$) or the potential fraction of species affected by a given exposure concentration of a chemical[4,5]. The SSD approach is increasingly used in environmental risk assessment[4,6]. One of the main advantages of the SSD approach compared to the AF approach is that SSDs can be used to develop community-level benchmarks, while the AF approach relies solely on the data for the most sensitive species tested[6]. However, SSDs require substantial amounts of relevant and comparable ecotoxicity data.

To determine PNEC, we assembled a list of 50 PFAS chemicals which included chemical names, short names and chemical CAS information. We collected ecotoxicity data from the U.S. EPA ECOTOXicology Knowledgebase (ECOTOX), on October 3rd, 2024, using CAS. The ECOTOX database is the most comprehensive publicly available source for single chemical toxicity data for aquatic life, terrestrial plants and wildlife, and the data are derived predominantly from the peer-reviewed literature. All data are openly available and downloadable from the provided link[1].

From this database, queries for single PFAS-chemical exposures from laboratory-generated aquatic ecotoxicity data were performed, and only EC50, LC50 and NOEC for effect groups development, growth, morphology, mortality, reproduction and population were collected. The total number of entries, number of LC50, EC50 and NOEC data, and how many trophic levels covered in the tests were summarized for each PFAS chemical. Due to low availability of PFAS ecotoxicity data, providing community- or regional-specific PNECs was not realistic (see Table 7.4-2 below), and the AF approach was selected for PFAS hazard assessment within SOS-ZEROPOL2030.

PNEC for individual PFAS chemicals were calculated by dividing the lowest available EC50, LC50 or NOEC with an AF ranging 10-1000. The criteria used for derivation of AF were adopted from the European Commission TGD (EC, 2003). If only acute toxicity data were available, an AF of 1000 was used. If one, two or three long-term NOECs were found for a given PFAS chemical, AFs were 100, 50 or 10, respectively.

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[1] http:/www.epa.gov/ecotox/

For 37 of the 50 PFAS chemicals, entries were found in the ECOTOX database, and for 13 no entries were found. These were perfluoropentane sulfonate (PFPeS, 175905-36-9), perfluorohexane sulfonate (PFHpS, 375-92-8), perfluorononanesulfonic acid (PFNS, 68259-12-1), perflurorodecane sulfonate (PFDS, 335-77-3), N-methylperfluorooctanesulfonamidoethanol (N-MeFOSE, 24448-09-7), 8:2 fluorotelomer sulfonate (8:2 FTS, 481071-78-7), 6:2 fluorotelomer phosphate diester (6:2 diPAP, 57677-95-9), 2H,2H,3H,3H-perfluoroundecanoic acid (H4PFDA, 34598-33-9), 7H-dodecafluoroheptanoic acid (HPFHpA, 1546-95-8), 3,7-dimethylperfluorooctanoic acid (3,7-DMPFOA, 172155-07-6), 4:2 fluorotelomer sulfonate (4:2 FTS, 414911-30-1, 4:2 chlorinated polyfluoroalkyl ether sulfonate (4:2 Cl-PFESA, CAS not available), and 4,8-dioxa-3H-perfluorononanoic acid (ADONA, 919005-14-4). Thus, for these 13 chemicals, no PNECs could be derived.

For the remaining 37 PFAS chemicals, number of data entries in the ECOTOX database varied from 2 to 686 enabling PNEC calculations using the AF approach. The chemicals with highest number of entries were PFOA (686 entries, 102 LC50s, 45 EC50s and 539 NOECs), PFOS (593 entries, 69 LC50s, 20 EC50s, 504 NOECs), PFBS (317 entries, 4 LC50s, 1 EC50 and 312 NOECs), and PFNA (121 entries, 18 LC50s, 12 EC50s and 91 NOECs).

The derived PNECs for the 37 PFAS chemicals ranged from 0.3 ng/L to 108 µg/L, and PNECs were dependent on the ecotoxicity data and the applied AF. Table 7.4-2 provides an overview of the number of entries in the ECOTOX databases distributed between different endpoints (EC50, LC50 and NOEC) and trophic level coverage as well as the AF used and PNEC calculated. Despite having the highest number of entries, PFOA, PFOS and PFNA had the lowest PNECs 0.3, 0.4 and 0.4 ng/L, respectively. For these chemicals, the lowest AF (10) was used due to high coverage of NOECs represented for different trophic levels. The highest PNEC was calculated for FRD-902 (108 µg/L) for which the lowest NOEC was 1.08 mg/L. Also here, the lowest AF was used.

*Table 7.4-2. Summary of all data (total, LC50, EC50 and NOEC entries) collected for the 50 PFAS chemicals (chemical name, short name and CAS included). The lowest EC50/LC50 and NOEC levels, as well as their trophic level coverage are included as well as individual assessment factors (AF) and calculated PNECs.*

