Guidelines for the implementation of innovative remediation solutions for PFAS contaminated groundwater

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LIFE SOuRCE

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Summary

This guideline presents **practical recommendations** and **technical considerations** for the implementation of **innovative remediation technologies targeting PFAS-contaminated groundwater**. The guidance is based on the experience and results obtained during the **LIFE SOuRCE project**, including full-scale demonstrations conducted at two representative European sites: Hovgården (Sweden) and the Barcelona region (Spain). Through these demonstrations, the project assessed the performance of an **integrated treatment strategy** combining **PFAS separation**, **concentration**, **polishing**, and **destruction technologies** to support the development of effective, scalable, and sustainable remediation solutions.

PFAS contamination poses a **significant challenge for groundwater management** due to the **persistence and mobility of these compounds in the subsurface environment**. Their limited retention by many soil types contributes to the development of extensive contamination plumes, often requiring **active remediation measures such as pump-and-treat systems**. At the same time, the European regulatory framework is becoming increasingly stringent, with growing attention being paid to both long-chain and short-chain PFAS. As a result, **remediation technologies must address a broad spectrum of PFAS** while consistently achieving increasingly demanding environmental quality objectives and discharge standards.

Performance of treatment technologies

The **LIFE SOuRCE** evaluated four complementary technology approaches representing different stages of the PFAS remediation chain, including separation, destruction and nature-based treatment solutions.

- **Surface Active Foam Fractionation (SAFF)** demonstrated excellent removal efficiencies for long-chain PFAS, reaching values close to 99% under optimized operating conditions. Although the removal of short-chain PFAS was initially lower, performance improved significantly through process optimization and the use of co-foaming agents. One of the main advantages of SAFF is its ability to treat large groundwater flows while generating only a small, concentrated waste stream for subsequent treatment.
- **Anion Exchange Resins (AEX)** achieved consistently high PFAS removal efficiencies across a broad range of compounds, including both long-chain and short-chain PFAS. The technology proved capable of reducing PFAS concentrations to very low levels and offers the additional advantage of resin regeneration, which contributes to reducing waste generation and operational costs over the long term.
- **Electrochemical Oxidation (EO)** was assessed as a destructive technology for the treatment of concentrated PFAS streams generated by upstream separation processes. The results confirmed its capacity to degrade PFAS and recover fluorine, supporting its role as a final treatment step within integrated remediation schemes. Technology showed the highest performance when treating concentrated streams,

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although operational aspects such as electrode scaling and maintenance requirements must be considered during system design and operation.

- **Phytoremediation (PHYTO)** implemented by constructed wetlands, demonstrated the capacity to retain PFAS and promote plant uptake, particularly for shorter-chain compounds. The technology provides additional environmental co-benefits and represents a low-energy treatment option. However, its treatment performance alone was insufficient to achieve the most stringent remediation targets, and the large land requirements associated with nature-based systems may limit their applicability in sites with restricted space availability.

The full-scale demonstrations carried out within **LIFE SOuRCE** confirmed the effectiveness of integrated treatment trains for PFAS remediation under different hydrogeological conditions.

At the **Hovgården landfill site in Sweden**, the combined treatment configuration based on **SAFF + PHYTO** achieved **nearly complete removal of long-chain PFAS (≥ C6)**, while **short-chain PFAS removal reached approximately 61%**. Process optimization studies indicated that the incorporation of suitable co-foaming additives could further increase short-chain PFAS removal efficiencies to values approaching 85%. In addition, the pump-and-treat system contributed to **hydraulic containment of contamination plume** and supported the **progressive reduction of PFAS concentrations downgradient of the source area**.

At the **Spanish demonstration site**, affected by historical firefighting activities, the treatment train combining **SAFF + AEX** proved **technically feasible and highly effective for PFAS removal**. Although the low permeability of the aquifer limited groundwater extraction rates and constrained the overall performance of the pump-and-treat system, the **AEX unit** consistently **achieved removal efficiencies close to 99% for both long-chain and short-chain PFAS**, demonstrating its suitability as a polishing technology for achieving very low residual concentrations.

These results from **LIFE SOuRCE project** indicate **SAFF and AEX represent the most mature and scalable technologies for large-scale PFAS remediation applications**. Both technologies demonstrated high treatment efficiencies, operational robustness, and suitability for continuous groundwater treatment under real field conditions. **EO** proved particularly valuable as a **complementary destruction technology for the treatment of concentrated PFAS streams** generated during the separation stage, contributing to the reduction of secondary waste and supporting a more sustainable remediation strategy. In contrast, **PHYTO** offers potential benefits such as a low-energy, nature-based solution, particularly for site management, containment, and complementary treatment applications, although its use may be **more appropriate for low-flow systems or specific site conditions**.

Overall, the **LIFE SOuRCE** highlighted the advantages of integrated treatment trains by combining PFAS concentration, separation and destruction technologies. Such configuration provides a more sustainable and cost-effective alternative to conventional PFAS remediation approaches.

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Recommendations for end users

Technology selection must be based on a detailed **conceptual site model incorporating hydrogeological conditions, PFAS distribution, and remediation objectives**. Pump-and-treat systems are most suitable for hydraulic containment and mass removal at sites with adequate groundwater extraction rates. SAFF is recommended for bulk PFAS removal and volume reduction, whereas AEX can be incorporated as a polishing step to achieve stringent treatment targets. EO is particularly suitable for the destruction of concentrated PFAS streams generated during treatment. PHYTO may provide additional benefits as a complementary nature-based solution under suitable site conditions. Finally, long-term monitoring and performance assessment are essential to ensure treatment efficiency and compliance with evolving regulatory requirements. **The LIFE SOuRCE demonstrations highlight the benefits of integrated treatment trains combining SAFF, AEX and EO as an effective and sustainable approach for PFAS groundwater remediation**.

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List of Abbreviations

AEX: Anion exchange

AFFF: Aqueous film forming foam

BDD: Boron Doped Diamond

CAC: Colloidal activated carbon

CAPEX: capital expenditure

CEC: Chemicals of Emerging Concern

CTAB: Cetyltrimethylammoniumbromide

CTAC: cetyltrimethylammonium chloride

DOC: Dissolved Organic Carbon

EC: European Commission

EO: Electrochemical Oxidation

GAC: Granular activated carbon

GW: Groundwater

HALT: Hydrothermal Alkaline Treatment

HDPE: High Density Polyethylene

HFPO-DA: Hexafluoropropylene oxide dimer acid (trade name Gen X)

KPI: Key Performance Indicator

LC: Long-Chain

LECA: Lightweight Expanded Clay Aggregate

MS: Member States

OPEX: operational expenditure

PE: Polyethylene

PEM: Polyethylene Medium density

PFAA: Perfluoroalkyl Acid

PFAS: Per- and polyfluoroalkyl substances

PFBA: Perfluoro-n-butanoic acid

PFPeA: Perfluoro-n-pentanoic acid

PFHxA: Perfluoro-n-hexanoic acid

PFHpA: Perfluoro-n-heptanoic acid

PFOA: Perfluoro-n-octanoic acid

PFNA: Perfluoro-n-nonanoic acid

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PFDA: Perfluoro-n-decanoic acid

PFUnDA: Perfluoro-n-undecanoic acid

PFDoDA: Perfluoro-n-dodecanoic acid

PFTrDA: Perfluoro-n-tridecanoic acid

PFTeDA: Perfluorotetradecanoic acid

PFHxDA: Perfluorohexadecanoic acid

PFOcDA: Perfluorooctadecanoic acid

PFBS: Perfluorobutanesulfonic acid

PFPeS: Perfluoropentane sulfonic acid

PFHxS: Perfluorohexanesulfonic acid

PFHpS: Perfluoroheptanesulfonic acid

PFOS: Perfluorooctanesulfonic acid

PFNS: Perfluorononane sulfonic acid

PFDS: Perfluorodecanesulfonic acid

PFUnDS: Perfluoroundecane sulfonic acid

PFDoDS: Perfluorodecane sulfonic acid

PFTrDS: Perfluorotridecanesulfonic acid

PHYTO: Phytoremediation

PP: Polypropylene

SAFF: Surface Active Foam Fractionation

SC: Short-Chain

TOP: Total Oxidizable Precursors

TRL: Technology Readiness Levels

6:2 FTSA: 6:2 Fluorotelomer sulfonate

6:2 FTOH 6:2 Fluorotelomer alcohol

8:2 FTOH: 8:2 Flurorotelomer alcohol

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List of Partners in LIFE SOuRCE

EUT: Fundació Eurecat

ENVY: EnvyTech Solutions AB

ESOL: ESOLVE Consultoría e Ingeniería Medioambiental S.L.

LAQ: Laqua Treatment AB

NOVA: Nova Diamant AB

SGI: Swedish Geotechnical Institute

SLU: Swedish University of Agricultural Sciences

UVA: Uppsala Vatten och Avfall AB

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1 Introduction

1.1 The LIFE SOuRCE Project

Per- and polyfluoroalkyl substances (PFAS) constitute a large family of nearly 15,000 man-made chemicals, widely recognized as *chemicals of emerging concern (CECs)* due to their persistence, mobility, and potential risks to both human health and the environment. A growing body of toxicological evidence associates PFAS exposure with **reproductive, developmental, and immunological disorders** in humans and animals. The main human exposure pathways are the intake of food and drinking water (DW), as PFAS are released into the environment during production, use, or disposal phases.

Conventional **PFAS-contaminated sites** in Europe include **landfills and areas impacted by aqueous film-forming foams (AFFF)**, where pollutants migrate into soils and water bodies, eventually reaching **groundwater and drinking water supplies**. Recent assessments estimate that more than **100,000 potential PFAS-emitting sites** exist across Europe. Since January 2020, the new **EU Drinking Water Directive (EU) 2020/2184** has introduced binding thresholds for PFAS: **0.1 µg/L for individual compounds** (up to 20 regulated substances), and **0.5 µg/L for their total concentration**.

Currently, the most widely applied remediation technology is Granular Activated Carbon (GAC) for drinking water and groundwater. However, GAC presents significant limitations: its effectiveness drops drastically for short-chain PFAS (<C7) and, importantly, it does not destroy PFAS but generates PFAS-rich solid waste, shifting rather than solving the problem.

For this reason, the **LIFE SOuRCE project** is dedicated to demonstrating an **innovative, integrated approach**, combining four cutting-edge remediation technologies:

- **Surface active foam fractionation (SAFF)**
- **Anion exchange (AEX)**
- **Electrochemical oxidation (EO)**
- **Phytoremediation (PHYTO)**

This multi-barrier strategy is designed to address both **long- and short-chain PFAS**, while ensuring **cost-effectiveness** (targeting operation costs of ≤ 0.1 €/m³). The approach has been tested in two pilot-scale European demonstration sites: **Hovgården Landfill (Uppsala, Sweden)** and **Barcelona region (Catalonia, Spain)**.

Specific objectives of LIFE SOuRCE

- Decontaminate PFAS-polluted groundwater.
- Demonstrate the feasibility and cost-effectiveness of innovative PFAS remediation technologies at full-scale.
- Reduce environmental impacts of remediation compared to conventional approaches (e.g., GAC).
- Minimize operational costs by lowering energy, reagent use, and treatment time.
- Develop versatile systems adaptable across different geological, geographical, and sectoral contexts.

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- Validate the **technical, social, economic, and environmental feasibility** of the SOuRCE solutions.
- Establish a **business model** for commercial exploitation of the developed technologies in Europe.
- Disseminate results to ensure reproducibility, scalability, and uptake across other sectors (e.g., treatment of wastewater, soils and drinking water).
- Support implementation of EU environmental strategies and policies.
- Foster **public awareness** on the challenges posed by PFAS contamination.

1.2 European regulatory framework for PFAS remediation

The **LIFE SOuRCE project** contributes directly to several key European policy and regulatory frameworks focused on the protection of water resources, human health, and the environment from hazardous substances. The project supports the objectives of the **European Green Deal**, the **Water Framework Directive (WFD)**, the **EU Drinking Water Directive 2020/2184**, the **REACH Regulation**, the **Priority Substances Directive**, the **Groundwater Directive**, the **EU POPs Regulation**, and other emerging European initiatives addressing PFAS contamination and sustainable water management.

Growing awareness of the **environmental persistence**, **widespread occurrence**, **mobility**, and **potential health impacts of PFAS** has led to increasingly **stringent regulatory requirements across Europe**. A major milestone was the adoption of the recast **Drinking Water Directive (EU) 2020/2184**, which introduced, for the first time at European level, **parametric values for PFAS in drinking water, including a limit of 100 ng/L for the sum of 20 selected PFAS and 500 ng/L for total PFAS**. These requirements are currently being incorporated into the **national legislation across Member States, resulting in progressively stricter obligations for PFAS monitoring, management and remediation**.

In Sweden, **the implementation of the Drinking Water Directive includes a limit value of 100 ng/L for the sum of 21 PFAS and an additional threshold of 4 ng/L for the combined concentration of four priority PFAS compounds** (PFOA, PFNA, PFHxS and PFOS) (SLV 2022). In Spain, RD 3/2023 transposes Directive (EU) 2020/2184 into national legislation, establishing **a parametric value of 100 ng/L for the sum of 20 regulated PFAS** (Table 1-1).

Table 1-1 PFAS included in the drinking water quality standards established by the European Union and implemented in Sweden and Spain

Substance	PFAS11 [a]	PFAS20 [b,f]	PFAS21 [c]	PFAS4 [d]	PFAS24 [e]
PFBA	x	x	x		x
PFPeA	x	x	x		x
PFHxA	x	x	x		x
PFHpA	x	x	x		x
PFOA	x	x	x	x	x
PFNA	x	x	x	x	x
PFDA	x	x	x		x
PFUnDA		x	x		x
PFDoDA		x	x		x

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Substance	PFAS11 [a]	PFAS20 [b,f]	PFAS21 [c]	PFAS4 [d]	PFAS24 [e]
PFTrDA		x	x		x
PFTeDA					x
PFHxDA					
PFOcDA					x
PFBS	x	x	x		x
PFPeS		x	x		x
PFHxS	x	x	x	x	x
PFHpS		x	x		x
PFOS	x	x	x	x	x
PFNS		x	x		
PFDS		x	x		x
PFUnDS		x	x		
PFDoDS		x	x		
PFTrDS		x	x		
HFPO-DA					x
ADONA					x
C6O4					x
6:2 FTSA	x		x		x
6:2 FTOH					x
8:2 FTOH					x

[a] PFAS included in the Swedish EPA regulation for the Σ11PFAS ≤ 90 ng/L, which was implemented in 2016.
[b] PFAS included in EU Directive 2020/2184 for Σ20PFAS ≤ 100 and total PFAS ≤ 500 ng/L. EU-Directive 98/93/EC (UE 2020).
[c] Additional PFAS included in Swedish regulation, ∑PFAS21 ≤ 100 ng/L, which is to be implemented starting 2026.
[d] PFAS included Swedish regulation for Σ4PFAS, which is to be implemented starting in 2026.
[e] The PFAS included in the Swedish groundwater environmental quality criterion limited to 4.4 ng/L PFOA equivalents for the Σ24 PFAS. (SGU, 2023)
[f] The PFAS included in Spanish regulation RD 3/2023 for the Σ20PFAS ≤ 100 ng/L.

The new **Groundwater Directive (EU) 2026/805**, **adopted on 30 March 2026**, introduces for the first time at European level groundwater quality standards for PFAS and establishes two regulatory thresholds. The first corresponds to the **sum of four priority PFAS compounds (PFOS, PFOA, PFNA and PFHxS)**, with a **groundwater quality standard of 4.4 ng/L**, reflecting the substances identified as posing the greatest concern and aligning with the scientific recommendations issued by the European Food Safety Authority (EFSA). The second threshold establishes **a value of 100 ng/L for the sum of 20 PFAS, corresponding to the group of compounds already regulated under the Drinking Water Directive**.

The **Groundwater Directive (EU) 2026/805** creates a direct link between groundwater and drinking water legislation, meaning any future modifications to the PFAS group or threshold values established under the Drinking Water Directive will automatically be reflected in the groundwater regulatory framework. Notably, the **Groundwater Directive (EU) 2026/805** does not establish a legally binding groundwater quality standard for Total PFAS. Instead, Member States (MS) are encouraged to **monitor total PFAS concentrations**, while the European Commission is expected to assess the potential introduction of such a standard during future regulatory reviews. **MS are required to transpose the Groundwater Directive (EU) 2026/805 into national legislation by 21 December 2027**.

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In Sweden, the groundwater quality assessment considers the environmental quality criterion established by the Geological Survey of Sweden (SGU), which sets a threshold of 4.4 ng/L expressed as PFOA equivalents for the sum of 24 PFAS compounds (PFAS24) (SGU, 2023). This approach incorporates relative potency factors derived from toxicological dose–response assessments of PFAS-induced liver effects, allowing the contribution of individual PFAS compounds to be weighted according to their relative toxicity (Bil et al., 2021).

For soil, the **Swedish Geotechnical Institute (SGI) has proposed preliminary guideline values** for PFOS of 3 µg/kg dry weight for sensitive land use and 20 µg/kg dry weight for less sensitive land use (Pettersson et al., 2015). SGI has also proposed a preliminary groundwater assessment value of 45 ng/L for PFOS. Although **these values are not legally binding**, they are used as **reference criteria during contaminated site investigations and risk assessments in Sweden**.

For surface waters, the **Swedish Agency for Marine and Water Management** has established **environmental quality standards for PFOS** (HVMFS 2019:25). These standards include **annual average concentrations of 0.65 ng/L for inland surface waters and 0.13 /L for other surface waters**, together with **maximum allowable concentrations of 36,000 and 7,200 ng/L, respectively** (HaV, 2019). These threshold values provide the regulatory basis for assessing the chemical status of surface water bodies with respect to PFOS contamination.

