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LIFE SOuRCE

Demonstration and evaluation of Sustainable On-site Remediation technologies for PFAS-ContaminatEd groundwater

LAYMAN report

Background

Per- and polyfluoroalkyl substances (PFAS) are a large group of several thousand synthetic chemicals widely used since the 1950s. Their appeal lies in their exceptional stability: PFAS contain extremely strong carbon–fluorine bonds and a molecular structure with a water repellent fluorinated “tail” and a hydrophilic head group. This combination makes them resistant to heat and degradation. Because of these properties, PFAS have been incorporated into countless everyday products, including non-stick cookware, water repellent textiles, food packaging, and firefighting foams.

Products Containing PFAS

However, the same characteristics that make PFAS useful also make them environmentally persistent and highly mobile. Often referred to as “forever chemicals,” they do not readily degrade in the environment and can travel long distances through soil, groundwater, and surface waters. As a result, PFAS contamination is now widespread, with detections in drinking water sources, soils, sediments, wildlife, and even remote areas such as the Arctic.

Exposure to certain PFAS has been associated with a range of health effects, including thyroid and liver dysfunction, increased cholesterol levels, weakened immune response, and elevated risks of certain cancers. Drinking water and food represent the main exposure pathways, especially for communities near industrial facilities, firefighting training areas, and landfills. Across Europe, thousands of sites are potentially contaminated, posing risks to both ecosystems and drinking water supplies.

Recognizing the scale of this challenge, the European Union has introduced stricter limits for PFAS in drinking water under Directive (EU) 2020/2184. Meeting these standards, and protecting public health, will require innovative and cost effective remediation technologies capable of addressing both long-chain and short-chain PFAS in contaminated environments.

PFAS molecules have a water-repelling fluorinated tail and a water-loving head, which makes them strongly surface-active. They gather where air meets water, and rising air bubbles can lift them into foam. The same thing happens in nature – for example when waves break and create sea foam. This property is also used in the LIFE SOuRCE project to separate PFAS from contaminated groundwater.