| Chemical name (short name, CAS) | Total entries | LC50 entries (n) | EC50 entries (n) | NOEC entries (n) | Lowest EC50/LC50 value (mg/L) | Number of trophic levels | Lowest NOEC value (mg/L) | Number of trophic levels | AF | PNEC (ng/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| Perfluorobutanesulfonic acid (PFBS, 375-73-5) | 317 | 4 | 1 | 312 | 85.6 | 3 | 0.0077000 | 3 | 10 | 770.0 |
| perfluorohexane sulfonate (PFHxS, 355-46-4) | 61 | 1 | 3 | 57 | 3.86 | 1 | 0.0004450 | 3 | 10 | 44.5 |
| perfluorooctanesulfonic acid (PFOS (n and Br), 1763-23-1) | 593 | 69 | 20 | 504 | 0.00244 | 3 | 0.0000040 | 3 | 10 | 0.4 |
| Perfluorobutanoic acid (PFBA, 375-22-4) | 61 | 13 | 5 | 43 | 83.6 | 3 | 0.0400000 | 3 | 10 | 4000.0 |
| perfluoropentanoic acid (PFPeA / PFPA, 2706-90-3) | 20 | 4 | 2 | 14 | 31.8 | 3 | 0.2508450 | 1 | 1000 | 250.8 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Perfluorohexanoic acid (PFHxA, 307-24-4) | 79 | 8 | 9 | 62 | 76.3 | 3 | 0.0010000 | 3 | 10 | 100.0 |
| Perfluoroheptanoic acid (PFHpA, 375-85-9) | 40 | 3 | 4 | 33 | 3.4675 | 2 | 0.2512035 | 2 | 1000 | 251.2 |
| perfluorooctanoic acid (PFOA, 335-67-1) | 686 | 102 | 45 | 539 | 0.4747 | 3 | 0.0000034 | 3 | 10 | 0.3 |
| Perfluorononanoic acid (PFNA, 375-95-1) | 121 | 18 | 12 | 91 | 0.2363 | 3 | 0.0000037 | 3 | 10 | 0.4 |
| Perfluorodecanoic acid (PFDA, 335-76-2) | 78 | 8 | 7 | 63 | 0.85 | 3 | 0.0009000 | 3 | 10 | 90.0 |
| perfluoroundecanoic acid (PFUnA, 2058-94-8) | 54 | 1 | 1 | 52 | 40.5019636 | 1 | 0.0093200 | 2 | 50 | 186.4 |
| Perfluorododecanoic acid (PFDoA, 307-55-1) | 31 | 0 | 2 | 29 | 112.380666 | 1 | 0.0098900 | 2 | 50 | 197.8 |
| perfluorotridecanoic acid (PFTrDA, 72629-94-8) | 37 | 0 | 0 | 37 | - | 0 | 0.0100000 | 1 | 100 | 100.0 |
| perfluorotetradecanoic acid (PFTeDA, 376-06-7) | 4 | 0 | 2 | 2 | 95.6917584 | 1 | 0.2499412 | 1 | 1000 | 249.9 |
| Perfluorohexadecanoic acid (PFHxDA, 67905-19-5) | 2 | 0 | 0 | 2 | - | 0 | 0.2523813 | 1 | 1000 | 252.4 |
| Perfluorooctadecanoic acid (PFOcDA, 16517-11-6) | 2 | 0 | 0 | 2 | - | 0 | 0.2468202 | 1 | 1000 | 246.8 |
| N-Methylperfluorooctanesulfonamidoacetic acid (N-MeFOSAA, 2355-31-9) | 2 | 0 | 0 | 2 | - | 0 | 0.2513306 | 1 | 1000 | 251.3 |
| N-ethylperfluorooctanesulfonamidoacetic acid (N-EtFOSAA, 2991-50-6) | 2 | 0 | 0 | 2 | - | 0 | 0.2516501 | 1 | 1000 | 251.7 |
| Perfluorobutane sulfonamide (FBSA, 30334-69-1) | 6 | 3 | 3 | 0 | 0.41 | 1 | - | 0 | 1000 | 410.0 |
| perfluorooctane sulfonamide (PFOSA / FOSA, 754-91-6) | 32 | 4 | 4 | 24 | 0.011 | 1 | 0.0011500 | 1 | 100 | 11.5 |
| Perfluorooctane sulfonamidoacetic acid (FOSAA, 2806-24-8) | 2 | 0 | 0 | 2 | - | 0 | 0.2507305 | 1 | 1000 | 250.7 |
| N-methylperfluorooctane sulfonamide (N-MeFOSA, 31506-32-8) | 2 | 0 | 0 | 2 | - | 0 | 0.2514529 | 1 | 1000 | 251.5 |
| N-Ethyl perfluorooctane sulfonamide (N-EtFOSA, 4151-50-2) | 21 | 6 | 0 | 15 | 0.189 | 1 | 0.2477821 | 1 | 1000 | 247.8 |
| N-ethylperfluorooctanesulfonamidoethanol (N-EtFOSE, 1691-99-2) | 4 | 0 | 0 | 4 | - | 0 | 0.0208000 | 1 | 100 | 208.0 |
| 6:2 fluorotelomer sulfonate (6:2 FTS, 27619-97-2) | 44 | 4 | 5 | 35 | 14.3 | 3 | 0.0100000 | 3 | 10 | 1000.0 |
| 10:2 fluorotelomer sulfonate (10:2 FTS, 120226-60-0) | 6 | 3 | 3 | 0 | 0.1 | 1 | - | 0 | 1000 | 100.0 |
| 8:2 Fluorotelomer phosphate diester (8:2 diPAP, 678-41-1 | 8 | 0 | 0 | 8 | - | 0 | 0.0103000 | 1 | 100 | 103.0 |
| 6:2 Fluorotelomer carboxylic acid (6:2 FTCA, 53826-12-3) | 34 | 5 | 7 | 22 | 1.29 | 3 | 0.1900000 | 2 | 50 | 3800.0 |
| 5:3 Fluorotelomer carboxylic acid (5:3 FTCA, 914637-49-3) | 4 | 0 | 2 | 2 | 22.5 | 1 | 0.2497395 | 1 | 1000 | 249.7 |
| 7:3 Fluorotelomer carboxylic acid (7:3 FTCA, 812-70-4 | 7 | 1 | 2 | 4 | 2.1 | 2 | 0.2520110 | 1 | 1000 | 252.0 |
| 2H,2H-perfluorodecanoic acid (H2PFDA, 27854-31-5) | 30 | 7 | 12 | 11 | 0.44 | 3 | 0.0820000 | 3 | 10 | 8200.0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6:2 chlorinated polyfluoroalkyl ether sulfonate or sulfonic acid (or 9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid) (6:2 Cl-PFESA, 73606-19-6) | 75 | 8 | 0 | 67 | 2.2 | 2 | 0.0001630 | 1 | 100 | 1.6 |
| 8:2 chlorinated polyfluoroalkyl ether sulfonate or sulfonic acid (or 11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid) (8:2 Cl-PFESA, 83329-89-9) | 17 | 0 | 0 | 17 | - | 0 | 0.0001520 | 1 | 100 | 1.5 |
| ammonium (2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoate) (FRD-902, 62037-80-3) | 28 | 11 | 2 | 15 | 8.89 | 3 | 1.0800000 | 3 | 10 | 108000.0 |
| hexafluoropropylene oxide dimer acid (FRD-903, 13252-13-6) | 47 | 14 | 1 | 32 | 0.01971 | 1 | 0.4895000 | 2 | 50 | 9790.0 |
| Perfluoro-2,5-dimethyl-3,6-dioxanonanoic acid (HFPO-TA, 13252-14-7) | 23 | 0 | 0 | 23 | - | 0 | 0.4867000 | 1 | 100 | 4867.0 |
| Sodium p-perfluorous nonenoxybenzene sulfonate (OBS, 70829-87-7) | 6 | 0 | 0 | 6 | - | 0 | 0.7319715 | 1 | 100 | 7319.7 |

### A.2.5. Detailed overview of the PFAS risk assessment tool (PFAS RAT)

The RAT has the following key features:

**Compound-specific filtering:** The PFAS RAT allows users to filter by specific PFAS compounds, including PFOS, PFOA, and an expanding list of novel PFAS, present in environmental monitoring data. This flexibility supports a targeted approach, enabling stakeholders to focus on individual compounds of interest to assess impacts and risks.