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2 Overview of treatment technologies for PFAS-contaminated groundwater

This chapter provides **a concise overview of the main technologies currently available** for the **remediation of PFAS-contaminated groundwater**. Detailed reviews and comparative assessments of these technologies are available in scientific literature (Held & Reinhard, 2020; Riegel et al., 2020 and Roest et al., 2021). To date, **most PFAS remediation strategies** are implemented as ***ex-situ* treatment systems**, typically in combination with **groundwater extraction and pump-and-treat approaches**. Although several ***in-situ* technologies** are under development, their **application at full scale remains limited** and, in many cases, additional validation is still required before broader deployment.

2.1 Remediation technologies

Remediation technologies for PFAS-contaminated groundwater are generally classified into three main categories: **sorption technologies**, **separation technologies**, and **destruction technologies**.

Sorption technologies remove PFAS from water through adsorption into solid materials. This group includes well-established technologies such as **activated carbon and ion exchange resins**, which are widely applied in full-scale groundwater remediation systems (DiGiuseppi et al., 2024). These technologies are effective for LC-PFAS, although their performance tends to decrease for SC-PFAS compounds. Sorption processes can be implemented either *in-situ* or *ex-situ*.

A wide range of **activated carbon products is commercially available for PFAS remediation applications**. Colloidal activated carbon (CAC), typically with particle sizes of 1–2 µm, can be injected directly into the subsurface to immobilize PFAS through adsorption onto soil particles (Carey et al., 2019). Alternatively, granular activated carbon (GAC), generally ranging from 500 to 1,000 µm in size, is commonly used in *ex-situ* treatment systems, often as part of pump-and-treat remediation schemes. In addition to conventional adsorbents, several **advanced sorption materials have been developed and commercialized, including RemBind®, MatCare™ and cyclodextrin-based polymers** (Roest et al., 2021). Regardless of the sorbent used, these technologies transfer PFAS from the aqueous phase to a solid matrix, generating a PFAS-enriched residual material that requires subsequent regeneration, treatment or final disposal.

Separation technologies are designed to concentrate PFAS into a smaller waste stream, reducing the volume requiring further treatment. Examples include **membrane-based systems** such as nanofiltration and reverse osmosis, **foam fractionation**, and **vacuum distillation**. These technologies achieve **high PFAS removal efficiencies**; nevertheless, they generate a **concentrated PFAS stream requiring appropriate management**, often through subsequent destructive treatment processes (Riegel et al., 2020). Operational considerations such as energy consumption, pretreatment requirements and resulting concentrate handling play an important role in determining their suitability for specific applications.

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Separation approaches may also be based on **precipitation and flocculation processes**, in which chemical reagents, such **as PerfluorAd®**, promote the formation of PFAS-containing flocs (Cornelsen et al., 2021). The resulting flocs are subsequently removed by sedimentation or filtration. Although this approach can significantly reduce PFAS concentrations, particularly in highly contaminated waters, additional polishing steps are required to achieve stringent treatment targets (Held & Reinhard, 2020). As with other concentration technologies, the process generates **PFAS-containing residuals requiring appropriate downstream treatment or disposal**.

Destruction technologies involve **the transformation of PFAS into simpler compounds through chemical, electrochemical, thermal or physicochemical processes**. Examples include electrochemical oxidation, advanced oxidation processes, UV-based treatments, plasma technologies, sonochemical processes, and supercritical water oxidation (Meegoda et al., 2020). Unlike separation and adsorption technologies, these approaches **eliminate PFAS rather than transfer them to another phase**, thereby reducing the generation of secondary waste streams. As a result, destructive technologies play a key role in integrated remediation strategies, particularly for the treatment of concentrated PFAS residuals generated during upstream treatment processes.

2.2 Technology readiness level

In addition to **the treatment performance**, the **maturity and commercial availability of remediation technologies** represent important factors when assessing their suitability for practical implementation. **Technology Readiness Levels (TRLs)** provide a widely recognized framework for evaluating the development stage of a technology, ranging from basic research and concept development (TRL 1–3), through laboratory and pilot-scale validation (TRL 4–6), to demonstration and commercial deployment under operational conditions (TRL 7–9) (DoD, 2025; EPA Victoria, 2024). **Technologies reaching TRL 7–9 are generally considered sufficiently mature for large-scale demonstration and operational implementation** (DoD, 2024). Table 2-1 summarizes the TRL classification of the main PFAS remediation technologies considered in this guideline.

TRLs provide valuable information regarding technology maturity; however, technology selection should also consider **additional factors** such as **treatment capacity**, **site-specific applicability**, **operational complexity**, **resource requirements**, and **economic aspects**, including capital and operational expenditures (CAPEX and OPEX). These parameters are often decisive in determining the overall feasibility, scalability, and long-term sustainability of a remediation solution.

Table 2-1 TRLs of selected PFAS groundwater remediation technologies, adapted from DiGuiseppi et al. (2024), DoD (2024), Roest et al. (2021), and States of Jersey (2025)

Technologies	TRL
Separation technologies	
GAC, AEX	8-9
SAFF	8-9
Nanofiltration, Reverse osmosis	7-9
Flocculation	6-7
Biochar, fluorogels, modified clays	4-6
PHYTO	4

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Technologies	TRL
Destruction technologies	
Ozone oxidation, persulfate oxidation	5-7
Sonolysis, photochemical oxidation	6-7
EO	5-8
Supercritical water oxidation	6-9
Hydrothermal Alkaline Treatment (HALT)	3-8
Microbial degradation	1-3

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3 LIFE SOuRCE treatment train

The **LIFE SOuRCE project** validated an **integrated treatment train for PFAS-contaminated groundwater** through pilot-scale demonstrations at two representative European sites: a **former firefighting training area in the Barcelona region (Spain) and a landfill site in Uppsala (Sweden)** (**Figure 3-1**). The treatment concept combines complementary technologies for PFAS concentration, separation and destruction within a single on-site remediation system.

The treatment train incorporates **SAFF** as a primary concentration technology, enabling PFAS removal through aeration and foam generation, with concentration factors reaching up to 15,000. Depending on site-specific requirements, **AEX** is applied as a polishing step to further reduce PFAS concentrations and achieve very low residual levels in treated groundwater, while **PHYTO** provides a complementary nature-based treatment barrier by PFAS retention and plant uptake. The concentrated PFAS streams generated by SAFF and during AEX resin regeneration are subsequently treated using **EO** equipped with BDD electrodes, facilitating PFAS degradation and fluorine recovery.

The combined application of these technologies provides a robust and scalable remediation approach capable of addressing both LC- and SC-PFAS under real operating conditions. The demonstration results confirmed the technical feasibility of the integrated treatment train while supporting the development of sustainable, cost-effective and transferable solutions for PFAS groundwater remediation across different European contexts.

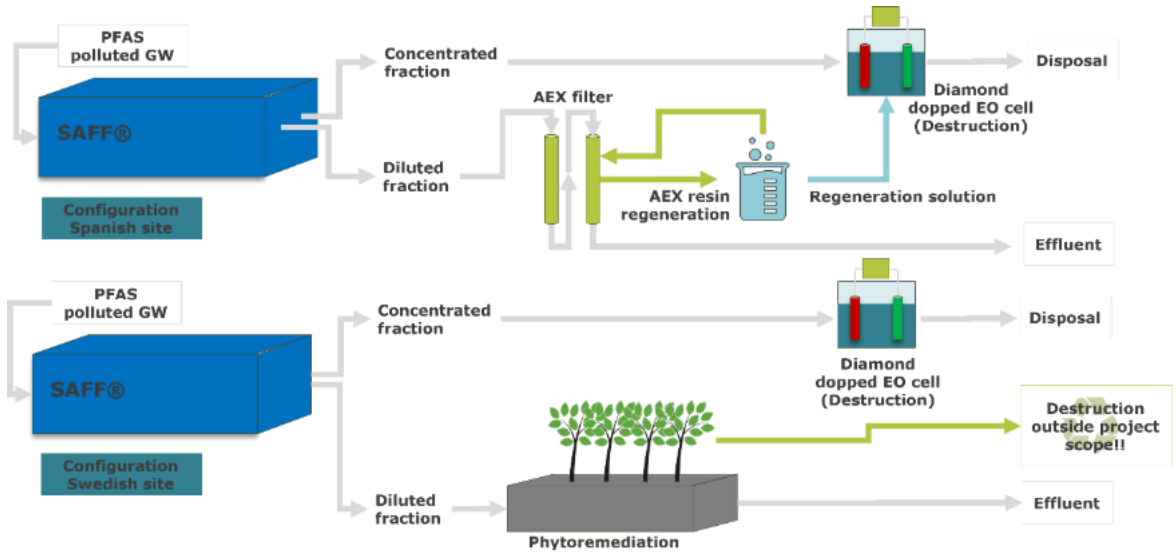

Figure 3-1. Schematic representation of the treatment train configurations demonstrated at the Spanish and Swedish pilot sites within the LIFE SOuRCE project

3.1 SAFF unit

The SAFF unit is a **concentration technology based on the surface-active properties of these compounds**. Owing to their tendency to accumulate at the air–water interface, PFAS preferentially adsorb onto the surface of air bubbles generated within the treatment system. During operation, air is introduced into a vertical treatment column containing contaminated groundwater. As the bubbles rise through the water column, PFAS are progressively transferred from the aqueous phase to the bubble surface and transported towards the top of the reactor.

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At the water surface, the bubbles accumulate and form a stable foam layer enriched in PFAS. This foam is continuously collected and collapsed to generate a reduced-volume liquid stream, commonly referred to as **foamate** (**Figure 3-2**), containing PFAS concentrations significantly higher than those present in the influent water. The foamate is subsequently processed through additional concentration stages, typically consisting of secondary and, if required, tertiary fractionation columns (**Figure 3-3**). Each stage further reduces the treated volume while increasing PFAS concentrations. Depending on the system configuration and operating conditions, **overall concentration factors ranging from 50,000 to over 2,000,000 times the initial PFAS concentration** are achievable.

This technology does **not destroy PFAS compounds** but substantially **reduces the volume requiring subsequent treatment**. As a result, SAFF is particularly suitable as a pre-concentration step upstream of destructive technologies, such as electrochemical oxidation, significantly improving overall treatment efficiency while reducing energy demand, reagent consumption and operational costs.

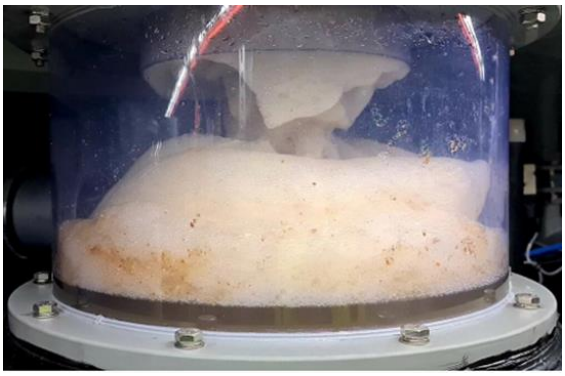

Figure 3-2 First fractionation stage of a SAFF system during operation. In this stage, the PFAS-enriched foam overflows from the central inner tube and is collected for further concentration in subsequent fractionation steps.

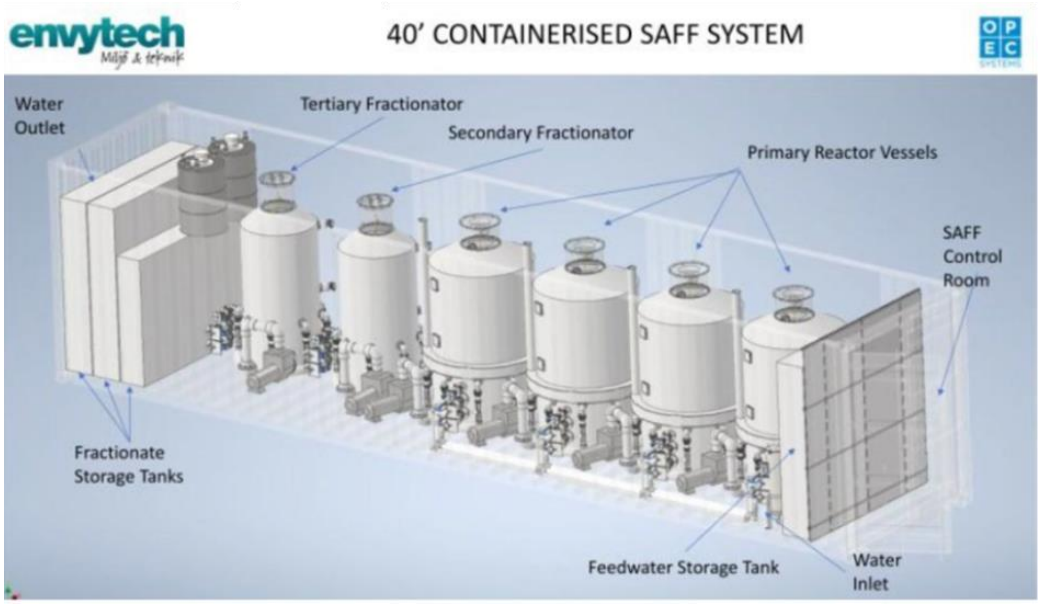

Figure 3-3 Schematic representation of a SAFF40 system. The demonstration conducted on the LIFE SOuRCE project employed a SAFF20 configuration comprising two primary fractionation columns and no tertiary fractionation stage.

SAFF has demonstrated particularly **high removal efficiencies for long-chain PFAS**, reflecting their stronger tendency to adsorb at the air–water interface. In contrast, **shorter-chain PFAS**

generally exhibit lower removal efficiencies due to their reduced surface activity and weaker affinity for air bubbles (Meng et al., 2018; Smith et al., 2022). Table 3-1 presents examples of PFAS removal efficiencies achieved in two full-scale SAFF applications, including the treatment of approximately 300 m³/day of landfill leachate (Burns et al., 2022) and 90–110 m³/day of contaminated groundwater (Burns et al., 2021). These reported results indicate a strong relationship between PFAS removal efficiency and adsorption behaviour at the gas–liquid interface, with compounds exhibiting adsorption coefficients above approximately 1 µm achieving near-complete removal (Burns et al., 2021).

Several studies have demonstrated the **potential of co-surfactant addition enhancing the removal of short-chain PFAS**. The **cationic surfactant cetyltrimethylammonium chloride (CTAC)** has been shown to significantly improve removal efficiency for a range of short-chain PFAS compounds (Lee et al., 2024), although improvements for PFBA remain limited. Enhanced PFBA removal has been reported through the use of **cetyltrimethylammonium bromide (CTAB)** (Klevan, Van Allen, Mukai, et al., 2025). Similarly, the zwitterionic co-surfactant SB12 has been reported to increase the removal of PFBS and PFPeS, while showing little influence on PFBA removal (Vo et al., 2023). The beneficial effect of co-surfactants is primarily attributed to improved foam generation and bubble stabilization, which increase the transfer of PFAS from the aqueous phase into the foam fraction (Meng et al., 2018).

Table 3-1 Typical PFAS removal efficiencies achieved by full-scale SAFF systems for selected long-chain and short-chain PFAS compounds (adapted from Burns et al., 2021; Burns et al., 2022).

PFAS	No of carbons	Adsorption coefficient, K (µm)	AFFF contaminated groundwater		Landfill leachate	
			Influent (ng/L)	RE (%)	Influent (ng/L)	RE (%)
PFBA	4	0.017	-	-	317	−1.06
PFPeA	5	0.058	-	-	531	4.16
PFHxA	6	0.22	755	46.7	541	37.3
PFHpA	7	0.58	367	81.5	329	≥97.0
PFOA	8	2.3	475	99.8	586	≥99.7
PFNA	9	9.3	116	≥98.9	83	≥98.7
PFDA	10	37	≤156	≥97.9	5.2	≥76.6
PFBS	4	0.18	-	-	112	15.7
PFHxS	6	0.97	1 026	98.4	96.6	≥98.8
PFHpS	7	5.1	117	≥98.9	-	-
PFOS	8	23	2 786	99.8	191	≥98.7
PFNS	9	370	≤13	≥90.6	-	-
6:2FTSA	8	-	≤100	≥93.7	40	97.2
8:2FTSA	10	-	≤32	≥95.8	-	-

Key advantages of the SAFF unit include **low energy requirements**, **limited operational costs**, **substantial reduction of PFAS-containing waste volumes**, and **applicability across a wide range of water matrices**. SAFF unit operates without the routine addition of chemical reagents, except in cases where co-surfactants are introduced to enhance the removal of short-chain PFAS. These characteristics make SAFF an attractive option as a primary PFAS concentration technology within integrated treatment trains (Padhye et al., 2026; We et al., 2024).

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3.2 AEX unit

The **AEX unit** represents one of the most mature and effective technologies currently available for PFAS removal from contaminated water and has been widely implemented in full-scale treatment applications (Boyer et al., 2021). Comparative studies have demonstrated **superior performance relative to GAC unit, particularly for short-chain PFAS compounds**, which are generally more difficult to remove using conventional adsorption processes (Gagliano et al., 2020).

The technology operates through a **reversible ion-exchange mechanism** whereby negatively charged species present in the aqueous phase are exchanged with counter ions, such as chloride (Cl^-), hydroxide (OH^-) or bicarbonate (HCO_3^-), associated with functional groups on the resin surface (Dixit et al., 2021). Initially developed for the removal of inorganic ions from drinking water, including sulphate, nitrate and uranium, anion exchange resins have gained increasing relevance for PFAS remediation due to their **high removal efficiency, operational simplicity, compact footprint and potential for regeneration and reuse** (Cheng and Knappe, 2024). These characteristics position AEX unit as a highly effective polishing technology within integrated treatment trains designed to achieve stringent groundwater remediation and discharge targets.