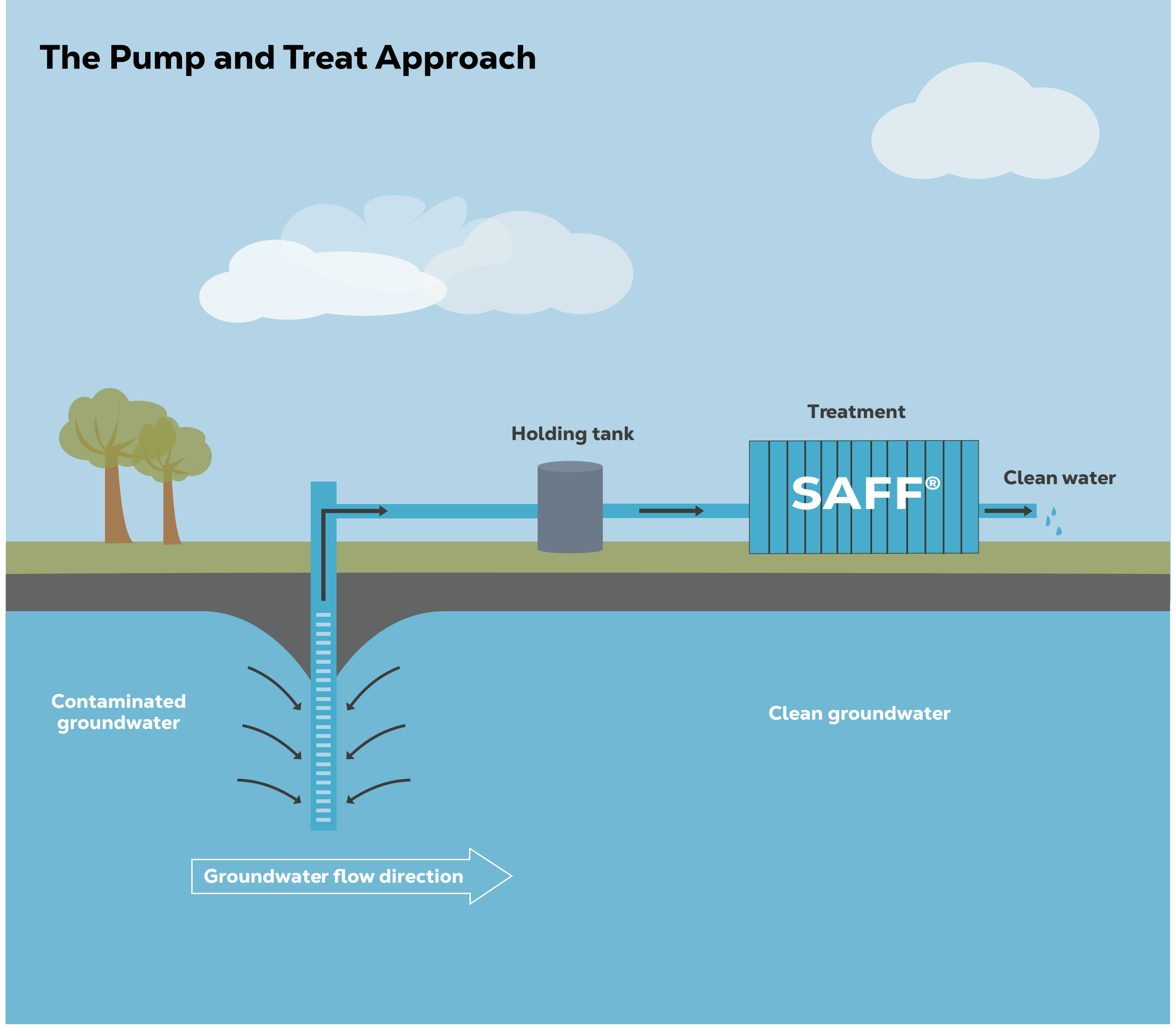
The LIFE SOuRCE project

The aim of the LIFE SOuRCE project was to demonstrate on site treatment trains for PFAS contaminated groundwater. This pump and treat solution integrated four complementary technologies – a separation step, two polishing steps, and a destruction process. The overall purpose of the project was to show that cleaning PFAS contaminated groundwater could be both effective and affordable.

Pump and treat is a well-established groundwater remediation technique widely used to manage contaminated sites. The process involves pumping groundwater to the surface through extraction wells for treatment. This process lowers the groundwater table and alters water flow in the area, causing contaminants to move toward the pumping wells.

Once the water has been treated, it can be returned to the ground or released into the environment, provided that contaminant levels are sufficiently low. The technique enables continuous monitoring of water quality and reduces the risk of contaminant spread.

The method works best in aquifers with moderate to high hydraulic conductivity and is particularly effective for quickly protecting water resources when contamination sources cannot be removed or treated on-site. In addition, the technique is well suited for contaminants that are mobile and highly soluble in water, such as PFAS.



The Pump and Treat Approach

Objectives and demonstration of treatment trains

At the start of the project, PFAS contamination was recognised as a major environmental and public health issue across Europe, especially at landfills, industrial areas, and former firefighting training grounds. LIFE SOuRCE objectives were to demonstrate treatment trains capable of removing more than 99% of long-chain and 95% of short-chain PFAS. The project sought to meet the new EU Drinking Water Directive limits of 0.1 μg/L for individual compounds (up to 20 regulated substances) and 0.5 μg/L for total PFAS—while keeping treatment costs low, at up to 0.1 €/m^3 of groundwater treated, making the solution applicable to a wide range of contaminated sites. To reach these objectives, the project demonstrated the following technologies as part of the treatment trains:

SAFF Surface active foam fractionation A physical separation and concentration process designed to remove PFAS from water through aeration, where the compounds attach to air bubbles and are lifted to the water surface as PFAS enriched foam.