**Dataset integration and selection:** Multiple datasets from European monitoring programmes have been integrated into PFAS RAT, providing a rich data foundation for PFAS risk assessments. Users can select specific datasets to ensure transparency regarding data sources, while also facilitating comparisons across different monitoring efforts. This integration allows for a more robust, comprehensive analysis of PFAS distribution across European seas.

**Multiple environmental matrices:** Recognising that PFAS compounds are distributed across various environmental compartments, the PFAS RAT offers a matrix selection feature. Users can filter data by environmental matrix, including water, sediment, and biota. This feature enables assessments of PFAS behaviour and bioaccumulation across ecosystems and provides insight into the risks associated with different exposure routes.

**Temporal filtering:** PFAS contamination levels and regulatory thresholds have evolved over time, and will continue to do so, making it essential to consider temporal trends. PFAS RAT includes a function to filter data by year, allowing users to analyse changes in PFAS concentrations over time, evaluate the effectiveness of regulatory measures, and identify emerging trends for novel PFAS compounds.

**Risk assessment and Assessment Factor application:** The PFAS RAT provides a risk assessment output based on AF hazard assessments, when these available for the selected compounds. For each compound, environmental concentrations are compared to established risk thresholds, such as PNECs, where available. The AF applied to each compound varies depending on its ecological risk profile. For compounds without established AFs, the tool allows users to apply provisional or analogous factors, following guidance from risk assessment protocols, to approximate potential environmental risks.

### A.2.6. Overview of PFAS risk assessment toxicity thresholds

For **PFOS**, the following assessment criteria were applied:

#### Water

The environmental status of concentrations in water is assessed using the annual average Environmental Quality Standard (EQS) for ‘other surface waters’, 0.13 ng/L. Mean concentrations significantly below the EQS indicate good environmental quality.

#### Biota (Environment)

- The Quality Standard secondary poisoning (QSsp) of 33 µg $kg^{-1}$ ww whole fish is used to assess the environmental status of PFOS concentrations.
- EU technical guidance document 27 describes the methods used to derive environmental quality standards (EQSs), including human health and secondary poisoning standards. Guidance document 32 describes the application of these EQSs and summarises the biota quality standards derived for the two different protection goals. Further details of the QSsp for PFOS can be found in the PFOS data sheet. Concentrations below the QSsp should not harm marine organisms.
- PFOS concentrations in fish muscle are assessed on a wet weight basis and are compared directly to the QSsp, given that fish muscle is a large proportion of the total body weight
- PFOS concentrations in fish liver are assessed on a wet weight basis and are compared to the QSsp multiplied by 5, the lowest of the range of conversion factors for whole fish to liver in Faxneld et al. (2014)
- PFOS concentrations in crustaceans are assessed on a wet weight basis and are compared directly to the QSsp (without any tissue conversion or trophic adjustment)
- PFOS concentrations in shellfish are assessed on a dry weight basis and are compared to the QSsp converted to a dry weight basis using typical species-tissue dry and lipid weights (without any tissue conversion or trophic adjustment)

#### Human Health

- The Quality Standard human health (QShh) of 9.1 µg $kg^{-1}$ ww is used to assess the human health status of PFOS concentrations.
- PFOS concentrations in fish muscle and crustaceans are assessed on a wet weight basis and are compared directly to the QShh

- PFOS concentrations in fish liver are assessed on a wet weight basis and are compared to the QShh multiplied by 5, the lowest of the range of conversion factors from whole fish to liver in Faxneld et al. (2014)[147]
- PFOS concentrations in shellfish are assessed on a dry weight basis and are compared to the QShh converted to a dry weight basis using typical species-tissue dry and lipid weights

**Sediment**

Because toxicological data of PFASs in sediment are lacking, the sediment PNEC was calculated based on equilibrium distribution. Thus, according to the technical guidance document of the European Union for the risk assessment of chemical substances (TGD) The $PNEC_{sediment}$ of PFOS has been set at 67 µg/kg[148]

For **PFOA**, the following assessment criteria were applied:

**Water**

The environmental status of concentrations in water is assessed using the annual average Environmental Quality Standard (EQS) for 'other surface waters', 0.03 ng/L. Mean concentrations significantly below the EQS indicate good environmental quality.

Insufficient exposure and toxicity data was available for sediments and biota meaning that a risk assessment for PFOA in these matrices cannot be conducted.

For **novel PFAS**, the following assessment criteria were applied:

**Water**

The environmental status of concentrations in water is assessed using the annual average Environmental Quality Standard (EQS) for 'other surface waters', 0.03 ng/L. Mean concentrations significantly below the EQS indicate good environmental quality.

Insufficient toxicity data was available for sediments and biota meaning that a risk assessment for PFOA in these matrices cannot be conducted.

## A.3. Existing value chain and technological actions and strategies

### A.3.1. Relevance, approach and challenges

The main question to be addressed, by providing factual information, is the following: "What effects on pollution can be expected from which interventions?" To address this question, it is necessary to have information about many aspects. In the task covered by this report, the product chain and the potential technological actions for mitigating the pollution are put central.

### A.3.2. Relevance of investigating the '*product chain*'

In the project proposal this aspect was called a value chain, a term often observed in reports such as this one. A value chain typically identifies where and how much value is added to a material or product in consecutive steps from raw material to the door of the consumer. This concept is very useful to understand the relations between companies in a sector and their interdependence. In the SOS-ZEROPOL project, however, economic aspects do not play a key role in the analysis while product and emission volumes are of high importance. Furthermore, usually a value chain is analysed from the viewpoint of a consumable end product (type), while the focus in this project is either on an intermediate chemical (in the case of PFAS) or on an end-of-life material (in the case of TWPs). To accommodate for this different focus, it was decided to refer to a 'product chain' instead of a value chain.

### A.3.3. Relevance of investigating 'mitigating actions and alternatives'

To support the discussions in the Living Labs, the scenarios that are built based on the outcomes of these discussions, as well as evaluations in other work packages, it is important to have a trustworthy and extensive overview of technological actions that can be taken to mitigate emissions of, specific for this report, PFAS. In the integrated assessment template, the measures were split between those that can currently be taken and those that will become available in the future, mostly for practical use in the discussions with stakeholders.