Recent developments have led to the commercialization of PFAS-selective ion exchange resins by manufacturers such as **Purolite, DuPont and Calgon Carbon Corporation**. These specialized resins consist of a **polystyrene matrix crosslinked with divinylbenzene and functionalized with proprietary amino-based groups** designed to enhance PFAS selectivity (Dixit et al., 2021). During operation, PFAS compounds are retained within the resin through a combination of electrostatic attraction and hydrophobic interactions, allowing the treated water to pass through the system with significantly reduced PFAS concentrations.

To optimize resin performance and extend operational lifespan, pretreatment stages are commonly implemented upstream of the AEX unit to reduce the concentration of competing ions and other constituents capable of occupying exchange sites and accelerating resin exhaustion.

Within the **LIFE SOuRCE project**, a pilot-scale AEX system was designed and constructed comprising **two cylindrical treatment vessels**, each with a maximum resin bed volume of 6.5 L. The first vessel functioned as a pretreatment unit and was filled with **Purolite C100, a cation exchange resin commonly used for water softening and the removal of dissolved cationic species**. The second vessel contained **Purolite PFA694E, a PFAS-selective anion exchange resin specifically developed for the removal of PFAS from contaminated water** and capable of achieving non-detectable concentrations.

Sampling ports were installed upstream and downstream of each treatment stage to facilitate operational monitoring and performance assessment throughout the demonstration period. The pretreatment unit played an important role in protecting the PFAS-selective resin by removing a substantial fraction of competing ionic species present in the groundwater. This configuration reduced the loading of non-target constituents onto the PFAS resin, thereby extending resin service life and improving overall treatment efficiency.

The demonstration carried out at the Spanish site confirmed the high treatment performance of the AEX technology, with PFAS removal efficiencies exceeding 90%. Significant reductions were achieved for both LC- and SC-PFAS compounds. The results demonstrate the capability

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of **AEX unit to effectively treat PFAS-contaminated groundwater across a broad range of compounds with different physicochemical properties and environmental behaviour**.

The evolution of treatment performance over time followed the characteristic operational stages typically observed in ion exchange systems. High removal efficiencies were achieved during the initial phase when the resin exchange capacity was largely available. As operation progressed, gradual occupation of active exchange sites resulted in a progressive decline in treatment performance until resin exhaustion was approached. These observations highlight the importance of appropriate monitoring, and resin regeneration or replacement strategies to ensure stable long-term operation and sustain PFAS removal efficiency.

3.3 PHYTO unit

The **PHYTO unit** is based on phytoremediation processes, which utilize plants and plant-associated biological mechanisms to reduce pollutant concentrations in environmental matrices. Depending on the **features of the contaminants and the treatment configurations**, **PHYTO unit** may involve plant uptake and accumulation, retention of microbial communities capable of contributing to contaminant attenuation (Newman & Reynolds, 2004; Mahajan & Kaushal, 2018).

The interaction between plants and PFAS has been extensively investigated, particularly in relation to contaminant uptake and transfer within agricultural systems (Felizeter et al., 2014; Krippner et al., 2014; Zhang et al., 2016). These studies have demonstrated the capacity of several plant species to absorb and accumulate PFAS, providing the scientific basis for the development of phytoremediation strategies targeting PFAS-contaminated environments (Mayakaduwage et al., 2022).

PHYTO can be applied directly to PFAS-contaminated soils through the cultivation of suitable plant species capable of promoting contaminant uptake, retention or stabilization (Nassazzi et al., 2023). For the treatment of contaminated water, several implementation approaches are available, including land application systems based on controlled irrigation (Ramstedt & Lundberg, 2024), hydroponic treatment systems (Ahuja, 2024), and constructed wetlands (Savvidou et al., 2024). Among these options, **constructed wetlands** have attracted increasing attention due to their ability to combine **physical, chemical and biological treatment mechanisms within a passive and low-energy treatment system**.

Within the LIFE SOuRCE project, a **subsurface-flow constructed wetland** was implemented at the Swedish demonstration site as part of the integrated treatment train. The wetland was planted with **Salix** species and filled with a filter substrate consisting of **biochar and peat**, selected both to support plant growth and to enhance PFAS retention through adsorption processes. The substrate was mixed with **light expanded clay aggregates (LECA)** to improve hydraulic conductivity and ensure adequate flow distribution throughout the system. The wetland was positioned downstream of the SAFF unit, taking advantage of the ability of Salix species to accumulate short-chain PFAS (Liljeström et al., 2025), compounds that are generally removed less efficiently by foam fractionation than their long-chain counterparts. In this configuration, the wetland acted as an intermediate polishing stage, providing additional PFAS removal prior to the final electrochemical oxidation treatment step

3.4 EO unit

The **EO unit** is a destructive treatment technology capable of degrading PFAS compounds through electrochemical reactions occurring within a reactor equipped with electrically conductive electrodes. The process involves the application of an electrical current to contaminated water flowing through an electrochemical cell containing an anode, a cathode and an electrolyte solution (Figure 3-4). Under these conditions, oxidation reactions take place either directly at the anode surface or indirectly through the generation of highly reactive oxidizing species, such as hydroxyl radicals, formed during the electrochemical process.

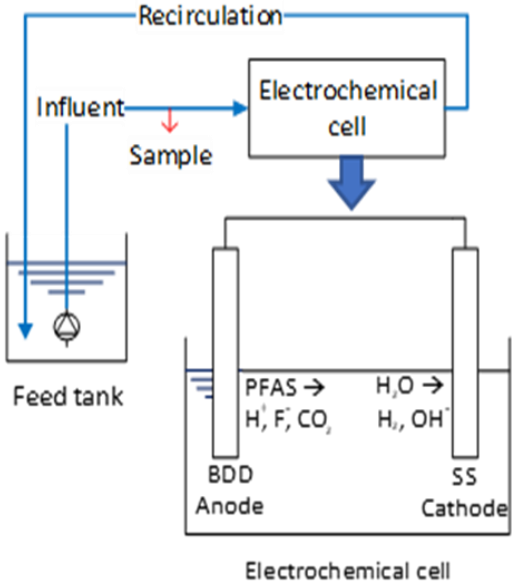

Figure 3-4 Schematic representation of the electrochemical oxidation process, illustrating the recirculation of PFAS-contaminated water through the electrochemical flow cell.

During treatment, PFAS molecules undergo a sequence of degradation reactions leading to the progressive shortening of the fluorinated carbon chain and the formation of intermediate compounds. Continued oxidation results in the breakdown of these intermediates into simpler end products, ultimately generating carbon dioxide, fluoride ions and water. Unlike separation technologies, electrochemical oxidation eliminates PFAS rather than transferring them to another phase, thereby reducing the generation of secondary waste streams requiring further management.

The effectiveness of the process depends on several operational parameters, including **electrode material**, **electrode spacing**, **current density**, **hydraulic retention time, treatment time,** and **water chemistry**. Among these factors, treatment time and current density are generally recognized as the most relevant operational parameters affecting PFAS destruction (Uwayezu et al., 2021). A variety of electrode materials have been investigated for PFAS treatment applications (Sharma et al., 2022). Boron-doped diamond (BDD) electrodes have demonstrated particularly high performance for PFAS destruction due to their ability to generate strong oxidizing conditions while maintaining chemical stability under prolonged operation. Nevertheless, the composition of the treated water influence process performance and may lead to the formation of undesirable oxidation by-products, including chlorate and perchlorate, particularly in waters containing elevated chloride concentrations (Radjenovic et al., 2020).

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Within the **LIFE SOuRCE project**, electrochemical oxidation was performed using **BDD electrodes**, which offer excellent chemical stability and high resistance to corrosion under demanding operating conditions, although their manufacture remains relatively costly (Mirabediny et al., 2023). Despite these investment costs, EO generally exhibits lower energy consumption than many alternative PFAS destruction technologies (Radjenovic et al., 2020).

Treatment performance is strongly influenced by both PFAS concentration and molecular structure. In general, **higher removal efficiencies are achieved for long-chain perfluorocarboxylic acids (C7–C18) than for shorter-chain compounds (C3–C6)** (Barisci & Suri, 2020). SC-PFAS, including PFBA, PFBS, PFPeA and PFPeS, have proven more difficult to degrade, particularly in complex matrices such as landfill leachates (Maldonado et al., 2021; Smith et al., 2023). This behaviour is partly attributed to the formation of short-chain PFAS as intermediate products during the sequential degradation of longer-chain compounds. In addition, the stronger affinity of long-chain PFAS for the electrode surface facilitates their electrochemical degradation.

Differences in degradation behaviour have also been reported between PFAS subclasses. Perfluorosulfonic acids (PFSAs) generally exhibit slower degradation kinetics than perfluorocarboxylic acids (PFCAs) (Smith et al., 2023). Nevertheless, overall destruction efficiencies achieved for PFSAs are often higher, indicating that slower reaction rates do not necessarily result in lower final removal performance (Uwayezu et al., 2021).

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4 Applying pump-and-treat for PFAS contaminated groundwater

4.1 Introduction

Pump-and-treat (P&T) is one of the most widely applied and well-established approaches for the management of contaminated groundwater. Its principles, benefits and limitations have been extensively documented in scientific and technical literature (e.g. Truex et al., 2017). The technology is based on the extraction of contaminated groundwater for above-ground treatment, allowing both plume containment and contaminant mass removal.

One of the **principal advantages** of P&T is its ability to provide **effective hydraulic control**. By extracting groundwater and creating inward hydraulic gradients, the system can contain contaminant plumes and limit their migration towards sensitive receptors, such as drinking water abstraction wells, surface waters and ecologically valuable areas. This containment function is particularly relevant at large or complex sites where rapid risk reduction is required.

P&T can also contribute to the **progressive reduction of contaminant mass within the aquifer**, particularly when extraction wells are located within or close to source areas and dissolved-phase plumes. Over time, decreases in contaminant concentrations and mass discharge may support the transition towards less intensive management strategies, including monitored natural attenuation or other passive remediation approaches.

Another important advantage of P&T is its **flexibility and compatibility with a wide range of remediation technologies**. Extracted groundwater can be treated using different physical, chemical or biological processes, while P&T systems can also be integrated with complementary *in-situ* remediation approaches, including thermal treatment, chemical oxidation, chemical reduction and bioremediation, to address source zones that are not effectively remediated through groundwater extraction alone.

In addition, the operation of P&T systems generates **valuable long-term monitoring datasets** that support the evaluation of plume behaviour, contaminant mass discharge and treatment performance. These data provide an important basis for system optimization, performance assessment and long-term remediation planning.

Despite these advantages, the **limitations of P&T** are well documented and often restrict its effectiveness as a standalone solution for complete aquifer restoration. One of the principal challenges is the **slow removal of contaminants stored in low-permeability zones or associated with the solid phase of the aquifer matrix** (Carroll et al., 2024). Diffusion-controlled mass transfer from less permeable regions can sustain contaminant release over extended periods, resulting in progressively lower extraction rates and diminishing remediation efficiency as operation continues. In addition, contaminant concentrations may increase again following system shutdown due to back-diffusion processes or continued leaching from residual source areas, complicating the achievement of long-term remediation objectives.

The applicability of P&T is also influenced by the **sorption behaviour of the target contaminants**. Compounds exhibiting strong sorption to soils and sediments may remain

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stored within the solid matrix and be released only gradually to groundwater, resulting in extended remediation timeframes and reduced treatment efficiency. Consequently, the **solid–solution partition coefficient (Kd) represents an important parameter when evaluating the suitability of P&T for a particular site**. In the case of PFAS, several commonly encountered compounds, including PFOA and PFOS, exhibit relatively high mobility in many groundwater systems (McGuire et al., 2014). Under favourable hydrogeological conditions, this behaviour supports the application of P&T as an effective strategy for plume containment and groundwater treatment, particularly when integrated with complementary remediation technologies.

4.2 Assessing solid-solution partitioning of PFAS in groundwater aquifers

The interaction between PFAS compounds and aquifer materials is a key factor influencing the performance of pump-and-treat remediation systems. The extent to which PFAS compounds partition between the aqueous and solid phases determines their mobility, availability for extraction, and ultimately the time required to achieve remediation objectives. For this reason, the determination of Kd coefficients constituted an important component of the **LIFE SOuRCE project** and was undertaken for aquifer materials collected from both demonstration sites.

The solid–solution partitioning behavior of a contaminant is commonly expressed through the partition coefficient (Kd), defined as:

$$\mathbf{Kd = Cs / Cw} \qquad \text{(Eq. 1)}$$

where *Kd* is the (linear) equilibrium solid–solution partition coefficient, *Cs* is the concentration associated with the solid phase, and *Cw* is the corresponding concentration in the aqueous phase.

Several **standardized leaching procedures have been developed to determine Kd coefficients** and support risk assessment and remediation planning. Recent work by Kleja et al. (2025) evaluated the applicability of two standardized ISO leaching tests for the determination of PFAS leaching behaviour and partitioning in soils: the batch leaching test (ISO 21268-2:2019), performed using either deionized water or 1 mM $CaCl_2$ at a liquid-to-solid ratio of 10, and the up-flow percolation test (ISO 21268-3:2019), using 1 mM $CaCl_2$ as the leaching solution. Both methods generated comparable Kd values across a range of PFAS compounds exhibiting different affinities for the solid phase.

From an operational perspective, the batch leaching test offers practical advantages due to its relative simplicity and lower resource requirements. However, the determination of partition coefficients for weakly sorbing PFAS can be associated with greater uncertainty under standard test conditions, particularly at a liquid-to-solid ratio of 10. In such cases, the low concentrations retained by the solid phase may result in increased uncertainty in the calculated Kd values, highlighting the importance of careful interpretation of partitioning data for highly mobile PFAS compounds.

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Within the **LIFE SOuRCE project**, Kd coefficients for aquifer materials from the two study sites were determined using two established approaches: (i) the batch leaching test at a liquid-to-solid ratio (L/S) of 2 in accordance with ISO 21268-1:2019, and (ii) the saturated paste method following FAO (2021).

The batch leaching tests were conducted on both (a) "natural" samples containing indigenous PFAS concentrations and (b) a subset of samples artificially spiked with a mixture of ten PFAS compounds (PFBA, PFPA, PFHxA, PFHpA, PFOA, PFNA, PFBS, PFHxS, PFOS, and 6:2 FTSA) at a concentration of 5 µg/kg dry weight (dw) of soil.

The Kd coefficient was calculated according to Eq. 1 and the concentration of PFAS associated with the solid phase (Cs) was estimated using a mass balance approach:

$$\mathbf{Cs = Cs,i - L/S \cdot Cw} \qquad \text{(Eq. 2)}$$

where *Cs,i* represents the initial concentration in the soil sample (µg/kg dry weight), *Cw* is the concentration measured in the equilibrium solution (µg/L), and *L/S* is the liquid-to-solid ratio (L/kg).

The **saturated paste method** is a well-established technique traditionally used in agricultural and soil sciences for the assessment of soil salinity and pore water chemistry (FAO, 2021). Although its application to PFAS-contaminated soils has received limited attention, the method offers a practical approach for evaluating contaminant partitioning under conditions that closely resemble the natural moisture content of field soils.

Within the **LIFE SOuRCE project**, the saturated paste method was successfully applied to soil samples collected at the Hovgården demonstration site. The procedure followed the methodology described by FAO (2021). Approximately 600 g of field-moist soil was placed in a suitable container and progressively mixed with deionized water until saturation was achieved, while avoiding the formation of free-standing water above the soil surface. Following homogenization, the saturated paste was allowed to equilibrate for 24 hours prior to further analysis. Subsequently, the paste was transferred to a Büchner funnel equipped with a 1.7 µm glass fiber filter. Phase separation was achieved by vacuum filtration. Both the solid and aqueous fractions were collected and analyzed for PFAS concentrations.

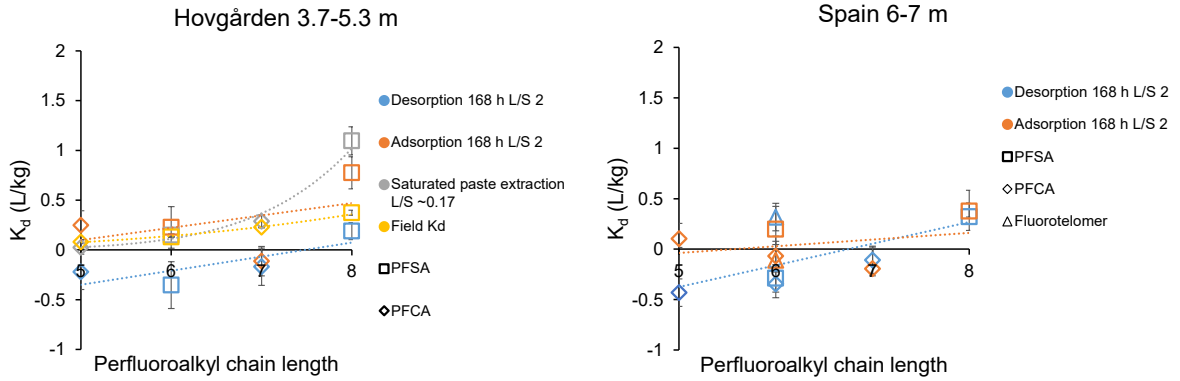

Figure 4-1 Comparison of PFAS solid–solution partition coefficients (Kd) determined using four independent approaches: batch desorption experiments, batch adsorption experiments, the saturated paste method, and field-derived estimates based on measured soil and groundwater concentrations.

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This approach enabled the direct determination of PFAS concentrations in the equilibrated solid phase (Cs). Furthermore, the relatively low liquid-to-solid ratio achieved (approximately 0.2) contributed to improved accuracy in Kd estimation (Liljeström et al., manuscript submitted).

As illustrated in **Figure 4-1**, the **estimated Kd values were generally low across all investigated samples and PFAS compounds**, **indicating limited sorption to the aquifer material and a strong tendency to remain in the aqueous phase**. For PFAS with carbon chain lengths below C8, Kd values were close to zero, confirming their high mobility and limited retention within the solid matrix.