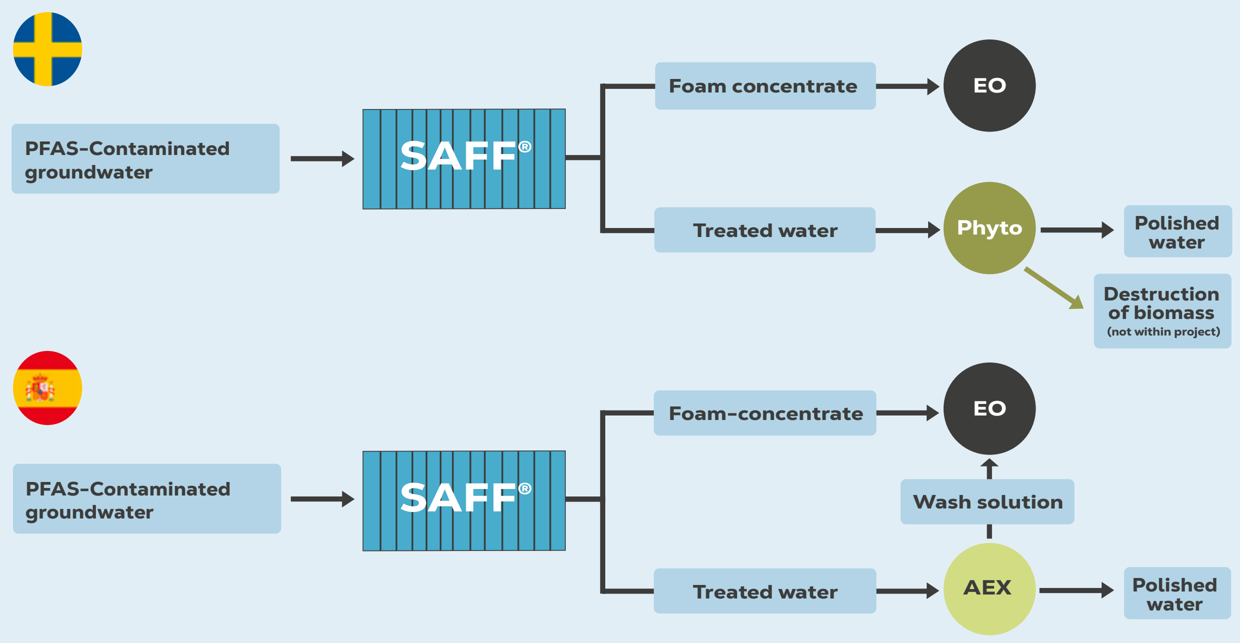
AEX Anion exchange filters A polishing step using columns packed with tailored resins to efficiently remove PFAS to non-detectable levels.

PHYTO Phytoremediation A polishing step using a subsurface constructed wetland planted with Salix (willow), designed to capture residual PFAS through plant uptake and substrate sorption.

EO Electrochemical oxidation A destruction process using boron-doped diamond electrodes to mineralise PFAS into fluoride ions (F^-) and CO_2.

These technologies were demonstrated at two different locations, a landfill in Sweden and a firefighting training site in Spain, which provided valuable insights into how well the treatment performs under different climates, soil conditions, and contamination levels. By applying the methods in such contrasting environments, it became clear how well they work and how adaptable they are when faced with real world challenges.

The demonstrated treatment trains



Swedish site

- Waste management facility
- Temperate climate
- PFAS source: landfill leachate
- 3–4 μg ΣPFAS/L groundwater
- High ionic strength and high DOC *(dissolved organic carbon)*

Spanish site

- Firefighting training site
- Mediterranean climate
- PFAS source: firefighting foam
- 0.2–60 μg ΣPFAS/L groundwater
- Low ionic strength and low DOC *(dissolved organic carbon)*

SAFF Surface active foam fractionation

SAFF (Surface Active Foam Fractionation) uses fine air bubbles to remove PFAS from contaminated water. When air is injected into the treatment columns, PFAS molecules attach to the rising bubbles and are lifted to the surface, where they form a PFAS-rich foam that can be separated and collected. This foamate then undergoes additional aeration steps, producing a very small volume of highly concentrated PFAS liquid that can be sent for permanent destruction using commercial technologies such as high-temperature combustion, or – as demonstrated in LIFE SOuRCE – treated directly on site using electrochemical oxidation.

The technology can remove up to 99.9% of long-chain PFAS, and with additives it can also achieve high removal rates for short-chain compounds. SAFF units are compact and can be installed in standard containers.

Within the LIFE SOuRCE project, a SAFF20 unit was used, with a treatment capacity of 10–20 m^3 of water per hour. In total, 28,000 m^3 of groundwater was treated at the Swedish site over eleven months, with an average energy consumption of 0.62 kWh/m^3.