### A.3.4. Challenges in this work

The research in this work package is based mostly on literature reviewing (scientific articles and patents but also producer's websites and popular science). For some parts, semi-structured interviews with experts were performed to obtain the required information. Due to the large number of different PFAS applications and individual companies that process the materials, it is impossible within the timeframe of this project to study all details in all parts of the chain for all products.

Diffuse emissions represent much higher volumes than point source emissions for PFAS. Even small quantities of the (persistent) chemical substances can have adverse health effects, therefore low concentrations of the chemicals that have been spread widely throughout the environment form a serious issue. Researchers try to link combinations of PFAS chemicals ("fingerprints") to specific usages. The knowledge generated by these efforts is very useful to understand emission pathways in the product chains and to decrease the uncertainty. Due to the large variation in PFAS chemicals used in similar products, combined with a large variation in background concentrations, this type of research often proves to be very complex. Data from such efforts could unfortunately not be used in this report, since only a few specific cases have been worked out in sufficient detail.

Evaluating technological measures that can be taken to reduce emissions and thereby decrease future pollution can be done from a broad technical perspective, when using literature as the main information source. In practice, the feasibility to integrate technical emission reduction measures into existing equipment, business processes, and policy will be different for each specific case. Many of the technical measures have not yet been developed at commercial scale for PFAS. It is very challenging to predict if and which emission mitigation technology will finally prove technically and commercially successful in the future.

### A.3.5. Product chains of and production routes towards selected types of PFAS

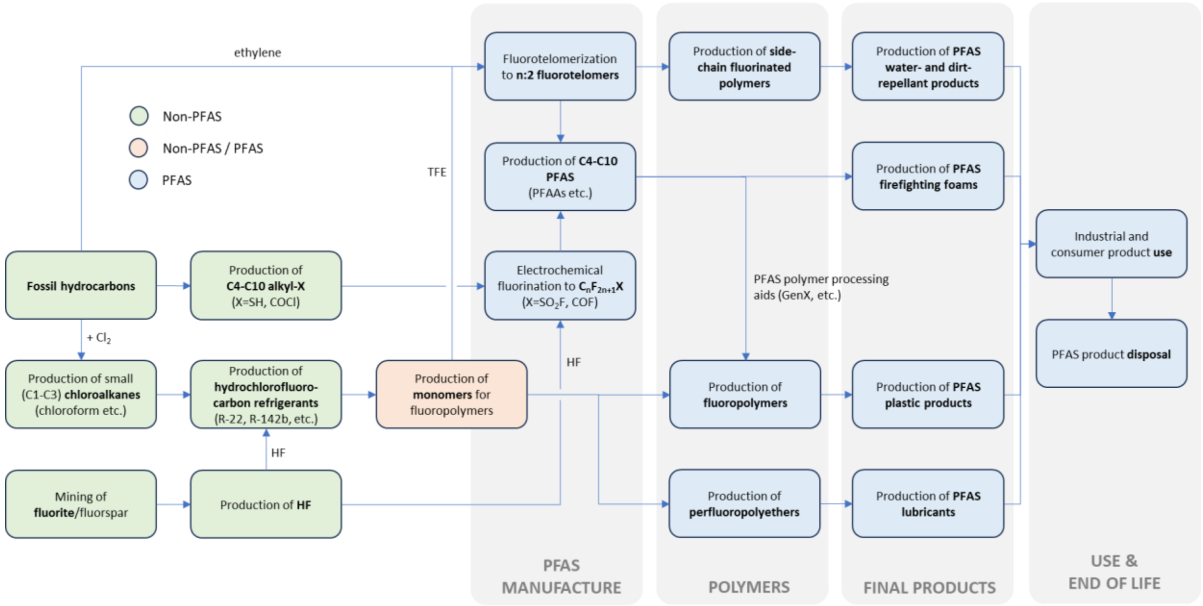

*Figure 7.4-8. General overview of the product chain of PFAS chemicals, polymers and end products.*

The primary feedstocks for PFAS are *hydrocarbons* from petroleum, coal or natural gas, and *hydrogen fluoride* (HF) from the mineral fluorite ('fluorspar') (Figure 7.4-8). ***Fluoropolymers and perfluoropolyethers***. Monomers for fluoropolymers and perfluoropolyethers are prepared by first chlorinating small (C1-C3) hydrocarbons to chloroalkanes and then exchanging most (but not all) of the chlorine atoms for fluorine by reaction with HF (Figure 7.4-9). This process yields hydrochlorofluorocarbons (HCFCs). These are applied as such as refrigerants, but are also subjected to pyrolysis at 550-750 °C to create monomers such as tetrafluoroethylene (TFE), hexafluoropropylene (HFP) and 1,1-difluoroethylene (vinylidene fluoride, VDF). Polymerization of TFE gives polytetrafluoroethylene (PTFE, 'Teflon®'), whereas polymerization of VDF yields polyvinylidene fluoride (PVDF). Co-polymerizing TFE and HFP results in fluorinated ethylene-propylene co-polymer (FEP). All three polymers are classified as fluoropolymers, since their polymer backbones consist of partially or fully fluorinated carbon atoms. Surfactants that are PFAS themselves (e.g. hexafluoropropylene oxide dimer acid (HFPO-DA) and ADONA, an ammonium salt of 4,8-dioxa-3H-perfluorononanoic acid) are used to stabilize the emulsions in which polymerization takes place. Perfluoropolyethers (PFPE) are liquid polymers with a relatively low molecular weight derived from TFE and HFP via an intermediate oxidation step. Their backbones contain carbon and oxygen. To illustrate the complexity of a production process for a single material, the sequence of steps performed to produce PTFE from chloroform is depicted in the Figure 7.4-10.