Negative Kd values were obtained in some cases when applying Eq. 2. These values do not represent physically meaningful partitioning behaviour and are attributed to uncertainties associated with the mass balance calculations, particularly when dealing with very low sorbed concentrations. Under such conditions, small analytical uncertainties may have a significant impact on the calculated partition coefficients.

The saturated paste method proved particularly useful for overcoming these limitations. Owing to the lower liquid-to-solid ratio and the possibility of directly measuring PFAS concentrations in both the solid and aqueous phases after equilibration, the method enabled a more reliable estimation of very low Kd values (<1). For the Hovgården sample collected at the same depth interval as the groundwater monitoring well screens, Kd values of 0.02, 0.1, 0.3 and 1.4 were determined for PFHxA, PFHxS, PFOA and PFOS, respectively.

The observed increase in Kd values with increasing PFAS chain length is consistent with previous studies (McGuire et al., 2014; Campos-Pereira et al., 2023; Brusseau, 2023) and reflects the stronger hydrophobic interactions associated with longer-chain compounds. Furthermore, the laboratory-derived Kd values obtained for the Hovgården samples showed good agreement with estimates derived from field measurements of soil and groundwater concentrations, supporting the environmental relevance and representativeness of the laboratory testing approach.

In summary, the solubility and sorption assessments conducted on aquifer materials from the Swedish and Spanish sites yielded the following **key outcomes**:

- **Rapid sorption kinetics (both adsorption and desorption)** were observed for all investigated PFAS compounds across the tested aquifer materials, with equilibrium consistently achieved within 0.5 to 4 hours (Liljeström et al., manuscript submitted).
- All materials exhibited **low sorption affinity**, as indicated by Kd ≤ 1. These results are consistent with field-derived Kd values obtained for the Hovgården aquifer, which likewise suggest limited sorptive retention capacity.
- From a geochemical perspective, both sites present **favourable conditions for the P&T remediation**, due to the low sorption potential and correspondingly high mobility of the investigated PFAS compounds.

The combined observation of rapid sorption kinetics and low sorption affinity indicates that, from a geochemical standpoint, **P&T represents a technically viable remediation option at both sites**. The limited retardation of PFAS implies that extracted groundwater is expected to reflect near real-time concentrations within the flowing system, thereby enhancing the predictability and efficiency of hydraulic capture. Furthermore, the absence of a significant

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sorbed contaminant reservoir suggests reduced tailing effects and a lower risk of long-term back-diffusion, both of which are factors that typically improve P&T performance.

Nevertheless, the overall effectiveness and long-term sustainability of P&T systems are highly dependent on site-specific conditions, including hydrogeological characteristics, groundwater flow dynamics and system design parameters.

4.3 Scenario simulations of a site cleanup using MODFLOW GMS

Complete restoration of the two demonstration sites included in the **LIFE SOuRCE project** through P&T alone is currently not considered feasible. At the **Spanish site**, the effectiveness of groundwater extraction is constrained by the hydrogeological conditions, particularly the **low hydraulic conductivity of the aquifer, which ranges from 3.1 × 10^{-4} to 1.3 m/day**. These conditions limit achievable pumping rates and restrict the hydraulic capture of the PFAS plume. In addition, firefighting training activities involving the use of PFAS-containing aqueous film-forming foams (AFFF) were still ongoing during part of the project period, representing a continuing source of contamination.

At the Swedish site, the contamination originates from a municipal landfill containing a substantial and largely undefined PFAS inventory. Under these conditions, PFAS release to groundwater is expected to continue over extended timeframes. Consequently, the primary objective of the P&T system implemented within **LIFE SOuRCE** was hydraulic containment of the contaminant plume through the establishment of an inward hydraulic gradient, rather than complete site restoration (see Chapter 4.4).

To evaluate the potential performance of pump-and-treat as a long-term remediation strategy under more favourable hydrogeological conditions, numerical simulations were conducted using data from the firefighting training area at Sundsvall–Timrå Airport in central Sweden.

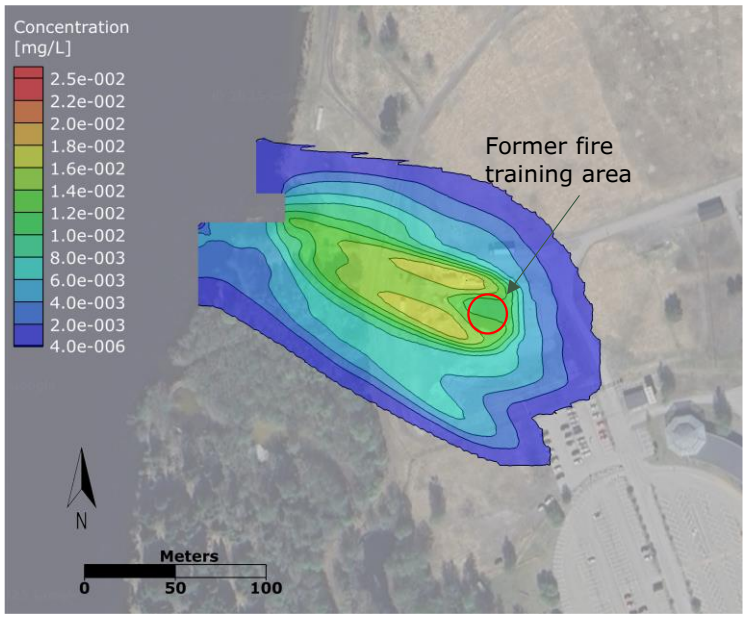

Figure 4-2 Conceptual representation of the current extent of the PFAS plume at Sundsvall–Timrå Airport. PFOS accounted for more than 90% of the total PFAS concentration at the site. Groundwater flow is directed towards the north-west, discharging into a nearby river located approximately 150 m downgradient of the former firefighting training area

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This site forms part of SGI's national program for the evaluation of PFAS remediation technologies and has been extensively characterized. The aquifer consists predominantly of sandy fluvial deposits with a hydraulic conductivity of approximately 20 m/day in the upper 5 m. Groundwater occurs at a depth of approximately 2 m below ground level, and the majority of the PFAS mass is located within the upper portion of the saturated zone. The initial plume configuration used in the simulations is presented in Figure 4-2.

To assess the influence of PFAS sorption behaviour on remediation performance, simulations were performed using two representative model compounds with Kd values of 1 and 10 L/kg, respectively. The modelling assumed homogeneous soil layers with decreasing hydraulic conductivity with depth. All simulations were conducted using the MODFLOW and MT3D-USGS modelling platforms. A detailed description of the modelling approach, assumptions and results is provided in Dahlin (2025).

One of the remediation scenarios evaluated by Dahlin (2025) considered groundwater extraction from a single pumping well operated at a flow rate of **14 m³/h**, corresponding to the optimal treatment capacity of the SAFF unit demonstrated within the **LIFE SOuRCE project**. Under the assumption of a PFAS compound exhibiting a **Kd value of 1 L/kg**, the simulations predicted near-complete removal of the contaminant plume after approximately five years of continuous operation (**Figure 4-3**). In contrast, substantially longer remediation times were estimated for compounds characterized by a **Kd value of 10 L/kg**, reflecting the greater degree of retention within the aquifer matrix and the slower release of contaminants to the groundwater phase.

The modelling results indicate that the relatively low Kd values determined for aquifer materials at both LIFE SOuRCE demonstration sites are favourable from the perspective of P&T remediation. These findings suggest that PFAS mobility is generally sufficient to allow effective groundwater extraction and treatment. Consequently, the applicability and overall performance of P&T systems at these sites are more strongly controlled by hydrogeological factors, including hydraulic conductivity, aquifer heterogeneity and groundwater flow conditions, than by PFAS sorption behaviour.

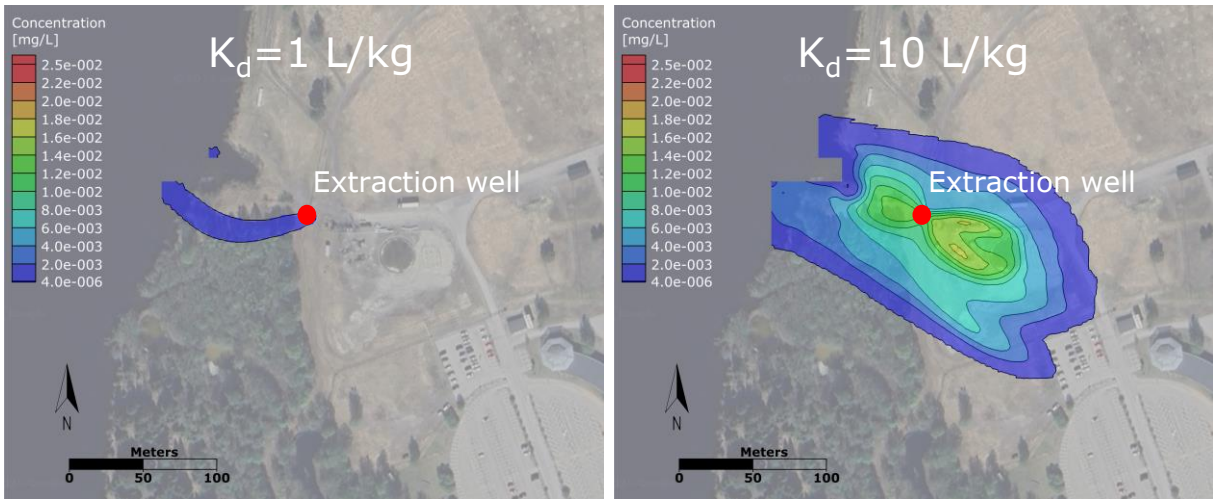

Figure 4-3 Simulated extent of the PFAS plume within the upper approximately 1 m of the aquifer after five years of continuous groundwater extraction at a pumping rate of 14 m³/h from a single extraction well. Simulations were performed using the MODFLOW and MT3D-USGS modelling platforms (Dahlin, 2025).

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4.4 Hydraulic containment of the PFAS plume at the Swedish landfill site

The **Hovgården waste management facility** has been in operation since 1971 and has historically been used for the disposal and management of various waste streams. The original landfill was initially established for the deposition of waste incineration ash and was subsequently used for different types of industrial waste. Household waste was not accepted at the site, resulting in comparatively limited inputs of organic material. Landfilling activities at the old disposal area ceased following the installation of a final cover system in 2019.

Groundwater investigations conducted at the site identified **the highest PFAS concentrations in monitoring wells located downgradient of the landfill in the direction of groundwater flow**. These observations indicate leachate migration from the landfill body, together with potential leakage from the existing leachate collection system, constitutes the primary source of PFAS contamination in the surrounding groundwater.

From a geological perspective, the landfill is located within a valley where anthropogenic fill and waste materials overlie natural clay and moraine deposits. The underlying bedrock consists predominantly of granitic gneiss intersected by water-bearing fracture zones. Hydrogeological investigations indicate a predominantly eastward groundwater flow direction, with estimated groundwater throughflow ranging between approximately 3 and 50 m^3/day depending on seasonal conditions.

Elevated chloride concentrations detected in downgradient groundwater during the 1990s highlighted the migration of landfill-derived contaminants beyond the disposal area. In response, an impermeable hydraulic barrier was installed in 1996 to limit groundwater flow from the landfill (**Figure 4-4**). The barrier consists of a 110 m long steel sheet barrier sealed against the underlying bedrock using bentonite. A surface drainage collection system was incorporated at the top of the barrier to intercept shallow groundwater and surface runoff.

Figure 4-4 Location of the groundwater monitoring wells included in the LIFE SOuRCE project (yellow circles) and the subsurface hydraulic barrier (red line). Base image source: Google Maps (Imagery ©2025 Airbus, Maxar Technologies; Map data ©2025).

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Despite these measures, groundwater quality monitoring performed downgradient of the barrier continued to indicate the presence of landfill-derived contaminants, suggesting groundwater migration beneath or around the structure. Based on these findings, a recent engineering assessment recommended the implementation of a P&T system to strengthen hydraulic containment and prevent the continued transport of contaminants beyond the landfill area. The proposed extraction wells were located immediately upgradient of the hydraulic barrier to maximize capture efficiency and establish an inward hydraulic gradient towards the treatment system.

Within the **LIFE SOuRCE project**, detailed investigations of the local hydrogeological conditions and groundwater availability were carried out in the area located upgradient of the hydraulic barrier during 2022 and 2023. As part of these activities, two new extraction wells (Production Wells 1 and 2; Figure 4-4) were installed in 2023 to assess their suitability for supplying groundwater to the demonstration treatment train.

The performance of the newly installed wells proved insufficient to provide the groundwater volumes required for continuous operation of the **LIFE SOuRCE** treatment train. Consequently, the majority of the influent water treated during the demonstration phase was supplied from two existing extraction points: the groundwater well designated **P3 Inside** and a well connected to the leachate and groundwater collection system located beneath the landfill (Figure 4-4). Combined abstraction rates from these sources ranged between approximately 60 and 150 m^3/day, depending on seasonal conditions and precipitation patterns. The P3 Inside well contributed approximately 36 m^3/day under typical operating conditions.

In addition to the extraction wells, a network of monitoring wells was used to assess groundwater levels and PFAS concentrations before, during and after P&T operation. These monitoring points provided essential information for evaluating hydraulic containment performance, groundwater flow behaviour and the influence of the remediation system on PFAS distribution within the aquifer (Figure 4-4).

The P&T system operated for a total of **336 days**, commencing in April 2024. During this period, approximately **27,900 m^3** of groundwater was treated through the SAFF system, including around **10,500 m^3** extracted from the **P3 Inside** groundwater well.

Groundwater level monitoring conducted throughout the operational period demonstrated a clear hydraulic influence of the extraction system, including a reversal of the groundwater flow direction immediately downgradient of the hydraulic barrier. Measurements performed at monitoring well **P24**, located approximately 300 m downgradient of the barrier, showed lower PFAS concentrations during the P&T operational period compared with concentrations observed prior to system start-up (**Figure 4-5**). These results indicate targeted groundwater extraction from the **P3 Inside** well, strategically positioned immediately upgradient of the hydraulic barrier, contributed to reducing PFAS migration beyond the landfill area and resulted in a measurable improvement in downgradient groundwater quality.

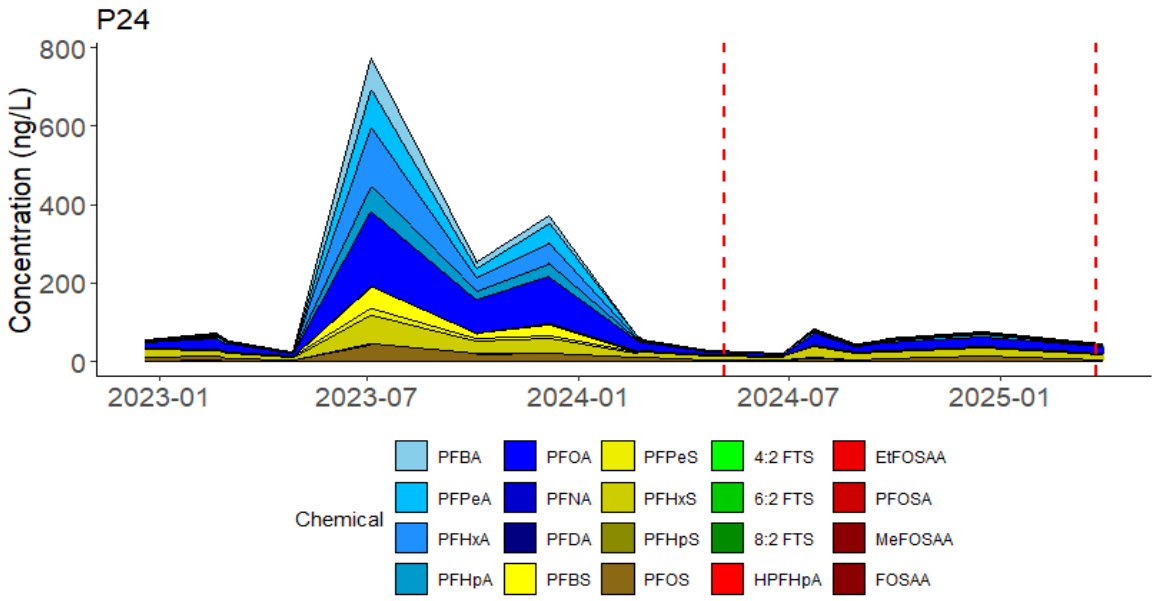

Figure 4-5 PFAS concentrations measured in groundwater monitoring well P24 during the monitoring period. The pump-and-treat operational phase is indicated by the interval between the two vertical dashed lines.

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5 Demonstration of the LIFE SOuRCE treatment train

The **LIFE SOuRCE project** demonstrated and evaluated integrated treatment trains for PFAS-contaminated groundwater under two distinct environmental and hydrogeological settings in Europe. The demonstration sites, located in Sweden and Spain, differed in climatic conditions, groundwater characteristics and contamination sources, providing an opportunity to assess the performance, robustness and adaptability of the proposed remediation approaches under contrasting operating conditions.

The treatment trains combined **complementary technologies** targeting PFAS separation, concentration, polishing and destruction (**Figure** 3-1). At the Swedish landfill site, the treatment train consisted of **SAFF** + **PHYTO + EO**. At the Spanish firefighting training site, the treatment train integrated **SAFF** + **AEX + EO**. These configurations were designed to address the specific site conditions while evaluating the effectiveness of integrated treatment strategies for the removal and destruction of both long-chain and short-chain PFAS under real operational conditions.