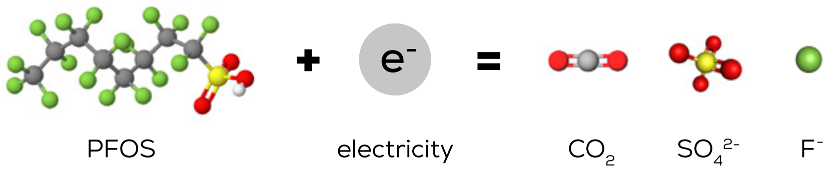
PHYTO Phytoremediation

Phytoremediation (PHYTO), the use of plants to remove pollution, was tested after SAFF treatment to enhance the removal of short-chain PFAS, which SAFF captures less efficiently. A subsurface flow wetland was built using a peat–biochar substrate planted with willow. The substrate mainly sorbed the remaining long-chain PFAS and supported plant growth, while the willows took up short-chain PFAS into their stems and leaves. With PHYTO included, total removal of 20 PFAS increased from 48% to 75%, largely because short-chain PFAS were more effectively captured.

The LIFE SOuRCE demonstration also revealed important limitations. Phytoremediation requires large land areas, as its effectiveness depends on how much water the plants can take up, making high flow treatment challenging. In addition, there is limited knowledge on how PFAS contaminated plant material should be handled after harvest. Willow leaves contain high concentrations of short-chain PFAS, and if they are not collected before leaf fall, PFAS will return to the environment. A solution to reduce this risk is to harvest the willows annually before the leaves fall. These challenges highlight that while PHYTO can improve PFAS removal, careful management is essential for safe and effective use.

The constructed wetland, shortly after being planted with willow in 2023

EO Electrochemical oxidation

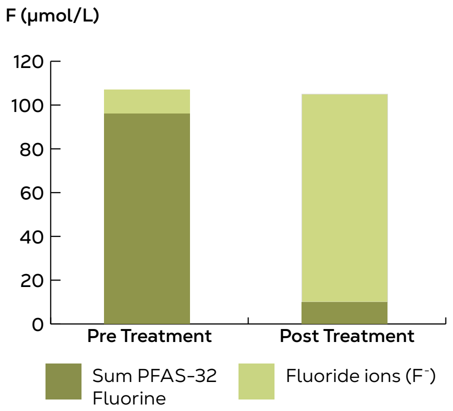


Electrochemical oxidation (EO) uses boron doped diamond electrodes to break down PFAS. When an electric current passes through the electrodes, highly reactive oxidizing radicals form on their surface. These radicals attack the PFAS molecules and split their strong carbon–fluorine bonds, converting them into harmless end products such as carbon dioxide (CO_2) and fluoride (F^-).

In the LIFE SOuRCE project, EO was used to destroy the PFAS that had been concentrated in the foam produced by the SAFF unit. Treating this highly concentrated waste stream made the process far more cost and energy efficient than treating groundwater directly. EO degraded up to 88% of the PFAS in the collected foam during the treatment period. Longer treatment times would have increased the degradation efficiency but also reduced the energy efficiency. Instead, the partially treated waste was returned to the SAFF unit for further concentration and then treated with EO again.

An immediate reduction of long-chain PFAS was seen when applying EO to the foam from the SAFF. Short-chain PFAS, however, initially increased in the treated liquid, showing that PFAS degrade sequentially, with longer chains being converted into shorter ones before these too are broken down.

Analyses of target PFAS, fluoride ions and mass balance calculations confirmed that 97–99% of the fluorine atoms from the destroyed PFAS ended up as free fluoride in the solution. This demonstrates that the carbon–fluorine bonds are fully broken during this process, and that almost all of the degraded PFAS had been completely mineralised.



AEX Anion exchange filters

Anion exchange (AEX) is a filter-based technique where PFAS are captured by special resins that attract negatively charged molecules. As water passes through the resin, PFAS bind to its surface, both through ion exchange and hydrophobic interactions, allowing clean water to flow onward. Pretreatment can be used to remove other charged substances, so the PFAS specific resin lasts longer and does not become saturated too quickly.