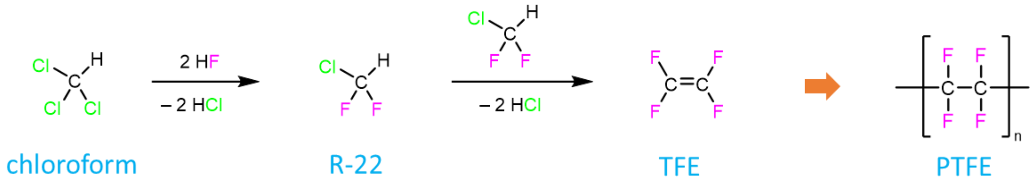

*Figure 7.4-9. Reaction scheme showing the synthesis route of PTFE starting from chloroform and HF.*

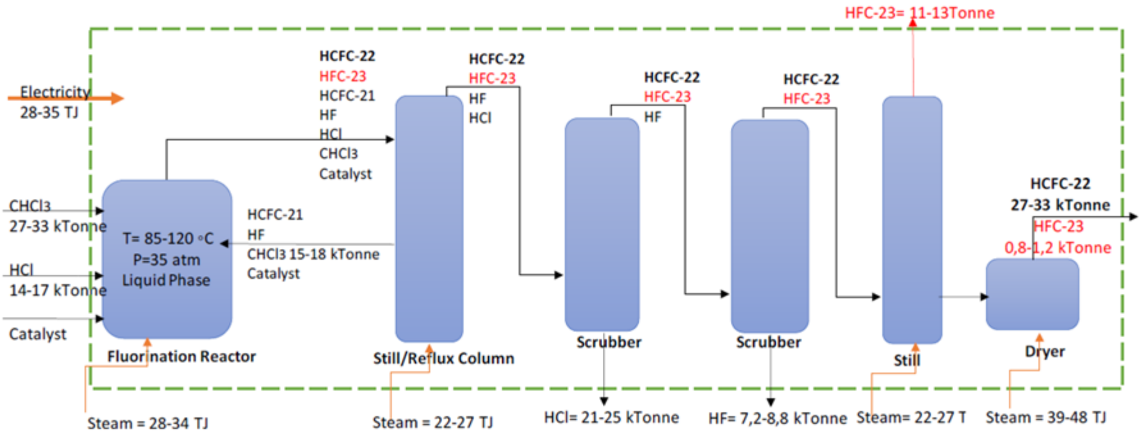

*Figure 7.4-10. Process steps required for the production of HCFC-22. Reused from Rodriguez et al. [149].*

To produce a chemical of sufficient quality and purity, a chemical process that typically consists of multiple steps needs to be designed and operated. The reaction scheme above shows that a single chemical reaction is required to produce HCFC-22 (alternatively R-22) from chloroform ($CHCL_3$) and hydrogen chloride (HCl). After the fluorination reactor, a distillation process is performed in the second step to separate the desired product from the other chemicals in the stream. After some additional purification and separation steps, the intended product is available.

***Short-chain (C4-C10) PFAS***. Two main processes are used to prepare short-chain (approx. C4-C10) PFAS. One is *electrofluorination*, in which a functionalized C4-C8 hydrocarbon derivative undergoes electrolysis in anhydrous HF, leading to the replacement of all the H atoms by F atoms. This process is used to produce PFAS molecules such as the 'legacy' PFAS surfactants perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) and shorter-chain versions of those. The chemical structure of the ammonium salt of PFOA, still used as a fluoropolymer processing aid in some parts of the world, is shown in Figure 7.4-11.

PFOA ammonium salt

*Figure 7.4-11. Molecular structure of perfluorooctanoic acid (PFOA).*

The second process is called fluorotelomerisation or simply *telomerisation*, in which a 'telogen', mostly perfluoroethyl iodide, $CF_3CF_2I$, is reacted with TFE (the 'taxogen') to create longer perfluorinated alkyl iodides known as 'Telomer A', e.g. perfluorooctyl iodide, $CF_3CF_2(CF_2CF_2)_3I$. In a second step, ethylene is inserted into the linear perfluoroalkyl iodide to give 'Telomer B', which in the case of perfluorooctyl iodide is $CF_3CF_2(CF_2CF_2)_3(CH_2CH_2)I$. These are subsequently modified to a range of fluorotelomer ('FT') derivatives, such as FT alcohols (FTOH), FT olefins, and FT sulfonic acids. FT alcohols such as $CF_3CF_2(CF_2CF_2)_3CH_2CH_2OH$ (denoted as *8:2 FT alcohol* or 8:2 FTOH, see Figure 7.4-12) are important starting materials for producing side-chain fluorinated polymers (see below).

8:2 FT alcohol

*Figure 7.4-12. Molecular structure of 8:2 fluorotelomer alcohol.*

***Side-chain fluorinated polymers***. The *n*:2 fluorotelomer alcohols (*n* is e.g. 6 or 8) described above can be converted to monomers which can be polymerized to *side-chain fluorinated polymers*. Examples are side-chain fluorinated polyacrylates, polymethacrylates or polyurethanes.

### A.3.6. Processing into end products

In task 4.1 of the SOS-ZEROPOL project, it has been established that PFAS are used in a large number of sectors and even more end products. The top five sectors / product categories in terms of annual PFAS usage have been identified in this task and are summarized in Table 7.4-3. Although the order of the sectors is different in the main document and the annex, the top five is the same.

*Table 7.4-3. Review of sectors / product categories that are associated with the highest usage volumes of PFAS.*

| **Sector ranking in terms of usage volume** | **Based on main document**[17] | **Based on Annex A** [16] |
|---|---|---|
| **#1** | Transport | TULAC |
| **#2** | TULAC (Textiles, Upholstery, Leather, Apparel, Carpets) | Medical devices |
| **#3** | Medical devices | Gases |
| **#4** | Gases | Food contact materials |
| **#5** | Food contact materials | Transport |

The main PFAS usages per sector have been described in great detail in Annex A of the PFAS restriction report. Table 7.4-4 provides a shorter summary of the use cases of PFAS in sectors that use high volumes of these chemicals.

*Table 7.4-4. Main types of PFAS used in the sectors with the highest usage volumes.*

| Sector | Selected usages [16, 63] | PFAS chemicals (and their physical shape) |
|---|---|---|
| TULAC | Stain-, water- and oil-repellent coatings for wide variety of textiles; chemical protective suits and fire brigade suits, aids in dyeing and bleaching processes; antifoaming agents in textile treatments; emulsifier in surface finishing agent; additives for leather hydrating, pickling, degreasing and tanning processes; shoe leather brightening, | Surfactants, as part of a solution, sprays, (dispersion and emulsion) coatings, typically based on C6 chemistry. PTFE and PVDF membranes for water-tight clothing. Wide range of C4 and C6 PFAS for heat and chemical resistant protective workwear. [150] |
| Medical devices | See Section 5.1.2 | See Section 5.1.2 |
| Gases | PFAS polymer production, commercial and industrial refrigeration, mobile and stationary air conditioning, non-flammable propellants for industrial and aeronautical use, foam blowing agent, fire suppressant | As discussed in Annex A of the REACH PFAS restriction report[16] |

| | | |
|---|---|---|
| Food contact materials | Packaging, consumer cookware, industrial food and feed production equipment. | Side-chain fluorinated polymers (mainly C6), PTFE (coating, wax and micronized powder), PFPE coatings, PVDF and PTFE membranes and tubing, FKM gaskets, and more. |
| Transport | Fuel hoses, electrical wire coatings, gaskets, bearings and seals, long-life and heavy-duty lubricants, fuel cell proton conductors and battery seals, hydraulic fluids, road signage, and many more | Mostly fluoropolymers (PTFE, PVDF, ETFE, PFA, etc) and fluoroelastomers (FKM, FFKM) |

The large diversity in products in or onto which PFAS are applied, inherently correlates with a large diversity in application methods. While it is unclear which volumes of PFAS are applied by which method, it is likely that some of the most important application methods are covered below.