5.1 Brief description of the demonstration sites

5.1.1 The Swedish site. Context and implementation

The Swedish demonstration site was located at the **Hovgården landfill**, approximately 10 km northeast of Uppsala. The facility, owned and operated by **UVA**, has been in operation since 1971 and covers an area of approximately **490,000 m²**, of which around **25% is sealed** with paved surfaces. As described in Chapter 4.4, an extensive site characterization programme was carried out between 2021 and 2023 within the **LIFE SOuRCE project**. The investigations included the installation of five new groundwater monitoring wells (22G01–22G04), piezometers, soil coring and sonic drilling campaigns, groundwater sampling, and hydraulic testing through slug and pumping tests (Figure 4-4). The results confirmed that PFAS contamination was primarily associated with the groundwater phase, while sorption of the surrounding soil materials was generally limited.

Groundwater monitoring identified elevated PFAS concentrations upgradient of the hydraulic barrier, with average **∑32 PFAS** concentrations ranging from **2,390 to 4,650 ng/L**. The PFAS profile was dominated by **PFOA** (approximately 31%), followed by **PFHxA** and **PFHxS** (approximately 15% and 14%, respectively), while **PFPeA** accounted for around 10% of the total PFAS concentration. Downgradient of the barrier, average concentrations decreased to approximately **749 ng/L**, although levels remained substantially above the Swedish groundwater quality criterion of **90 ng/L for ∑11 PFAS**. Further downgradient, at monitoring well **P24**, average PFAS concentrations were approximately **189 ng/L** prior to the implementation of the pump-and-treat system.

Additional characterization using the **Total Oxidizable Precursor (TOP) assay** indicated a negligible presence of PFAS precursors within the groundwater. These findings suggest that the contamination was dominated by stable perfluorinated compounds rather than precursor substances capable of transforming into PFAS over time, thereby simplifying the interpretation of treatment performance and long-term contaminant behavior.

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Groundwater quality was strongly influenced by landfill leachate and was characterized by elevated concentrations of dissolved salts, particularly sodium (Na^+), calcium (Ca^{2+}), chloride (Cl^-), and sulphate (SO_4^{2-}), as well as relatively high levels of dissolved organic carbon (DOC). The groundwater exhibited circumneutral pH conditions (7.01 ± 0.09) and high ionic strength, with average concentrations of 935 ± 164 mg/L Na^+, 316 ± 26 mg/L Ca^{2+}, 1,111 ± 229 mg/L Cl^-, and 740 ± 163 mg/L SO_4^{2-}. Dissolved organic carbon concentrations averaged 34 ± 8 mg/L. In addition, elevated concentrations of iron and manganese were observed at several monitoring locations, indicating reducing conditions within parts of the aquifer.

5.1.2 The Spanish site. Context and implementation

The Spanish demonstration site is located approximately 50 km northeast of Barcelona and covers an area of approximately **4,050 m²**, of which around 50% is covered by concrete pavement. Since the early 1990s, the site has been used for firefighter training activities involving the regular application of fluorinated AFFF, typically during one or two training sessions per month. These activities were identified as the principal and ongoing source of PFAS contamination affecting both soil and groundwater.

A comprehensive site investigation campaign was carried out by ESOL between September and November 2021. The investigations included the installation of six groundwater monitoring wells (MW01–MW06) to depths of approximately 10 m, together with soil and groundwater sampling programs (**Figure 5-1**). The results confirmed the presence of a complex PFAS contamination profile comprising both short-chain and long-chain compounds. The predominant PFAS detected were **PFHxA, PFPeA, PFHxS, PFOS and PFHpA**. Maximum soil concentrations reached **77 µg/kg** at monitoring location MW01 (3.2 m depth), while groundwater concentrations reached up to **41 µg/L total PFAS** in the most impacted areas, particularly around monitoring well MW04.

In addition to the PFAS compounds currently included in European regulatory frameworks, the fluorotelomer sulfonate **6:2 FTS** was detected in groundwater at concentrations of up to **30 µg/L**, highlighting the importance of considering PFAS precursors and emerging fluorinated compounds in future monitoring and remediation programmes. The general groundwater chemistry differed considerably from that observed at the Hovgården site. Concentrations of dissolved salts and dissolved organic carbon (DOC) were substantially lower, reflecting the absence of landfill leachate influence. Groundwater pH values were near neutral, ranging from **6.58 to 7.15**, while DOC concentrations remained relatively low (**1.1–5.0 mg/L**). Chloride and sodium concentrations ranged from **34.8–52.5 mg/L** and **28.2–47.9 mg/L**, respectively, indicating a comparatively low salinity groundwater matrix. Sulphate concentrations varied between **33 and 59 mg/L**, whereas ammonium concentrations were below the analytical detection limit in all monitoring wells. Overall, the groundwater exhibited lower mineralization and organic matter content than the groundwater at the Hovgården site, providing more favorable conditions for the evaluation of the treatment technologies.

The site was also affected by the presence of additional contaminants associated with firefighting activities. These included total petroleum hydrocarbons (TPH), with concentrations reaching **7,400 mg/kg in soil** and **120 µg/L in groundwater**, together with traces of naphthalene and several heavy metals. The occurrence of these co-contaminants is relevant when assessing treatment performance, as they may influence the operation and efficiency of the technologies evaluated within **LIFE SOuRCE**, including SAFF, AEX and EO.

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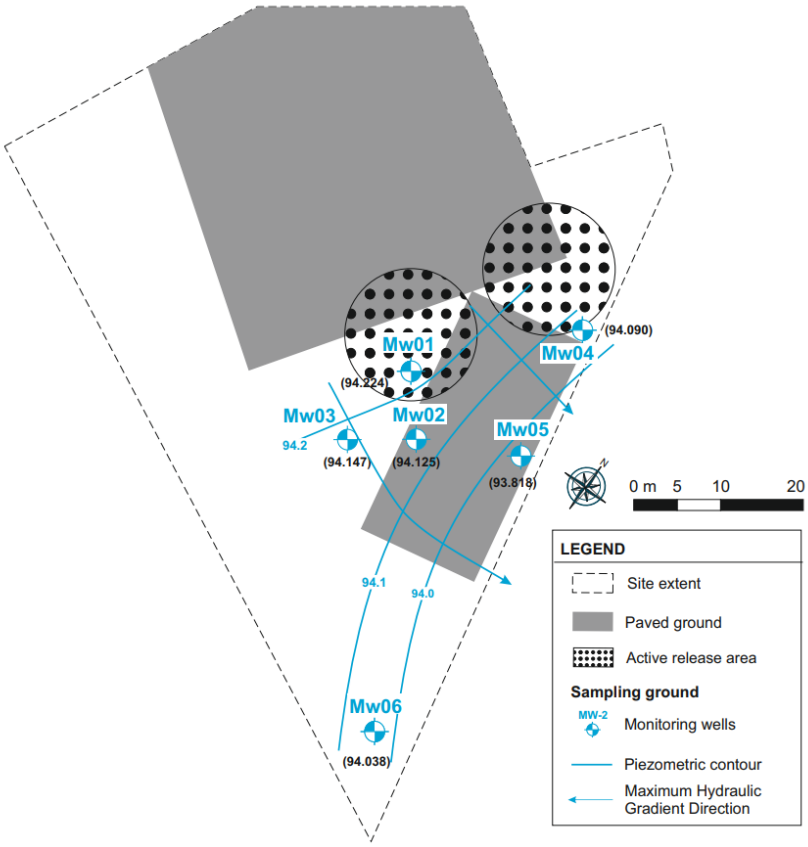

Figure 5-1 Piezometric map of the Spanish demonstration site showing the groundwater flow pattern and the location of the monitoring wells installed during the site investigation and demonstration activities.

Hydrogeological investigations identified a stratigraphic sequence composed of quaternary alluvial and colluvial sediments overlying fractured granodioritic bedrock. Groundwater occurs within an unconfined aquifer characterized by an average water table depth of approximately **5.8 m below ground level** and a predominantly eastward groundwater flow direction, with an average hydraulic gradient of approximately **1.5%**. Hydraulic conductivity values varied considerably across the site, ranging from **1.3 m/day** at MW01 to **3.1×10^{-4} m/day** at MW04, highlighting the pronounced heterogeneity of the subsurface materials and the variable groundwater flow conditions encountered within the aquifer.

5.2 Risk reduction effectiveness

5.2.1 The Swedish site

The treatment train demonstrated at the Swedish site integrated SAFF, PHYTO and EO within a multi-stage treatment approach designed to concentrate, remove and ultimately destroy PFAS present in groundwater.

The SAFF unit served as the primary treatment step, separating and concentrating PFAS from the extracted groundwater stream (**Figure 3-1**). The PFAS-enriched concentrate generated by the SAFF process was subsequently treated in an EO unit equipped with BDD electrodes to promote PFAS degradation. Following treatment, the concentrate was recirculated to the SAFF system for further processing and concentration.

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The groundwater treated by the SAFF unit was directed to a PHYTO unit configured as a subsurface-flow constructed wetland, providing an additional polishing stage prior to final discharge. Due to the smaller treatment capacity of the wetland compared with the SAFF and EO systems, only a portion of the SAFF-treated water could be processed through the PHYTO unit during the demonstration period. The remaining SAFF effluent, together with the treated outflow from the constructed wetland, was transferred to the site's existing landfill leachate treatment facility before final discharge to the receiving environment.

5.2.1.1 Performance of the SAFF system

A **SAFF20 containerized system**, developed and manufactured by EPOC Enviro and operated by ENVY, was deployed at both LIFE SOuRCE demonstration sites. The system comprised two **primary foam fractionation vessels**, each with a capacity of 2.6 m^3, in which air was introduced through venturi spargers to generate bubbles and promote the transfer of PFAS to a foam phase. The resulting PFAS-enriched foamate was subsequently directed to a 1.6 m^3 **secondary fractionation vessel**, where a second concentration step further increased PFAS levels while reducing the final waste volume.

The **highly concentrated foamate produced in the secondary vessel was extracted using a vacuum pump and transferred to a dedicated storage tank prior to treatment by EO unit**. To maximize PFAS recovery and process efficiency, the **liquid stream remaining after secondary fractionation was recirculated to the primary fractionation vessels**. The treated water leaving the primary vessels was either directed to the constructed wetland system implemented at the Swedish site or transferred to the site's conventional leachate treatment facility for further management and final discharge.

During the **336-day demonstration period**, the SAFF unit treated a total of **27,937 m^3** of groundwater, corresponding to an average treatment rate of **83 m^3/day**. Operational interruptions associated with maintenance and system adjustments resulted in a cumulative downtime of **64 days**. Excluding these periods, the average treatment rate increased to **103 m^3/day**. Throughout the demonstration, the system operated below its maximum treatment capacity of approximately **300 m^3/day**, primarily due to limitations in groundwater availability rather than process constraints.

Influent PFAS concentrations remained relatively stable over the monitoring period, with **Σ24 PFAS** concentrations ranging between **1,670 and 2,690 ng/L**. The PFAS profile was dominated by **perfluorocarboxylic acids (PFCAs)**, which accounted for **74 ± 2.2%** of the total PFAS concentration, while **short-chain PFAS** represented **59 ± 4.5%** of the PFAS mass. Among the individual compounds, **PFOA** consistently exhibited the highest concentrations, with an average value of **492 ± 118 ng/L**. PFAS precursors included in the target analytical program contributed only a minor fraction of the total PFAS burden (**1.5 ± 0.2%**), while results from the TOP assay indicated a relatively limited contribution from unidentified oxidizable precursors (**12 ± 2.8%** of total PFAS).

The SAFF unit achieved an average removal efficiency of **48.3 ± 6.6% for Σ20 PFAS**, with treatment performance strongly dependent on PFAS chain length. LC-PFAS were removed very effectively, with an average removal efficiency of **98.8 ± 2.0%**, whereas the average removal efficiency for SC-PFAS was only **22.8 ± 7.2%**. These results are consistent with the established behavior of foam fractionation systems, where long-chain PFAS exhibit a stronger affinity for the air–water interface and are therefore transferred more efficiently to the foam

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phase. In contrast, short-chain PFAS display lower surface activity and consequently lower removal efficiencies (Burns et al., 2021).

Although the SAFF process substantially reduced the concentrations of long-chain PFAS, the treated groundwater remained dominated by short-chain compounds. As a result, residual PFAS concentrations in the effluent exceeded the **100 ng/L limit for Σ20 PFAS** established under the EU Drinking Water Directive (EU) 2020/2184.

Previous research has demonstrated the **potential of co-foaming agents to enhance the removal of short-chain PFAS** (Klevan, Van Allen, Xia et al., 2025). Within the **LIFE SOuRCE project**, **three types of co-foaming surfactants** were evaluated: Polyethylene glycol sorbitan monolaurate (Tween 20, CAS 9005-64-5) and Polyethylene glycol sorbitan monooleate (Tween 80, CAS 9005-65-6), both commonly used food emulsifiers, as well as a proprietary cationic surfactant used in the water treatment industry (composition undisclosed due to patent protection). Each additive was tested at **concentrations of 4, 6, and 10 mg/L** and was dozed into the primary FF vessels via the unit's internal dosing system.

The addition of co-foaming agents consistently improved the removal of short-chain PFAS compared with the baseline performance of the SAFF system. Among the tested additives, the cationic surfactant achieved the highest removal efficiency, reaching 70% at a dosage of 10 mg/L. This result is consistent with previous studies identifying cationic surfactants as particularly effective enhancers for PFAS removal through foam fractionation processes (Klevan, Van Allen, Xia et al., 2025).

The non-ionic surfactants Tween 20 and Tween 80 showed similar performance, achieving short-chain PFAS removal efficiencies of 52% and 54%, respectively, at the highest tested concentration (10 mg/L). Although these values were lower than those obtained with the cationic surfactant, they nevertheless represent a substantial improvement over the baseline treatment performance. These findings are particularly relevant as they demonstrate that non-toxic and commercially available additives can significantly enhance PFAS removal while offering a potentially more environmentally benign alternative to conventional co-foaming agents.

5.2.1.2 Destruction of PFAS using EO

EO was applied at **cubic-meter scale to degrade PFAS concentrated in the foamate generated by the SAFF process**. The treatment was carried out using **BDD electrodes configured as both anode and cathode** within a 1 L flow cell (**Figure 5-2**). Over the operational period, a total of 6.2 m^3 of foamate was treated across nine batches. During the same period, the SAFF unit processed 27,937 m^3 of contaminated water, corresponding to a volume reduction factor of 4,506.

The EO treatment achieved substantial reductions in PFAS concentrations in the foamate. **A gradual decrease in degradation rates was observed throughout each treatment batch, indicating a mass-transfer limitation at the electrode surface**. As PFAS concentrations declined, the reaction rate decreased accordingly, reflecting the lower availability of target compounds for oxidation. This behaviour is consistent with observations reported in previous studies employing BDD-based electrochemical systems (Smith et al., 2023).

An initial increase in SC-PFAS concentrations was observed during the EO treatment, indicating the progressive transformation of longer-chain PFAS into shorter-chain compounds. This behaviour is consistent with the degradation mechanism previously described for PFCA

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and PFSA, whereby sequential defluorination and carbon-chain shortening occur through a stepwise "unzipping" process (Mirabediny et al., 2023). As treatment progressed, concentrations of SC- PFAS also decreased, suggesting their further degradation and eventual mineralization to carbon dioxide and fluoride ions, or transformation into ultra-SC-PFAS and other fluorinated intermediates not included in the analytical scope of this study.

To assess the fate of fluorinated compounds during treatment, a fluorine molar balance was performed for two batches (**Figure 5-3**). The results showed fluorine recoveries of 99% and 97%, respectively, demonstrating an almost complete mass balance following EO treatment. Although the fluorine recoveries achieved in the present study were exceptionally high, similar results have been reported in previous investigations (Liang et al., 2022), confirming the potential of EO using BDD electrodes to achieve near-complete PFAS mineralization.

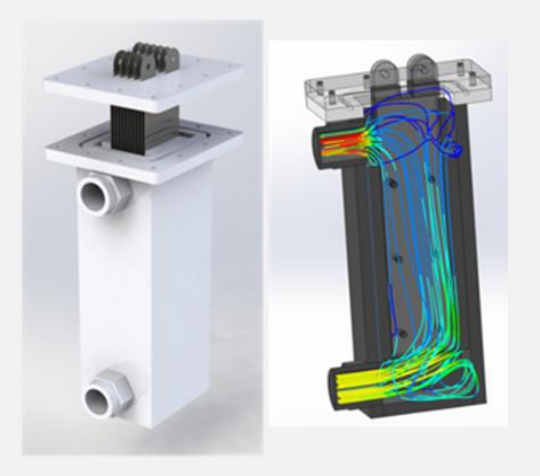

Figure 5-2 EO flow cell used in the experiments (1 L volume, 10 dm² electrode area, flow rate of 10 L/min). The colored lines in the right-hand image indicate the flow paths and relative flow velocities within the cell (red = high velocity, blue = low velocity).

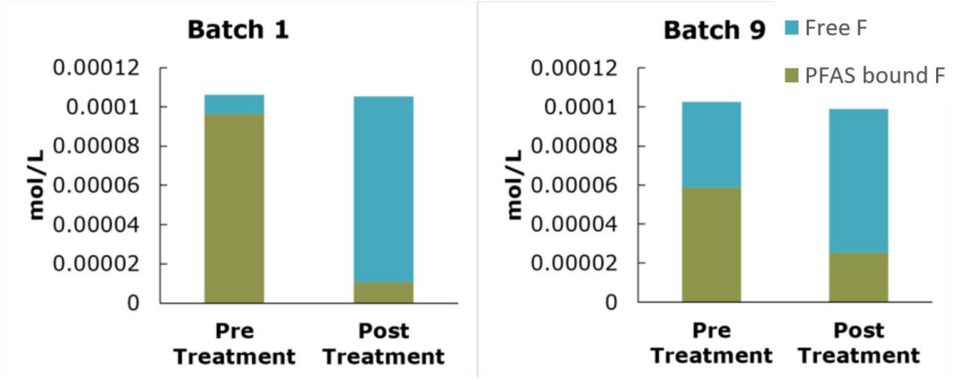

Figure 5-3 Fluorine molar balance before and after electrochemical oxidation (EO) treatment (mol/L). PFAS-bound fluorine was calculated from the PFAS32 target analysis.