AEX is effective on a wide range of PFAS, including both long-chain compounds like PFOS and PFOA and more mobile short-chain PFAS such as PFPeA and PFHxA. In the LIFE SOuRCE project, removal efficiencies above 99% were achieved at the Spanish site for a total of 20 PFAS, including both long-chain and short-chain PFAS, specifically PFOS, PFOA, and PFHxA.

The performance followed three typical phases: initially, fresh resin delivered very high removal; over time, efficiency dropped as the resin became increasingly saturated; and finally, regeneration or replacement was needed to restore treatment performance. These patterns highlight the importance of maintenance routines to ensure consistently high removal rates.

Life Cycle Assessment and Life Cycle Costing

To understand the environmental and economic performance of the LIFE SOuRCE treatment trains, a full Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) were carried out using real operational data from the two demonstration sites located in Spain and Sweden. The analyses compared the LIFE SOuRCE system with a conventional treatment based on granular activated carbon (GAC), using a functional unit of 1 m³ of treated groundwater and a cradle to grave system boundary.

The LCA results showed that the environmental impacts of the treatment trains differed significantly between the two sites, mainly due to scale effects and site-specific conditions. At the Spanish site, the SAFF unit dominated impacts, not because the technology itself is inherently impact intensive, but because only a very small groundwater volume was available during the demonstration period, resulting in high impacts per cubic meter.

In Sweden, where much larger water volumes were treated and electricity is mainly supplied from renewable sources, the impacts were significantly lower. Across both sites, EO contributed only marginally to the total environmental footprint. The comparison with the GAC baseline showed that the LIFE SOuRCE at pilot scale had higher impacts per cubic meter, primarily due to limited scale and oversized equipment, factors that are expected to improve substantially at industrial scale. An industrial upscaling scenario confirmed this, showing a reduction in environmental impacts of approximately 94% when operating at full design flow.

The LCC analysis followed the same boundaries and demonstrated similar scale-related effects. The Spanish pilot exhibited a high total cost (39 €/m³) during the demonstration period because equipment costs were spread over the very small treated volume. In contrast, the Swedish pilot, treating nearly 28,000 m³ of groundwater, achieved a cost of 0.24 €/m³, already comparable to the estimated cost of GAC treatment (0.33 €/m³) while additionally enabling PFAS destruction. Scaling up the SAFF+AEX+EO treatment on-site to industrial scale would reduce treatment costs further to roughly 0.15€/m³ treated water. Across both pilots, SAFF represented the largest share of capital expenditure, while AEX (where applied) was the most cost intensive stage during operation because of resin replacement and disposal.

Overall, the LCA and LCC results demonstrate that the SAFF+AEX+EO treatment train is an effective, scalable and economically competitive solution for PFAS remediation, with strong potential for replication in industrial water treatment applications, supporting the development of safer, cleaner and more circular water management in Europe.

Human Health and Environmental Risk Assessment

Human health and environmental risks from PFAS in groundwater were assessed before and after the LIFE SOuRCE treatment trains were implemented at the two demonstration sites: 1) an industrial and agricultural area in Spain (Human Health Risk Assessment), where SAFF, AEX and EO were applied and 2) a Swedish river ecosystem (Environmental Risk Assessment), where SAFF, PHYTO and EO were used.