PTFE represents the largest usage volume among all fluoropolymers (53% according to Plastics Insights[151]), which warrants a more detailed review of common processing methods. Most PTFE products are made by drying aqueous dispersions. PFAS-containing coating materials are usually dispersions of polymers and additives. Aqueous dispersions have the important advantage that water is a cheap medium compared to organic solvents. Material costs in coating production are much lower for water than for any synthetic solvent. Moreover, investments required for industrial application of water are limited to drying equipment, while synthetic solvents typically require additional safety equipment (e.g. fire protection, ventilation) as well as additional permits.

Dispersions of PTFE can be made in many (slightly) different processes, as described extensively by Puts, Crouse and Ameduri.[152] Emulsion polymerisation has long been the most economically and technically attractive method. From a technical point of view, the most preferred dispersing agents are however PFAS themselves, especially when producing polymers with high molecular weight.[69] Especially perfluorooctanoic acid (PFOA) has been used for this purpose for a long time, but this is now banned in the EU. HFPO-DA (Gen-X) and Ammonium 4,8-dioxa-3H-perfluorononanoate (ADONA) are examples of feasible alternatives, which however bear generally similar health risks as PFOA.

After adding the required additives and other functional components, the dispersions are ready for use as coating materials. To create a PTFE powder, an aqueous dispersion is dried, agglomerated and ground to obtain a powder with the desired particle size.[152] Note that for polyvinylidene fluoride (PVDF) – the fluoropolymer with the second-highest sales volumes – production processes are similar to those for PTFE. [153]

Processing of PTFE into plastic products is more challenging than with most other common polymers. PTFE with a molecular weight that is sufficiently high (>$10^6$ g/mol) to obtain useful mechanical properties has a very high melt flow ($10^{10}$-$10^{13}$ Pa.s at 380 °C). [154] This unusual property causes practical difficulties when using PTFE to shape products using common processing techniques such as melt extrusion, injection moulding and thermoforming. Specific copolymers have been engineered to overcome this issue.[154] Alternatively, shaping of PTFE plastics can be done using PTFE powder in ram extrusion or paste extrusion with a subsequent heating step that is similar to a sintering process for ceramics. [134, 155] Literature does not describe the potential liberation of PFAS emissions in such processes. Isoparaffinic solvents are recommended for use as lubricant in these processes. [155] Next to inorganic pigments, no other materials are mentioned to be added to the PTFE before producing the final plastic. Isoparaffins are thus likely the main or only chemicals to be emitted during the processing of PTFE into an end product. The main PFAS emissions during the processing of PTFE into a final product are therefore likely scrap and off-quality products.

Application of aqueous coatings (e.g. barrier coatings for paper and moulded fibre, or for metal coating) is typically done in an industrial setting by methods such as blade coating, rod coating, gravure coating and spray coating. Material losses are typically low in a run, as unused coating materials are recycled internally. Losses may occur in larger quantities at the beginning and end of a process run, those materials will be directed to the wastewater treatment plant of the mill or factory. Wastewater plants that don't employ nanofiltration or reverse osmosis will typically not be able to remove PFAS from the water.

### A.3.7. Use phase

The typical persistence of PFAS suggests that very little changes in the chemical composition take place during the use phase. However, especially side-chain fluorinated polymers are known to be labile and to cause the release of very persistent perfluoroalkyl acids (PFAAs).[156]

Textile is estimated as the sector with the highest PFAS emission volumes and side-chain fluorinated polymers are often used.[16] Textile usage creates wear of the fabric; fibres are liberated into air as dust particles and into washing water as fibres or parts thereof. Both dust[157] and washing water[158] are known to contain measurable amounts of PFAS that also contribute significantly to human intake of PFAS.

Cosmetics are usually deemed to end up in the environment, likely through wastewater, and are therefore another example of a product category of which a significant share of emissions is to be expected from the use phase. A recent study has shown that cosmetics may account for at least 4% of the precursor-derived PFAAs measured in wastewater in the San Francisco Bay area.[159]

Gaseous PFAS are likely to leak out of the containing device (e.g. air conditioning or refrigeration systems) over time and some are designed for single use (i.e. propellants). In conclusion, there are many ways for PFAS to enter into the environment during the use of products and thus to leave the product chain.

### A.3.8. 'Drop-in' solutions for replacing PFAS

Replacing PFAS by a less harmful and persistent alternative that provides the minimally required functionality is likely the most effective technological action to decrease emissions. PFAS have been used extensively in durable water repellent (DWR) coatings for outdoor clothing. The main purpose of the PFAS coating is to repel water from the surface of the garment, providing comfort to the wearer. Aqueous dispersions of C6 and C4 PFAS also provide properties that are desirable but not required for such clothing, including oil-repellence and low surface tension.[160] Alternative coating technologies, based on hydrocarbons or silicone chemistry, could be used to provide water repellence to clothing but provide only limited oil repellence. [47, 160]. Although data gaps clearly exist and hinder proper evaluation of the environmental effects of such coatings, it is clear that alternatives to PFAS are more environmentally benign for this specific application.[47]

Another example of a successful replacement of PFAS relates to pans with a ceramic anti-stick coating. For a long time, ceramic coatings couldn't compete with PFAS. In the past few years, certain pans with ceramic coatings have been shown to have higher release forces than pans coated with certain types of PFAS (PTFE and PFA were tested), especially after a higher number of usages.[161] A significant share of consumers have adopted the use of non-stick pans with ceramic coatings, as shown by a survey in Portugal.[162] Other consumers may be inspired by the past and rediscover the merits of cast iron skillets. Manufacturers of pans with non-PFAS coatings currently often indicate this on packaging materials and in advertisements, although many also branded PTFE-coated pans as 'PFOA-free' or the like[163]. Based on the number of blog posts on this topic, numerous consumers consider the nature of the coating material into consideration when buying a new pan. This reconfirms that technological interventions are more effective when combined with efforts in marketing and communication.