The treatment efficiency for Σ32 PFAS varied considerably between batches, ranging from 10% to 88%, with an average PFAS removal of 3.3% per Ah/L applied. The variability in performance was partly attributed to the operational challenges encountered during the demonstration period. In particular, calcium carbonate precipitation resulted in scaling of the electrodes (**Figure 5-4**), reducing electrode activity and restricting flow through the treatment system. Mitigation of scaling should therefore be considered in future system optimization, for example through pH control in the foamate reservoir to maintain conditions below pH 7.

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Furthermore, several power interruptions occurred during batch operations, affecting process continuity and contributing to the lower treatment efficiencies observed in some batches. Despite these operational constraints, the results demonstrate the potential of EO treatment for the degradation of concentrated PFAS streams generated by the SAFF process.

Figure 5-4 EO cell before operation (left) and after treatment (right), illustrating the accumulation of calcium carbonate precipitates and humic substances on the electrodes.

5.2.1.3 Performance of the PHYTO system as a polishing step

For the PHYTO stage, a **subsurface flow constructed wetland** was designed and installed. The system consisted of a 7.2 m × 20.45 m treatment basin surrounded by a gravel embankment and lined on the bottom and sides with a 1.14 mm EPDM Geogard geomembrane to ensure hydraulic isolation from the surrounding environment (**Figure 5-5** and **Figure 5-6**).

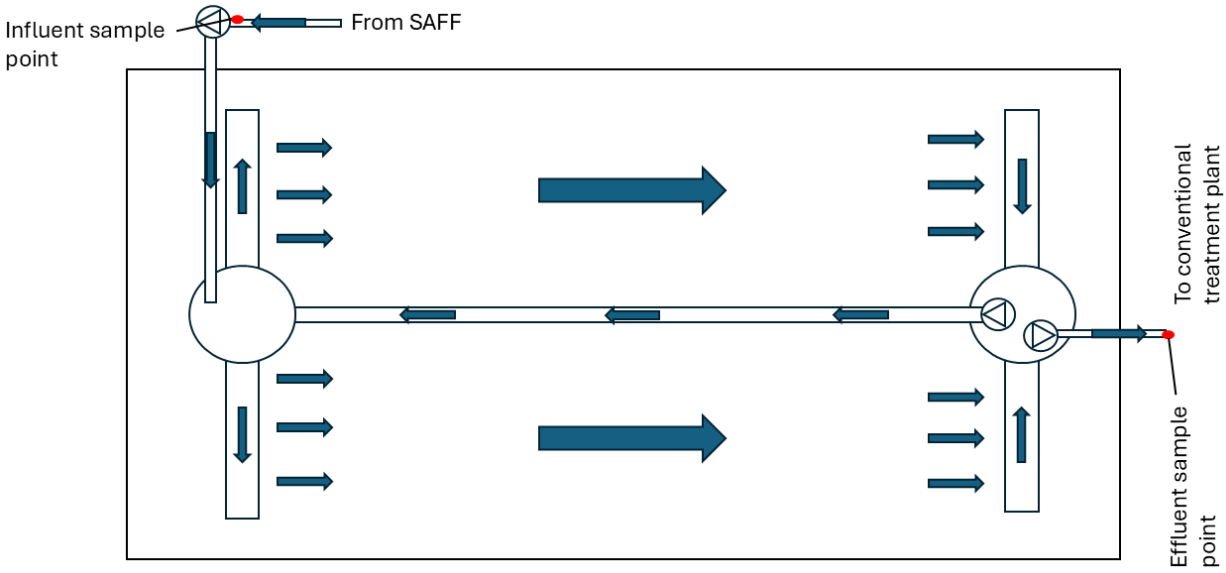

Figure 5-5 Top-view schematic of the PHYTO unit, including the water flow direction within the treatment system (not to scale).

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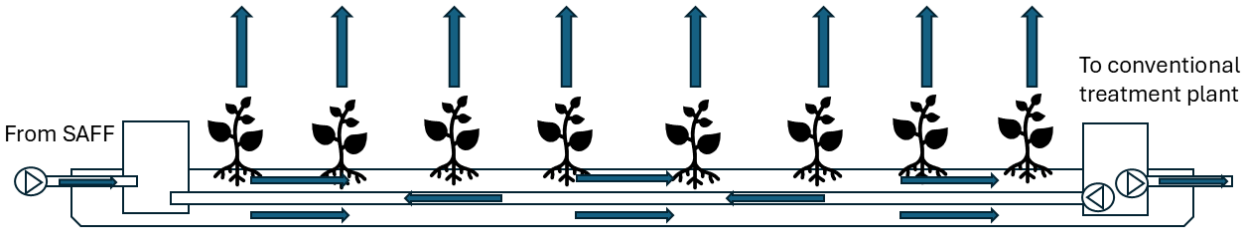

Figure 5-6 Cross-sectional schematic of the PHYTO unit illustrating the water flow direction within the system (not to scale).

A 500 mm diameter plastic well was installed at each end of the wetland. These wells were connected to perforated medium-density polyethylene (PEM) distribution pipes across the full width of the basin, providing uniform water inlet and collection along the treatment area. In addition, the two wells were interconnected by a 32 mm PEM pipe to facilitate hydraulic control and water transfer within the system.

The treatment basin was filled with **alternating sections of LECA and a reactive substrate composed of biochar, peat, and LECA** (volumetric ratio of 1:1:8). The substrate configuration was designed to combine hydraulic conductivity with enhanced sorption capacity and plant support.

The wetland was **planted in May 2023 with 1,624 willow cuttings** (Salix spp., clone Wilhelm), each approximately 40 cm in length and spaced at 30 cm intervals. To promote plant establishment, the **unit was irrigated with on-site technical water between June and August 2023**. In August 2023, a total of 100 kg of NPK fertilizer was applied to support vegetation growth. The fertilizer contained 7.9% NO_3^-, 12.7% NH_4^+, 3.6% PO_4^{3-}, 6.6% P, 0.9% Mg, and 3% S. **Irrigation with treated water from the SAFF unit commenced in May 2024**.

During the operational period, the **PHYTO unit treated a total of 73 m³ of PFAS-contaminated water over 177 days of operation**. The corresponding influent and effluent volumes were monitored throughout the demonstration period to evaluate hydraulic performance and treatment efficiency.

Based on the recorded influent and effluent volumes, the total evapotranspired volume during the demonstration period was estimated at 54.7 m³. This corresponds to an average evapotranspiration rate of 2.16 L/m²·d, which is in the same range as values reported for an irrigated Salix field in Uppsala, Sweden, where average evapotranspiration was estimated at 2.6 L/m²·d over a five-year period (Persson & Lindroth, 1994).

No significant differences were observed in individual PFAS concentrations or in Σ20-PFAS concentrations between the influent and effluent of the wetland unit. This indicates that **the wetland did not substantially reduce PFAS concentrations in the treated water and, therefore, is not suitable as a polishing step when the objective is to produce a PFAS-free effluent**.

Despite the substantial reduction in water volume resulting from evapotranspiration, PFAS concentrations in the effluent remained largely unchanged. This indicates that PFAS were retained within the wetland system rather than becoming concentrated in the remaining water phase. The mass balance showed reductions of 50% for short-chain PFAS, 64% for long-chain PFAS, and 51% for Σ20-PFAS, while the overall water volume decreased by 48%.

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The removal of SC-PFAS closely matched the reduction in water volume, suggesting that these highly mobile compounds were primarily removed by plant water uptake and subsequent evapotranspiration. In contrast, the greater removal observed for LC-PFAS indicates the contribution of additional retention mechanisms, most likely sorption to plant biomass and the wetland substrate.

The highest PFAS removals were observed during the summer months (June–August 2024), corresponding to periods of highest evapotranspiration activity. This seasonal trend suggests a strong relationship between water uptake by vegetation and PFAS retention within the wetland system. In contrast, PFAS removal was limited during September and October. In September, PFAS concentrations measured in the effluent were higher than those in the influent, while evapotranspiration rates were lower than those recorded during the summer period. During October, precipitation exceeded evapotranspiration, resulting in a net increase in water volume within the system and the release of a greater volume of water than was applied. These hydrological conditions likely reduced the overall PFAS retention capacity of the wetland and influenced the treatment performance observed during the autumn months.

The average Σ20-PFAS burden per Salix plant increased from 507 ng in June 2024 to 1,280 ng in September, before decreasing to 117 ng in December (**Figure 5-7a**). The increase observed during the growing season reflects both biomass production and the continued accumulation of PFAS within plant tissues as water uptake and transpiration progressed. Most of the accumulated PFAS was associated with leaf tissues, which accounted for 84% and 82% of the total plant PFAS burden in June and September, respectively. In contrast, PFAS concentrations in the roots contributed only marginally to the overall PFAS mass balance.

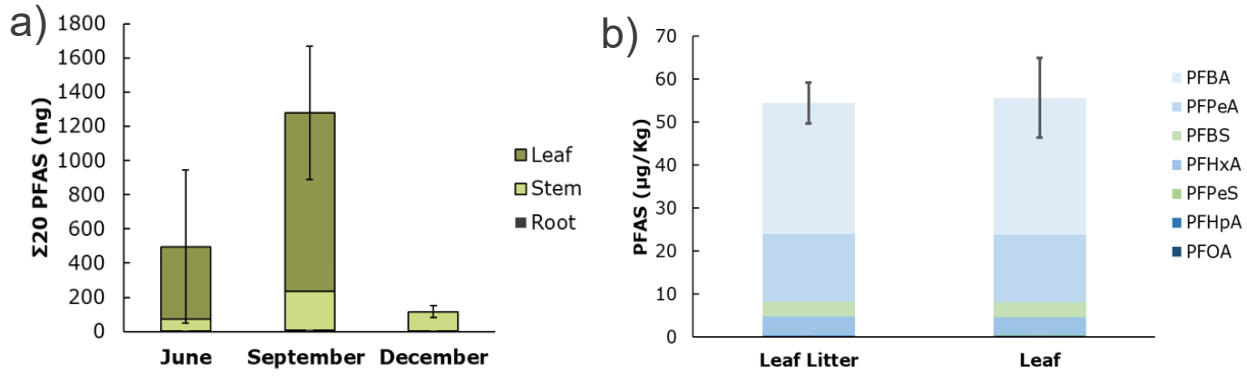

Figure 5-7 (a) Average Σ20-PFAS mass per Salix plant in June, September, and December 2024. (b) Σ20-PFAS concentration and composition in leaves collected from trees and from the ground during the October leaf abscission period. Values are presented as mean ± SD (n = 8).

A marked reduction in total PFAS within the *Salix* biomass was observed between September and December. This decrease was primarily associated with leaf abscission occurring during autumn. The absence of a corresponding decline in PFAS concentrations in fallen leaves (**Figure 5-7b**), compared with leaves remaining on the trees during the same period, indicates that PFAS were not significantly re-translocated from leaves to stems or roots prior to leaf fall. This behaviour differs from that of many plant nutrients, which are commonly reallocated to perennial tissues before senescence.

These findings highlight the importance of biomass management in PFAS phytoremediation systems. In particular, **the collection and removal of fallen leaves are essential to prevent the reintroduction of accumulated PFAS into the environment through litter decomposition and subsequent release to soil or water**.

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A **PFAS-mass balance** was established for the wetland system over **two assessment periods: May–June 2024 and May–September 2024**. The calculations combined **estimated hydraulic balances, derived from the difference between influent and effluent water fluxes, with the corresponding PFAS concentrations measured during each period**. To evaluate PFAS retention within the system, the distribution of PFAS among the different wetland compartments was quantified. These compartments included the aqueous phase, above- and below-ground *Salix* biomass, the reactive substrate, and the LECA media. The resulting mass balance provided an estimate of PFAS removal and retention pathways within the PHYTO unit during the monitoring period.

Despite the uncertainties associated with PFAS analysis across different matrices and the relatively low sampling frequency, the mass balance closure achieved was considered satisfactory for a demonstration-scale system. PFAS recoveries reached 67% for the period from 28 May to 27 June 2024 and 69% for the period from 28 May to 26 September 2024 (**Figure 5-8**). During initial operational period, PFAS entering the wetland were mainly retained within the pore water, resulting in a progressive increase in PFAS concentrations in the water phase. By the end of June, pore water concentrations had stabilized at levels similar to those observed in the SAFF effluent, suggesting that equilibrium between the influent water and the wetland water compartment had largely been established.

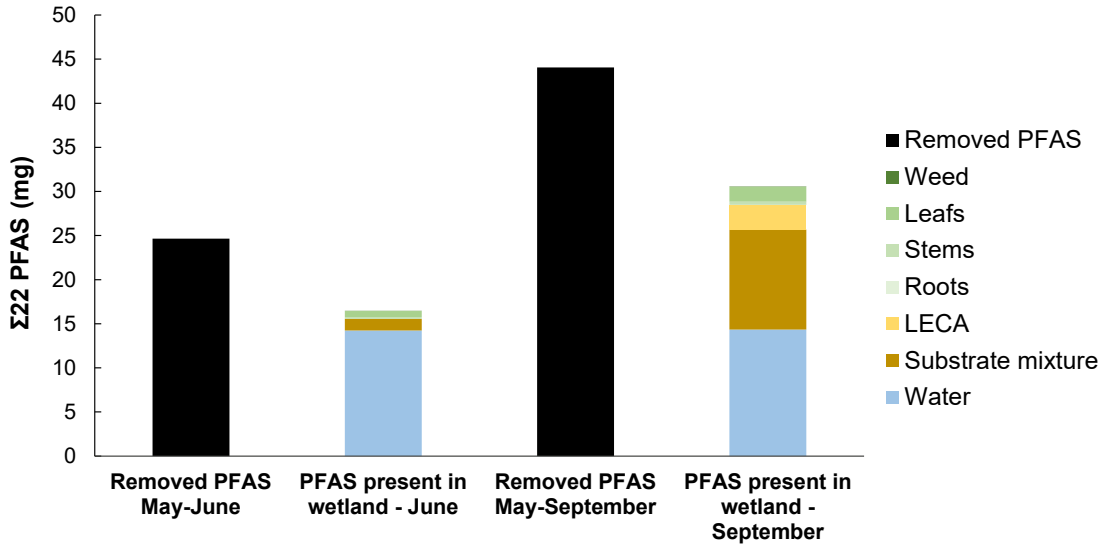

Figure 5-8 Σ20-PFAS mass balance and distribution within the wetland system on 27 June and 26 September 2024.

Between June and September 2024, PFAS retention was dominated by sorption processes within the wetland media. The reactive substrate accounted for the largest fraction of retained PFAS (37%), followed by LECA (9.1%) and uptake into *Salix* leaves (5.5%). Overall, PFAS associated with total plant biomass represented 6.9% of the recovered mass balance. Although this contribution was relatively modest compared with the amounts retained in the substrate and dissolved within the wetland water, it is consistent with the large mass of substrate and water present in the system relative to the biomass compartment. Similar PFAS partitioning patterns have been reported in previous wetland studies (Chen et al., 2012; Zhang et al., 2020). These findings reflect the first year of operation of the wetland system. **Over longer operational periods, plant uptake is expected to become increasingly important as a PFAS removal pathway, as concentrations in the pore water and substrate gradually**

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approach equilibrium. In addition, the contribution of vegetation is likely to increase as the Salix stand matures and biomass production increases, considering that the plants were only one to two years old during the demonstration period.

5.2.1.4 Performance of the LIFE-SOuRCE treatment train

The combined treatment train, **SAFF unit followed by the PHYTO polishing system**, achieved overall removal efficiencies of **99.6% for LC-PFAS and 61.2% for SC-PFAS** during the demonstration period (**Table 5-1)**. Based on the co-foaming agent evaluation, the continuous application of the most effective additive, namely the cationic surfactant at a dosage of 10 mg/L, could further enhance treatment performance, increasing the projected removal efficiencies to **99.9% for LC-PFAS and approximately 85% for SC-PFAS**.

Table 5-1 Overall PFAS removal efficiencies achieved under the different treatment scenarios

Treatment train	LC-PFAS removal (%)	SC-PFAS removal (%)
SAFF	99	23
SAFF with 10 mg/L cationic surfactant	100	70
PHYTO	64	50
SAFF + PHYTO	100	61
SAFF with 10 mg/L cationic surfactant + PHYTO	100	85

Additional improvements in SC-PFAS removal could be achieved through optimization of the wetland design, particularly by increasing the treatment area and consequently reducing the hydraulic loading rate. Based on the observed SC-PFAS removal per unit surface area, calculations indicated a hydraulic loading rate of 1.53 $L/m^2 \cdot d$ would be required to achieve an overall SC-PFAS removal of 95%, compared with the loading rate of 2.88 $L/m^2 \cdot d$ applied during the demonstration period. This estimate was derived from the measured PFAS mass removal per unit wetland area and the average influent concentration throughout operation. The use of the most effective co-foaming agent during the SAFF treatment stage would further improve overall system performance, allowing the target short-chain PFAS removal of 95% to be achieved at a slightly higher hydraulic loading rate of 1.7 $L/m^2 \cdot d$.

Based on these scenarios, the **estimated wetland area requirements** are:

- **5.6 ha for the treatment configuration demonstrated during the project**;
- **11 ha to achieve 95% removal of SC-PFAS**; and
- **9.4 ha to achieve 95% removal of SC-PFAS when the optimal co-foaming agent is applied in the SAFF process**.

These estimates assume PFAS concentrations in the pore water remain stable under reduced hydraulic loading rates and increased evapotranspiration. They further assume that the Salix vegetation can tolerate the potential accumulation of dissolved salts associated with lower effluent volumes.