A similar case is that of skiing wax. Wax with PFAS components brings clear competitive advantages compared to wax that doesn't contain PFAS. The skiing and biathlon federations FIS and IBU have banned the use of PFAS-containing ski wax, which will significantly decrease the demand for these products even though their gliding performance is superior. Examples of such replacements in industrial context include polyether ether ketone (PEEK), polyamide-6,6 (PA66) or polyphenylene sulphide (PPS) with specific fillers that could replace PTFE in tribological applications and non-halogenated fire retardants.[164]

Multiple assessments of PFAS-free alternatives have been executed and published; in many cases reasonable alternatives were available or become available when the market interest spawned.[163, 165] Arguments against the replacement of PFAS-containing objects are often very comparable, as pointed out by Ateia *et al.*[163]; recognition of these objections helps to convince stakeholders.

Note that phasing out a specific PFAS for toxicity reasons and replacing it by another PFAS material is considered a regrettable replacement. There are multiple downsides of this strategy from a pollution point-of-view, the most important being that the toxicity profile and potential degradation routes of many 'novel' PFAS are insufficiently studied while the persistence remains intact. In view of regulatory pressure, there has been a trend toward the replacement of banned PFAS by those with a short chain length.[125] In the recent past, some replacements for PFOA and PFOS have been shown to have significant negative effects themselves.[65] Based on this observation, much care is required when introducing new PFAS to the market or when using alternative PFAS in a product.

### A.3.9. End-of-life

Any product in general can have several end-of-life routes, depending on use cases, quantities used, location of usage, etc. The same is true for PFAS-containing products. Given that there is no system in place to indicate that a product is (partially) made from or using PFAS and that by no means a simple inspection or measurement could be used to confirm the presence of PFAS, it is currently and will remain impossible to sort out PFAS-containing products from PFAS-free products. A proper estimate of PFAS volumes can only be done if specific products are investigated and measurements are done to close the mass balance. Some specific examples follow below.

Wastewater from households has been shown to contain PFAS in relatively high quantities and concentrations, often even higher than concentrations in industrial wastewater of industrial sectors that use PFAS in their processes. The wastewater is in the EU typically treated in a wastewater treatment plant (WWTP). Conventional WWTPs are generally not very effective in preventing PFAS from entering the natural environment, however.[166] Although specific investigations have been performed towards the fate of PFAS in durable water repellent (DWR) coatings, it is currently unknown what amount of PFAS remain in textiles until it reaches its end of life.[167] End-of-life textiles may be reused or repurposed, though many pieces will end up in landfills and municipal waste incineration processes. Practical research has shown that textiles are a likely source of PFAS in landfill leachates.[12, 168] The fate of PFAS when treated in municipal waste incinerators is a largely unexplored area of research, partially due to significant challenges in translation results from pilot trials into reliable expectations for commercial incinerators.[169]

## A.4. Mapping current governance strategies/efforts/arrangements

### A.4.1. Background information

A quick scan of governance efforts at the regional and level within these three regions showed that limited governance efforts exist at the regional and national levels. Governance arrangements that address PFAS within these regions are not yet institutionalised, also because much relevant EU legislation is currently being revised, meaning that the transposition and implementation of EU legislation has not yet begun. In response, we paid more attention to identifying overlap and disconnects between current EU regulatory developments around zero pollution of PFAS and regional, national and industry governance efforts to address production, use and end-of-pipe of PFAS in the Northeast Atlantic and Black Sea regions.

### A.4.2. Methodology

Through a range of personal communications and semi-structured interviews with expert stakeholders, we gained a more in-depth understanding of the relations between the national-, regional- and EU-level regulatory developments, as well as which discourses and power relations influence the shaping of current regional and national regulation and policies related to the selected pollutant.

### A.4.3. Scoping three regional case studies

The case study pollutant selection by regional sea was aligned with that of the living labs to optimise the utility of findings in both directions and to create the possibility of data triangulation. The case study pollutants for each regional sea were determined by the SOS-ZEROPOL2030 project team at the consortium meeting in Potsdam in October 2023. Criteria included the relevance to the overall project objectives, and the level of public awareness of the pollutant in the region.

The scoping in terms of a sectoral and/or life cycle stage focus was finalised at a meeting in Wageningen in January 2024 with project partners present from WP3 and WP4. Criteria for narrowing down on a sector included:

- Salience - covering a significant source of pollution emissions
- Geographical - having a tangible link to the region
- Life cycle stages - addressing interaction along the product chain
- Policy relevance - link to policy developments
- Living labs - the possibility for a constructive dialogue in the Living Labs
- Project relevance - the potential broader applicability of lessons from the case study to other pollutants

The medical sector in the Northeast Atlantic was selected for PFAS because it would touch on policy debates of ‘essential use’, has a clear connection to the region and is specific enough to allow stakeholders to make the step from challenges to criteria for change to occur in the living labs. For the Black Sea the awareness level of PFAS is still very low, which makes a sectoral approach difficult. That is why we chose to focus on public administration and the process of implementing revisions of EU directives with a focus on monitoring and drinking water. For TWP pollution, there are two stages in the life cycle where significant gains can be made: Production of tyres (including the chemical ingredients) and the end-of-pipe collection through improved wastewater treatment facilities. These were both chosen to be able to cover the pollutant life cycle.

The preparatory work resulted in three regional case studies (Table 7.4-5) which cover not only the distinct geographical areas of the SOS-ZEROPOL2030 project and consortium, but also various thematic focuses and sectors as demonstrated in the table.

*Table 7.4-5 Overview of the scoping results of the three regional case studies.*

| Region in Focus | Pollutant | Regional Convention | National focuses | Sector |
|---|---|---|---|---|
| North-East Atlantic Sea | PFAS | OSPAR Convention | Netherlands & France | Medical |
| Black Sea | PFAS | Bucharest Convention | Bulgaria & Romania | Public Administration (monitoring & drinking water) |

### A.4.4. Data collection and analysis

The work involved a comprehensive overview of the academic literature on PFAS in the Northeast Atlantic and Black Sea regions. The desk study, along with the review work conducted in WP2, allowed for the foundation of the existing research on the governance of PFAS in Europe (if any). Scholarly databases such as Web of Science and Google Scholar were queried using key works relevant to the research focus (i.e., Govern, Policy, PFAS Pollution, North- Mediterranean). In addition, a search of grey literature, including policy documents, news articles, and industry press releases allowed for another layer of verification as to the state of knowledge.