5.2.2 The Spanish site

The LIFE SOuRCE treatment train implemented at the Spanish demonstration site integrated complementary treatment technologies for the removal and destruction of PFAS compounds from contaminated groundwater. Groundwater was first extracted and treated using the SAFF system, where PFAS were concentrated by foam fractionation. The treated water, containing substantially reduced PFAS concentrations, was collected in an intermediate storage tank

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prior to downstream treatment. At the same time, the PFAS-enriched foamate generated by the SAFF process was transferred to EO unit for PFAS destruction.

Following SAFF treatment, the water underwent further polishing in an AEX system comprising two resin filters connected in series: a Purolite C100 softening resin and a PFAS-selective Purolite PFA694E resin. This treatment step provided additional removal of residual PFAS remaining in the bulk water after foam fractionation. Residual streams generated during resin regeneration were subsequently treated in the EO unit to destroy PFAS compounds.

The pilot-scale demonstration was operated in batch mode between January 2023 and January 2024, with each treatment cycle processing 5,000 L of contaminated groundwater. PFAS concentrations were monitored throughout the demonstration period at all key process locations, including the influent and effluent of both the SAFF and AEX treatment units. This monitoring strategy enabled the evaluation of treatment performance for each batch and the assessment of PFAS removal across the different stages of the treatment train.

5.2.2.1 Performance of the SAFF system

Both LIFE SOuRCE demonstration sites were equipped with a **SAFF20 containerized foam fractionation system** manufactured by EPOC Enviro and operated by ENVY. The process relied on **two primary fractionation vessels** (2.6 m^3 each), where air injected through venturi spargers generated fine bubbles, facilitating PFAS adsorption at the air–water interface and subsequent foam formation. The resulting foamate was transferred to a **secondary concentration vessel** with a capacity of 1.6 m^3 for further PFAS enrichment and additional reduction of the concentrate volume.

The PFAS-rich foamate generated during the secondary concentration step was collected by means of a vacuum pump and stored in a dedicated holding tank before being transferred to the EO unit for PFAS destruction. To enhance PFAS capture and minimize losses, the liquid fraction after secondary fractionation was recirculated back to the primary fractionation vessels for further treatment.

The pilot-scale demonstration was conducted between **January 2023 and January 2024 in batch mode**, with each treatment cycle processing 5,000 L of contaminated groundwater. A total of **86.7 m^3** of groundwater was treated during the operational period. **Batch operation was dictated by the hydrogeological characteristics of the site, particularly the low productivity of the aquifer**, which limited groundwater abstraction rates and prevented continuous operation of the treatment system. Recovery periods were therefore required between treatment cycles to allow groundwater levels to replenish and the SAFF feed tank to be refilled. Consequently, the **demonstrated treatment capacity reflected groundwater availability rather than limitations of the SAFF technology itself**. PFAS concentrations were monitored in the influent and treated water for each batch, enabling treatment performance to be evaluated throughout the demonstration period.

PFAS removal performance of SAFF unit varied considerably throughout the demonstration period (**Figure 5-9**). In general, the highest removal efficiencies were achieved during the initial batches, with **total PFAS removals exceeding 70% and LC-PFAS removals frequently above 90%.** Higher removal efficiencies were generally observed for LC-PFAS and during periods with elevated influent PFAS concentrations, owing to the greater tendency of these compounds to adsorb at the air–water interface and partition into the foam phase. In contrast, SC-PFAS were removed less efficiently and showed greater variability in treatment performance throughout the operational period.

The fluctuations in SAFF unit performance were largely associated with variations in influent PFAS concentrations and groundwater characteristics during operation. As the SAFF process relies on the optimization of the air injection rates and bubble size according to influent water quality, changes in PFAS loading and matrix composition directly influenced the efficiency of the foam fractionation process. These challenges were particularly evident at the Spanish demonstration site, which remained an active source area throughout the project. As a result, influent PFAS concentrations and groundwater composition varied considerably over time, creating dynamic operating conditions that affected the consistency of SAFF performance.

The SAFF unit was not operational during Batch 11 (Figure 5-9). Groundwater treatment during this period therefore relied exclusively on the AEX system, and no SAFF removal efficiency was calculated for this batch.

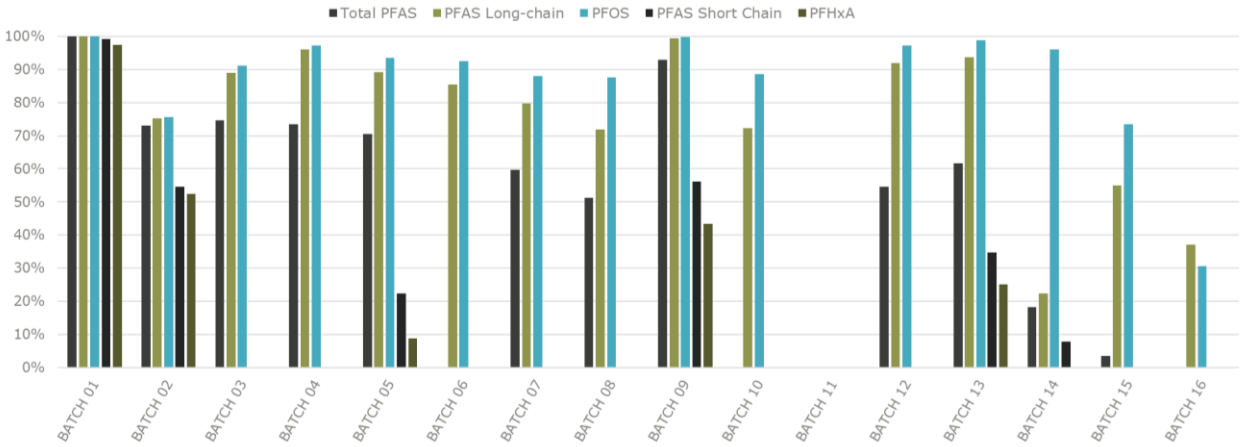

Figure 5-9 PFAS removal efficiency of the SAFF system at the Spanish demonstration site.

5.2.2.2 Performance of the AEX system

The AEX polishing unit installed at the Spanish demonstration site consisted of two resin vessels operated in series, each with a bed volume of 6.5 L. Water was first passed through a Purolite C100 softening resin and subsequently through a Purolite PFA694E resin specifically designed for PFAS removal.

Among the technologies evaluated at the Spanish site, the AEX system delivered the highest treatment performance, consistently achieving PFAS removal efficiencies above 90% throughout the operational period (**Figure 5-10**). Complete or near-complete removal was observed for most monitored PFAS groups, including total PFAS, LC-PFAS, PFOS, SC-PFAS and PFHxA, demonstrating the broad-spectrum effectiveness of the technology across compounds with markedly different physicochemical properties.

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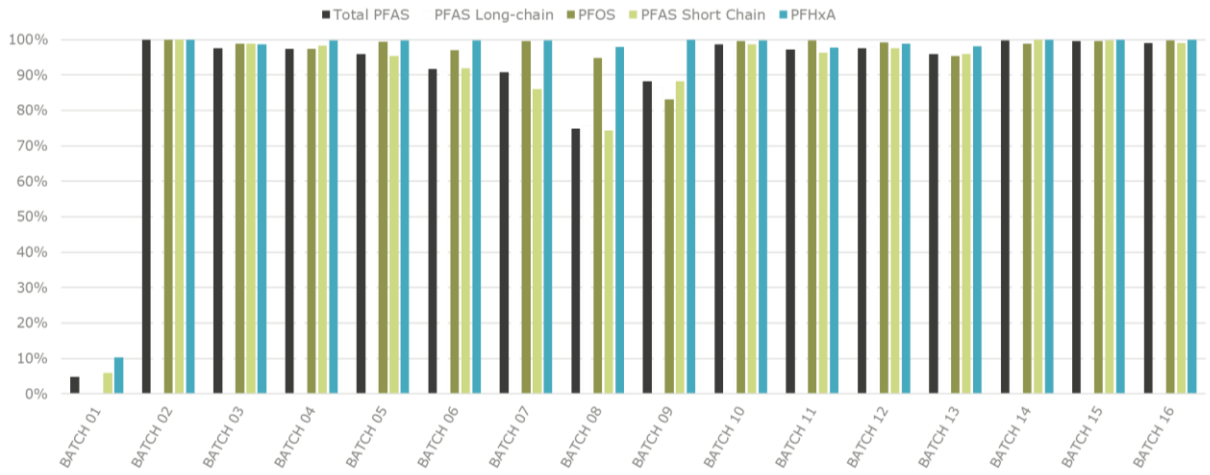

Figure 5-10 PFAS removal efficiency of the AEX unit at the Spanish demonstration site.

The system maintained excellent treatment performance during most of the demonstrations, with removal efficiencies close to 100% for all the PFAS categories. Temporary reductions in performance were observed during Batches 7 and 8, where total PFAS removal decreased to approximately 75–88%, accompanied by lower removal of SC-PFAS. These marked reductions coincided with progressive exhaustion of the Purolite PFA694E resin as available adsorption sites became increasingly occupied.

Following resin exhaustion, regeneration of the Purolite PFA694E resin was performed using an ethanol–water solution **applied using by backwashing procedure, based on regeneration approaches reported** in the scientific literature for the desorption and recovery of PFAS from ion-exchange resins. The regeneration efficiencies obtained at the Spanish demonstration site reached 33% for total PFAS, with values ranging from 21% for PFOS to 73% for PFOA. These regeneration rates were significantly lower than those observed during laboratory-scale testing, where the same ethanol–water regeneration procedure resulted in near-complete recovery of the resin adsorption capacity.

Despite the relatively low PFAS desorption efficiencies achieved during regeneration, treatment performance recovered following resin regeneration and remained consistently above 95% during subsequent batches. The regenerated resin continued to provide high PFAS removal efficiencies until replacement with fresh resin during the final stage of operation, after which near-complete PFAS removal was again achieved. These results indicate partial PFAS desorption was sufficient to restore a substantial fraction of the resin treatment capacity under the operating conditions applied.

The lower regeneration observed at pilot scale is likely related to the gel-type morphology of the PFA694E resin. Compared with macroporous resins, the smaller pore structure can hinder penetration of the regenerant solution into the resin matrix and limit access to sorbed PFAS. In addition, intraparticle diffusion limitations may reduce desorption efficiency under continuous-flow operating conditions. These factors likely contributed to the discrepancy between laboratory- and pilot-scale performance and highlighted the need for further optimization of regeneration procedures for full-scale applications.

These findings emphasize the need for further optimization of resin regeneration procedures for field applications and demonstrate the challenges associated with translating laboratory-scale performance to continuous pilot-scale operation. Alternative regeneration strategies based on alcohol–salt formulations, together with adjustments to operating conditions, may

offer opportunities to improve PFAS desorption efficiency and enhance resin recovery under pilot- and full-scale conditions (Liu and Sun, 2021).

5.2.2.3 Destruction of PFAS using EO

EO was employed as a destructive treatment step for PFAS concentrated in the waste streams generated by the treatment train, namely the foamate produced during SAFF operation and the regenerant solution generated during AEX resin regeneration. Treatment was performed using BDD electrodes configured as both anode and cathode in a 0.5 L flow cell (Figure 5-2).

During the demonstration period, approximately 15L SAFF foamate and 12L AEX regenerant solution were generated and treated by EO across several batches. Over the same period, the SAFF system processed 86.7 m^3 of contaminated groundwater, corresponding to an overall volume reduction factor of approximately 3,200 between the treated groundwater and the concentrated residual streams subjected to EO treatment.

An increase in SC-PFAS concentrations was observed during EO treatment, reflecting the formation of SC-PFAS as intermediate products generated through the degradation of LC-PFAS. This behavior is consistent with the degradation pathways described in the literature (Mirabediny et al., 2023). As oxidation treatment progressed, SC-PFAS concentrations subsequently declined, indicating their further degradation and eventual mineralization to carbon dioxide and fluoride ions, or transformation into ultra-short-chain PFAS and other fluorinated intermediates not included within the analytical scope of this study.

To evaluate the extent of PFAS degradation during EO treatment, a fluorine molar balance was performed by comparing the fluorine distribution before and after treatment. Fluoride recoveries of up to 113% were obtained, indicating near-complete closure of the fluorine mass balance. Although slightly exceeding the theoretical value, this result is attributed to analytical uncertainty and falls within the expected variability of the analytical method. Together with PFAS degradation efficiencies of up to 60%, these results support the conclusion that EO unit promoted substantial PFAS mineralization limiting the formation of unidentified fluorinated transformation products.

5.2.2.4 Performance of the LIFE SOuRCE treatment train

The integrated treatment train, combining the SAFF unit with the AEX polishing system, achieved overall removal efficiencies of **99.9% for LC-PFAS** and **92.3% for SC-PFAS** throughout the demonstration period (Table 5-2).

Table 5-2 Removal efficiencies for different treatment scenarios

Treatment	LC-PFAS removal (%)	SC-PFAS removal (%)
SAFF	70	0
AEX	89.1	89
SAFF + AEX	99.9	92.3

The results confirmed **the robustness and reliability of the integrated treatment train under real operating conditions**. Although SAFF unit exhibited limited removal of SC-PFAS, reflecting the inherent constraints of foam fractionation and the operational conditions of the Spanish demonstration system, the **downstream AEX polishing unit effectively compensated for this limitation achieving excellent removal efficiencies for the remaining SC-PFAS**. Consequently, the combined treatment train delivered consistently high overall PFAS removal performance, meeting the project objectives for groundwater remediation while supporting compliance

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with stringent environmental requirements. The successful integration of both technologies further confirmed the **suitability of the proposed treatment train for replication and large-scale deployment at PFAS-contaminated sites across Europe**.

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6 Upscaling of LIFE SOuRCE solutions

6.1 Upscaling strategy

The upscaling strategy within the **LIFE SOuRCE project** demonstrates the **technical, economic, and environmental feasibility** of transferring the developed solutions/technologies from the **pilot-scale operation** to **full-scale industrial implementation**. This approach represents a key stage in the transition from research to commercial deployment, ensuring the technologies validated under controlled pilot conditions maintain high levels of efficiency, reliability and sustainability at larger scale and under real-world operating environments.

6.2 Technical feasibility and performance indicators

The transition from pilot-scale demonstrations to full-scale industrial implementation requires a thorough assessment of technical feasibility to ensure the developed solutions achieve equivalent or improved performance under real operational conditions. This step is essential to validate the **robustness**, **reliability**, and **adaptability** of these technologies beyond the controlled environment of the pilot scale.

A comprehensive assessment of **engineering design**, **system configuration**, and **operational parameters** represents a key element in the upscaling process. Special attention is placed on evaluating the scalability of essential components, the system's performance under higher hydraulic loads and pollutant concentrations as well as the optimization of removal processes in relation to energy demand and resource efficiency.

Operational flexibility and **robustness** constitute essential aspects of the upscaling step, as they define the ability of the technology to function reliably under a wide range of variable and dynamic conditions. At industrial scale, treatment systems must demonstrate the ability to adapt to the **variations in influent quality**, **fluctuations in the flow rate**, and **a range of environmental and/or site-specific factors**, maintaining stable, predictable, and high-performance operation over extended periods. Such flexibility becomes particularly significant during **the transition from controlled pilot conditions to real-world applications**, where influent characteristics and operational parameters are seldom uniform.

Simultaneously, **advanced automation**, **process control**, and **real-time monitoring strategies** play a crucial role in large-scale implementation. **Intelligent control systems** contribute to continuous process operation and enable proactive maintenance along with efficient resource management.

A well-defined **set of performance indicators** establishes the **quantitative framework** for assessing the technical outcomes of the total upscaling process. These metrics offer objective reference points to evaluate, optimize, and benchmark system performance. Key indicators generally encompass, but are not restricted to:

- The **contaminant removal efficiency** evaluates the effectiveness and selectivity of the treatment processes, reflecting the system's ability to capture or transform target pollutants efficiently.
- **Energy efficiency, expressed per unit of treated water**, provides a key assessment of system performance. Tracking energy consumption is fundamental for evaluating operational expenditure and reducing the environmental footprint. Additionally, this

value establishes a benchmark for the comparison of alternative treatment strategies and upscaling options.

- The assessment of the **volume and characteristics of waste generated** is crucial for planning downstream management, ensuring regulatory compliance, and evaluating environmental impacts. Detailed knowledge of waste streams informs strategies for treatment, storage, and disposal.
- The **system reliability, uptime, and maintenance frequency** measure operational resilience and the level of maintenance required. High reliability and consistent up time indicate stable and uninterrupted performance whereas maintenance frequency provides insight into the resources needed for inspection, servicing and repairs.

Based on **these performance indicators**, each of the technologies in the **LIFE SOuRCE** treatment train is analyzed individually to evaluate its feasibility and potential for industrial-scale implementation.

SAFF-system demonstrated substantial scalability potential for industrial applications. A 20-foot **SAFF20** unit, equipped with two fractionation steps and internal hyperconcentrate storage, can treat 10-20 m^3/h depending on water type and PFAS-concentration. Cycle times and energy demand vary with contaminant load and water foaming potential, affecting pump operation. Operational experience indicates the units consistently achieve optimal treatment of groundwater containing **PFAS-compounds with six or more carbon atoms (≥C6)** at their designed capacities, while shorter-chain PFAS (<C6) may require longer batch cycles, causing a slight reduction in throughput. The expected volume of waste generated by the SAFF-system depends on the type of water being treated and its contamination load. Based on operational experience from previous projects, **landfill leachate** typically produces less than **1 m^3 of waste per 40,000 m^3** of treated groundwater, reflecting the system's high efficiency in concentrating contaminants. In the case of the **groundwater**, which generally contains lower contaminant concentrations, the waste volume is even smaller -approximately **10 liters per 40,000 m^3** of treated water-.