To gain further insight into developments in the Northeast Atlantic and Black Sea regions, we contacted various expert stakeholders (Table 7.4-6). Especially in the Black Sea region, the lack of governance efforts for PFAS resulted in difficulties in identifying relevant interviewees or information on the topic. As a result, we either had informal interviews or email-based correspondence where we put several concrete questions to the expert and therefore no audio recording was needed. We refer to this as ‘personal communication’ in Table 7.4-6.

We did two semi-structured interviews which were recorded for internal note taking purposes. All interviewees consented to take part in the interview and were provided full GDPR compliance information on the project before taking part.

The sampling of respondents for personal communications or semi-structured interviews was purposeful based, i.e. based on the stakeholder (organisation’s) expertise, knowledge available on the topic, and region the interviewee was focused on. We also applied the snowball sampling method – that is gaining additional key contacts via previously conducted interviews.

*Table 7.4-6 Organisations interviewed or contacted in relation to the governance of TWP.*

| **Organisation contacted** | **Date** | **Type of contact** |
|---|---|---|
| PFAS in the Northeast Atlantic region | | |
| Dutch Ministry of Health, wellbeing and sport | 12.03.2024 | Personal communication |
| OSPAR convention | 22.04.2024 | Personal communication |
| Union of Waterboards, NL | 09-03-2024 | Personal communication |
| Chemsec personal communication | 20.03.2024 | Personal communication |
| PFAS in the Black Sea region | | |
| Black Sea Commission | 05.04.2024 & 11.04.2024 | Personal Communication |
| Black Sea NGO Network | 20.03.2024 | Personal communication |
| Green Balkans | 28.05.2024 | Personal communication |
| Black Sea Advisory Council | 29.05.2024 | Personal communication |
| Danube Delta National Institute | 29.05.2024 | Personal communication |

# B Abbreviations

| | |
|---|---|
| SO | SINTEF Ocean |
| WR | Stichting Wageningen Research |
| VLIZ | Vlaams Instituut voor de Zee |
| MIO-ECSDE | Mediterranean Information Office for the Environment, Culture and Sustainable Development |
| UCC | University College Cork |
| RIFS | Research Institute for Sustainability |
| GRIDA | GRID Arendal |
| WU | Wageningen University |
| NTNU | Norwegian University of Science and Technology |
| SOS-ZEROPOL2030 | Source to Seas - Zero Pollution 2030 |
| PFAS | per- and polyfluoroalkyl substances |
| REACH | registration, evaluation, authorisation and restriction of chemicals |
| HFO | hydrofluoroolefin |
| TFA | trifluoroacetic acid |
| HF | hydrofluoric acid |
| PFOS | perfluorooctanesulfonic acid |
| PFOA | perfluorooctanoic acid |
| WWTP | wastewater treatment plant |
| TULAC | textiles, upholstery, leather, apparel and carpets |
| EEA | European Economic Area |
| PFAA | trifluoroacetic anhydride |
| SCFP | side-chain fluorinated polymer |
| ITRC | Interstate Technology and Regulatory Council |
| PFBA | perfluorobutanoic acid |
| PFBS | perfluorobutanesulfonic acid |
| FTOH | fluorotelomer alcohol |
| FP | fluoropolymer |
| PFPE | perfluoropolyether |
| PLC | polymers of low concern |
| LCx | lethal concentration for x% of the test organisms |
| ECx | effective concentration causing a biological response in x% of the test organisms |
| NOEC | no observed effect concentration |
| SSD | Species sensitivity distribution |
| PFNA | perfluorononanoic acid |
| PFDA | perfluorodecanoic acid |
| FOSA | perfluorooctanesulfonamide |
| FOSE | perfluorooctanesulfonamido ethanol |
| PTFE | polytetrafluoroethylene |
| PVDF | polyvinylidene difluoride |

| | |
|---|---|
| FEP | fluorinated ethylene propylene |
| DWR | durable water repellent |
| PFCA | perfluoroalkyl carboxylic acid |
| CFC | chlorofluorocarbon |
| GWP | global warming potential |
| MSW | municipal solid waste |
| NSMW | non-specific medical waste |
| SMW | specific medical waste |
| PVC | polyvinyl chloride |
| HFPO | 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy) propanoic acid |
| ADONA | 4,8-dioxa-3H-perfluorononanoic acid |
| PFA | perfluoroalkoxy alkane |
| GC-MS | gas chromatography could with mass spectrometry |
| PP | polypropylene |
| HRVAC | heating, refrigeration, air conditioning and cooling |
| GHG | greenhouse gas |
| OSPAR | Convention for the Protection of the Marine Environment of the North-East Atlantic |
| EQSD | Environmental Quality Standards Directive |
| WFD | Water Framework Directive |
| BC | Bucharest Convention |
| EEB | European Environmental Bureau |
| NEA | Northeast Atlantic |
| BS | Black Sea |
| CAS | Chemical Abstracts Service |
| PNEC | predicted no-effect concentration |
| HC | hazardous concentration |
| AF | assessment factors |
| SVHC | substance of very high concern |
| PBT | persistent, bioaccumulative and toxic |
| POP | persistent organic chemical |
| ECHA | European Chemicals Agency |
| GDP | gross domestic product |
| AFFF | aqueous film-forming foam |
| SSA | sea spray aerosol |
| ETFE | ethylene tetrafluoroethylene |
| FKM | Fluorine Kautschuk Material, a family of fluorocarbon-based fluoroelastomer materials |
| PFSA | perfluoroalkyl sulfonates |
| PEC | predicted environmental concentration |
| RQ | risk quotient |
| PFDS | perfluorodecanesulfonic acid |
| PFPA | perfluorophosphonic acid |

| | |
|---|---|
| PFNS | perfluorononane sulfonic acid |
| FW | freshwater |
| SW | seawater |
| HCFC | hydrochlorofluorocarbons |
| TFE | tetrafluoroethylene |
| HFP | hexafluoropropylene |
| VDF | vinylidene fluoride |
| FFKM | a family of perfluorinated fluoroelastomer materials |
| PEEK | polyether ether ketone |
| PA | polyamide |
| PPS | polyphenylene sulphide |

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