AEX-system demonstrated substantial scalability potential for industrial applications. Its **modular design and simple operation** enable flexible adaptation to different flow rates and treatment capacities, facilitating its integration into existing treatment infrastructures. The system consistently achieves efficient and simultaneous removal of both SC- and LC-PFAS compounds, such as PFOA, PFOS, PFNA, GenX, PFHxS and PFBS, meeting current regulatory requirements (non-detect or single-digit part per trillion, ng/L). Compared with GAC-systems, the AEX technology provides **higher selectivity** toward the most regulated PFAS compounds, resulting in **extended media lifespan**, **reduced replacement frequency**, and **minimal process interruptions**. Additionally, the **saturated resin** can be **regenerated using suitable organic solvents**, extending its service life and reducing notably the waste generation. In cases where **regeneration is no longer viable**, safe management can be achieved through **landfill disposal** or **thermal destruction methods**, such as incineration, which fully degrade PFAS-molecules and **prevent their reintroduction into the environment**. Many waste-to-energy facilities also recover the energy contained in the resin's organic bonds during this process, enhancing the overall sustainability of the treatment system.

PHYTO-system demonstrated limited scalability potential for industrial applications. Treating large volumes requires **extensive land areas**, leading to the **generation of PFAS-contaminated biomass**, which must be carefully managed and disposed of. In northern European countries,

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cold winter conditions affect the PHYTO-system's ability to maintain stable and consistent operation, potentially affecting overall performance. In addition, the growth rate of the plants and the seasonal variability of biomass production may limit its capacity, posing challenges for continuous year-round operation. Therefore, maintaining adequate plant care and performing regular monitoring are essential to preserve PHYTO's operational effectiveness. Despite its scalability limitations, the PHYTO-system offers outstanding energy efficiency and negligible reagent consumption, being a sustainable and environmentally attractive option.

The EO-system, designed for batch rather than continuous operation, performs **optimally under controlled conditions**, achieving **very good results at high pollutant concentrations**, with strong potential as a complementary or polishing treatment step**.** However, its efficiency tends to decrease at relatively low pollutant levels, where mass-transfer limitations reduce the effective degradation rate and extend the treatment time. Based on the literature, EO systems have achieved PFAS removal efficiencies typically ranging from **80 % to over 99 %**, depending on factors such as the electrode material, current density, batch length, and water matrix characteristics. In general, SC-PFAS are generally more resistant to degradation, while LC-PFAS such as PFOA and PFOS achieve higher removal and mineralization rates under optimized operating conditions. The technological maturity of the EO is still developing compared to the more established and reliable SAFF and AEX solutions.

6.3 Economic analysis

A comprehensive economic evaluation is an essential component of the upscaling strategy, as financial viability plays a decisive role in the long-term adoption and market potential of the developed solutions. The cost-benefit analysis provides a holistic view of the economic aspects of moving from pilot-scale operations to full-scale industrial applications, considering both direct costs and broader socio-economic impacts.

The assessment involves a detailed examination of **capital expenditures (CAPEX)**, including equipment procurement, infrastructure adaptation, installation and commissioning, as well as **operational expenditures (OPEX)**, covering energy consumption, consumables, maintenance and waste management. These parameters are compared with performance data from pilot testing to estimate expected costs on industrial scale across different operational scenarios.

Beyond direct costs, the analysis examines **indirect and long-term economic benefits** associated with implementing **LIFE SOuRCE** technologies. These include potential reductions in waste management expenses due to the production of smaller, more concentrated waste streams, decreased frequency of media replacement compared with conventional treatment systems, and cost savings stemming from improved process efficiency and automation. Additional benefits include improved regulatory compliance, reduced environmental risks, and enhanced sustainability outcomes, contributing to a stronger market presence and the potential for new business growth.

To estimate **CAPEX** for scaling up (**Table 6-1**), the costs and capacities of the pilot-scale AEX, PHYTO, and EO units are projected to industrial-scale using conservative scaling factors. Based on the costs and capacities of the pilot-scale equipment, the expected cost at industrial-scale is projected by considering the ratio between industrial and pilot capacities. On the contrary, for the SAFF unit, the prototype developed at pilot-scale is suitable for full-scale operation, and its cost is therefore directly included in the overall capital investment.

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Table 6-1 Estimated CAPEX for each unit at pilot and industrial scale

Unit	Prototype cost (€)	Estimated industrial cost (€)	Notes
SAFF	426,500	426,500	Same prototype used at full scale; pilot cost directly considered
AEX	15,000	78,300	Scale using conservative factor based on capacity increase
PHYTO	36,800	2,699,500	Theoretical values; larger surface implementation may not feasible
EO	3,250	25,000	Includes CAPEX for batch operation and buffer tank installation

The **AEX unit**, with a pilot-scale cost of € 15,000 and a capacity of 25 L/min, is estimated to require about 78,300 € at industrial scale for 20 m^3/h. Similarly, the **PHYTO unit**, which cost 36,800 € at 424 L/d, is projected to reach approximately 2,699,500 € when scaled up to 20 m^3/h. Nevertheless, these values for the PHYTO-unit are purely theoretical, as implementing a significantly larger surface area would not be practically feasible. **Assuming a bed depth of 0.4 m, the required area would be approximately 66 ha, equivalent to just over 90 football fields**.

Based on the experimental data at pilot-scale, the resulting waste fraction was approximately 0.022 % of the total treated volume of groundwater, which corresponds to around 39 m^3 of waste per year at an industrial scale. The **EO unit** operates in batch mode, optimized according to the **hydraulic retention time in the electrochemical cell** to ensure maximum treatment efficiency. To handle the industrial-scale flow, operation in batches of 500 L, similar to values described in the **pilot-scale deliverable** (*D.B.3.1. Final report on the demonstration in the Swedish site*) is required. An estimated treatment duration of 14 days necessitates the interim storage of the concentrated solution produced by the SAFF-system before EO treatment. Assuming a retention time comparable with pilot-scale, **only one buffer tank** is necessary to hold the solution and ensure a smooth, continuous workflow between the SAFF concentration and EO-system. Thus, the capital expenditure includes CAPEX for batch operation and buffer tank installation.

To estimate OPEX for scaling up, key operational parameters such as energy consumption, resin replacement frequency, and waste management costs were considered. Based on the pilot-scale performance data (~100 m^3/day, 0.13 € per m^3, reported in the *D.C.1.4. Final LCA & LCC* report) as a reference, the operating costs were scaled up to an industrial capacity of 20 m^3/h (≈480 m^3/day) through a conventional scaling model. Applying a typical cost–capacity exponent (β = 0.7–0.8), the estimated operating cost for the integrated SAFF + AEX + EO system is approximately 0.09 € per m^3, reflecting the expected economies of scale. Therefore, pilot data provided a solid basis for establishing reliable cost correlations and supporting the economic assessment of large-scale deployment.

6.4 Environmental and social impacts

The upscaling of **LIFE SOuRCE** technologies is expected to generate significant **positive environmental and social outcomes**, directly aligned with EU-policies and international commitments on **water quality**, **chemical safety**, and **sustainable development**. Scaling up these solutions will enhance water quality, reduce pollution, and promote health, innovation, and regional cohesion.

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6.4.1 Environmental Impacts

- **Improvement of groundwater quality:** The implementation of the integrated **LIFE SOuRCE** treatment system -combining SAFF, AEX, EO and PHYTO- will enable the effective removal and destruction of both LC- and SC-PFAS. This significantly lowers the risk of contaminant migration into surface waters and drinking water sources, directly supporting the objectives of the Water Framework Directive and ensuring safer water for both human consumption and ecosystems.
- **Prevention of secondary pollution:** Unlike conventional solutions such as granular activated carbon (GAC), which tend to concentrate PFAS in residual waste streams, the **LIFE SOuRCE** approach is designed to destroy contaminants or stabilize them for long-term control. This minimizes hazardous waste generation, reduces disposal requirements, and lowers overall environmental footprint of remediation activities.
- **Climate and resource efficiency:** Pilot-scale studies indicate that **LIFE SOuRCE** technologies substantially reduce energy use, chemical consumption, and water requirements compared with conventional methods. These improvements help mitigate **global warming**, reduce **ozone formation**, limit **fine particulate matter generation**, and conserve **fossil and mineral resources**, supporting the EU's transition to a climate-neutral and circular economy under the European Green Deal and the Circular Economy Action Plan.
- **Sustainable water and resource management:** The integrated approach of **LIFE SOuRCE** promotes responsible water consumption and resource management, helping to ensure long-term availability of clean water while minimizing impacts on human health and environmental quality.

Environmental impacts are assessed using the same indicators applied during the project, enabling a consistent and rigorous evaluation of energy use, emissions, water consumption, and other key metrics under realistic operating conditions. These calculations assume an industrial-scale flow rate of 20 m^3/h, corresponding to the maximum capacity of the SAFF-unit, and are based on the SAFF prototype and EO-cell from pilot studies, scaled up for full-scale operation.

Table 6-2 presents the full-scale results of these indicators for each technology (SAFF, AEX and EO); PHYTO is not considered due to its low viability over large areas.

Table 6-2 Full-scale results of key environmental indicators for each LIFE SOuRCE technology.

KPIs AT SPANISH SITE	Units	SAFF	AEX	EO
Global warming	Kg CO_2 eq emissions/ m^3 of GW treated	1.33E-01	3.03E-01	5.27E-03
Ozone formation, human health	kg NOx eq/ m^3 of GW treated	2.98E-04	5.23E-04	1.18E-05
Fine particular matter formation	kg PM2.5 eq/ m^3 of GW treated	1.29E-04	3.24E-04	5.10E-06
Terrestrial acidification	kg SO_2 eq/ m3 of GW treated	3.49E-04	7.53E-04	1.41E-05
Freshwater eutrophication	kg P eq / m^3 of GW treated	2.55E-05	9.99E-05	9.43E-07
Mineral resource scarcity	kg Cu eq / m^3 of GW treated	5.91E-04	1.76E-03	2.11E-05
Fossil resource scarcity	kg oil eq / m^3 of GW treated	3.99E-02	9.36E-02	1.58E-03
Water consumption	m^3 / m^3 of GW treated	1.86E-03	5.07E-03	7.40E-05

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6.4.2 Social impacts

Human health protection: Reducing PFAS concentrations in drinking water sources mitigates exposure to persistent and bioaccumulative chemicals, directly addressing a major public health challenge. This leads to improved health outcomes and reduced healthcare costs associated with long-term PFAS exposure.

Public trust and societal acceptance: The demonstration of effective, transparent, and safe remediation strategies enhances trust among citizens, regulators, and water utilities. Public acceptance is further enhanced through the dissemination of project results and the visible improvement of environmental quality.

Employment, innovation and skills development: The scale-up of the **LIFE SOuRCE** solutions is expected to generate new employment opportunities in the environmental engineering, water treatment, and monitoring sectors. In addition, the project contributes to skills development and enhances Europe's innovation capacity, reinforcing the EU's leadership in advanced water remediation technologies.

Replicability cohesion, and policy relevance: Successful implementation of the **LIFE SOuRCE** technologies in diverse hydrogeological contexts -such as the demonstration sites in Spain and Sweden- confirms their adaptability and scalability. This enhances their potential for replications across the EU, promoting environmental cohesion, policy alignment, and a unified European response to PFAS-pollution.

7 Recommendation for end users

1. **Site characterization**
    - Develop a comprehensive CSM including PFAS sources, hydrogeological conditions, co-contaminants, transport pathways and potential receptors.
    - Characterize the PFAS composition at the site, as treatment performance may vary significantly depending on the dominant compounds present.
    - Determine key hydrogeological and geochemical parameters, particularly hydraulic conductivity and Kd, as these strongly influence remediation efficiency.
    - Use CSM to establish realistic remediation objectives, such as source containment, mass reduction, plume control, or complete remediation.
2. **Applicability of pump-and-treat systems**
    - Evaluate the suitability of P&T systems based on the site-specific hydrogeological conditions and PFAS behaviour.
    - Consider P&T as a preferred option at sites where PFAS **exhibit low sorption and rapid desorption**, facilitating groundwater extraction and contaminant capture.
    - Assess alternative remediation strategies in **low-permeability aquifers**, where limited groundwater abstraction rates may significantly reduce P&T effectiveness.
    - Consider hydraulic barriers, *in-situ* stabilization technologies, or plume management approaches when groundwater extraction is insufficient to achieve remediation objectives.
    - Design pumping systems to maintain **hydraulic containment** (e.g., landfills) and prevent downgradient migration of PFAS-contaminated groundwater when plume control is the primary objective.
3. **Selection of treatment technologies based on PFAS profile**
    - Select **treatment technologies according to the PFAS composition and chain-length distribution** identified during site characterization.
    - Use **SAFF as a primary separation technology**, particularly at sites dominated by LC-PFAS (≥C7), where removal efficiencies of approximately 99% can be achieved.
    - Consider **AEX resins as a polishing step, especially at sites with elevated concentrations of SC-PFAS or when very low effluent PFAS concentrations** are required. During the **LIFE SOuRCE** demonstration, AEX achieved removal efficiencies above 90% for both long- and short-chain PFAS.
    - **Lower removal efficiencies** can be expected for SC-PFAS (<C7) when SAFF is operated without additives, with overall removals of approximately 60% observed during the demonstration.
    - The **addition of co-foaming agents** (e.g. Tween-based additives or cationic surfactants) can significantly **improve SC-PFAS removal**. The best-performing cationic surfactant increased SC-PFAS removal to approximately 70%, while the combined SAFF treatment train achieved projected removals of up to 85% for SC-PFAS.

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4. **Destruction of concentrated PFAS streams**
    - **Prioritize the destruction of concentrated PFAS waste streams** whenever feasible, rather than transferring PFAS to secondary waste.
    - **Combine separation/concentration technologies with destructive treatment steps** to reduce the volume of PFAS-contaminated waste requiring final management.
    - **Apply EO to high-strength PFAS streams**, such as SAFF foamate or AEX regeneration liquids.
    - **Avoid using EO directly on raw groundwater**, as the technology is less efficient at low PFAS concentrations.
    - Prevent **electrode fouling** by maintaining **pH < 7** and implementing routine monitoring for scaling.
5. **Use phytoremediation under appropriate site conditions**
    - **Do not consider phytoremediation systems as a standalone solution** when very low PFAS concentrations in the treated effluent are required.
    - Use constructed wetlands as a c**omplementary treatment step to promote PFAS retention** and immobilization within the treatment system.
    - Consider phytoremediation as a **water management tool capable of reducing treated water volumes** through evapotranspiration.
    - Ensure **land availability before selecting phytoremediation**, as large treatment areas may be required to achieve meaningful PFAS mass removal.
    - Incorporate **long-term biomass management strategies**, including harvesting and disposal of PFAS-containing plant material, into the system design.
    - Account for **seasonal variations in evapotranspiration and plant growth**, which may influence treatment performance and water balance.
6. **Optimize treatment train configuration**
    - **SAFF + AEX + EO configuration**, **high PFAS removal efficiencies** and non-detectable PFAS concentrations in the effluent.
    - **SAFF + PHYTO + EO configuration,** sufficient land availability and water volume reduction through evapotranspiration is a relevant treatment objective.
    - Evaluate **PFAS mass fluxes, expected concentrate generation, and regulatory discharge** limits during the design phase to ensure appropriate sizing of each unit.
    - **Position SAFF upstream of polishing and destructive treatment technologies** to reduce PFAS loads entering downstream processes and minimize operational costs.
    - **Integrate concentration and destruction technologies** whenever possible to reduce secondary waste generation and improve overall treatment sustainability.
7. **Practical and economic factors during technology selection**
    - Using **SAFF unit**, **large volumes of PFAS-contaminated water** require treatment with **low waste generation and relatively low operational costs**.

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- Using **AEX unit**, **stringent discharge limits or very low residual PFAS concentrations** must be achieved, particularly in applications related to drinking water production or sensitive receiving environments.
- Using **EO for the treatment of concentrated PFAS waste streams** (e.g. SAFF foamate and AEX regeneration solutions).
- Consider the **land requirements, and biomass management** needs associated with phytoremediation systems.

8. Monitoring and long-term management strategy

- **Implement a monitoring program covering PFAS concentrations** in both influent and effluent streams to verify treatment performance and regulatory compliance.
- **Monitor groundwater abstraction rates and hydraulic gradients** when pump-and-treat systems are used to ensure effective plume capture and hydraulic control.
- **Track energy consumption, operational stability, and potential electrode** scaling in EO systems to optimize treatment efficiency and maintenance requirements.
- **Monitor wetland performance**, including PFAS accumulation in vegetation and substrate, when phytoremediation systems are implemented.
- **Develop a long-term biomass management plan for phytoremediation systems**, including periodic harvesting and collection of leaves and plant material to minimize the potential re-release of accumulated PFAS to the environment.

9. Integrate environmental and regulatory considerations

- Account for the **ongoing evolution of PFAS regulations** when selecting remediation technologies, prioritising solutions capable of addressing both short-chain and long-chain PFAS.
- Evaluate the **environmental footprint of the treatment train**, including energy consumption, waste generation, and requirements for residual waste management.
- Consider **SAFF generates limited waste volumes through concentration of PFAS into foamate**, while AEX operation may produce regeneration waste streams requiring further treatment or disposal.
- **Ensure compliance with applicable local, national, and European regulations** governing PFAS concentrations in water, discharge permits, and management of PFAS-containing waste streams.

10. Engage stakeholders from the early stages of project development

- Involve **site owners, regulators, water authorities, and other relevant stakeholders** throughout project planning and implementation to facilitate decision-making and regulatory acceptance.
- Promote **early dialogue when innovative or emerging PFAS treatment technologies** are being considered.
- Establish **realistic remediation objectives**
- **Communicate expected treatment outcomes**, operational requirements, and long-term management needs to ensure alignment among all stakeholders.

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