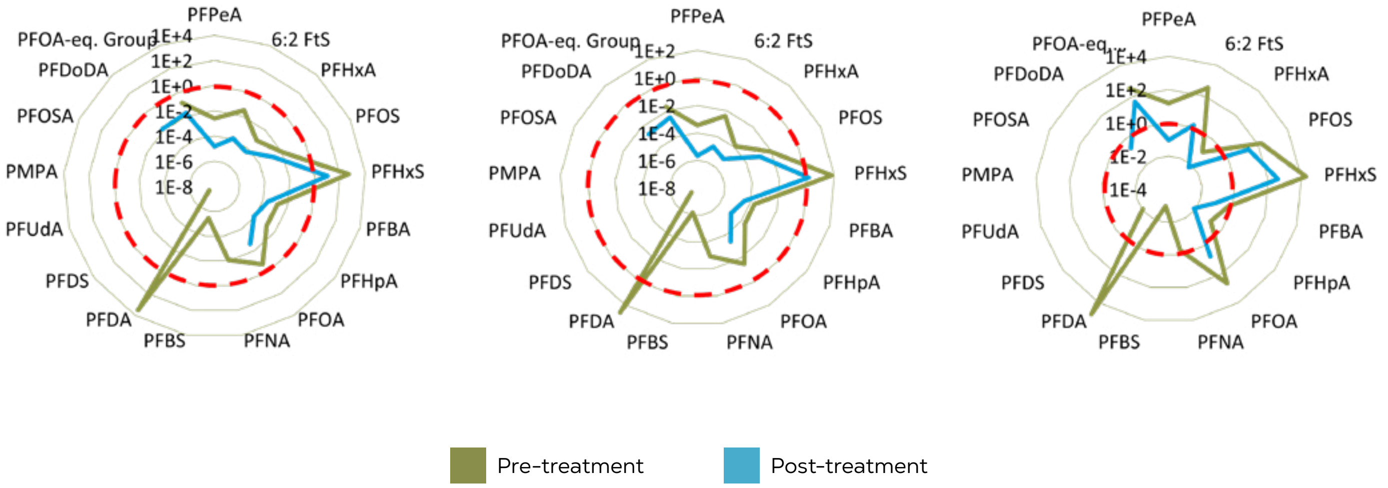
In the human health assessment, two exposure scenarios were evaluated. The first scenario addressed industrial workers who may ingest PFAS-contaminated water or experience dermal exposure during cleaning activities, such as washing equipment or vehicles. The second scenario examined two potential receptors: 1) farmers exposed through ingestion and skin contact with irrigation water and 2) the general population (divided into two groups; adults and children) who could be exposed by consuming crops (lettuce) containing PFAS as a result of irrigation with contaminated water. For this receptor, ingestion was identified as the primary exposure pathway.

For the environmental risk assessment, risks to the freshwater ecosystem in a Swedish river were evaluated.

Both demonstrated treatment trains, combining SAFF, EO, and AEX or PHYTO, significantly lowered PFAS related risks, achieving more than 98% risk reduction for human health and 52–60% risk reduction for the environment.

Risk assessment, based on PFAS concentrations in the treated water compared with groundwater concentration before treatment, showed clear risk reductions although final risk results exceed acceptable threshold values (carcinogenic risk below 1×10^{-5}, a noncarcinogenic hazard index below 1, and ecological toxicity units below 1).

In summary, the results show that the tested treatment trains are highly effective in reducing PFAS related risks in the extracted groundwater and will also be able to lower risks in downstream groundwater and surface waters when this pump and treat solution is applied at full scale. This supports the project's conclusion that the tested combinations of technologies (SAFF+AEX/PHYTO+EO) offer a scalable and competitive approach for PFAS remediation, contributing to safer and more circular water management across Europe.



Toxic risk for: Left) Scenario 1: On-site worker, Centre) Scenario 2a: Farmer, and Right) Scenario 2b: Vegetable ingestion (child). Red dashed line is acceptance threshold (Hazard Quotient, HQ=1). Note that radial axes are in logarithmic scale.

Main conclusions & future challenges

Transferability of project results

The LIFE SOuRCE project demonstrated practical and transferable solutions for cleaning PFAS-contaminated groundwater, designed to be applied at different types of contaminated sites across Europe. The flexible and modular treatment approach allows adaptation to different groundwater conditions, PFAS contamination profiles, and regulatory frameworks. The technologies were tested under real-world conditions, confirming their applicability across a wide range of sites and operational settings. As a result, the project has generated practical knowledge and guidance that enables stakeholders to apply the demonstrated treatment technologies at other PFAS-contaminated sites across Europe.

Assessment of benefits and impacts

The project has shown that technologies are available to both separate and destroy both long-chain and short-chain PFAS compounds at a reasonable cost compared to conventional treatment methods such as granular activated carbon (GAC). However, the final configuration of the treatment train depends strongly on site-specific factors such as the volume of water to be treated, the chemical composition of the influent water, and the target values that must be achieved. Beyond the technical outcomes, the project provides valuable knowledge for water authorities, site managers, and policymakers. The results support informed decision-making for groundwater remediation and contribute to EU objectives related to water quality protection and chemical pollution reduction.

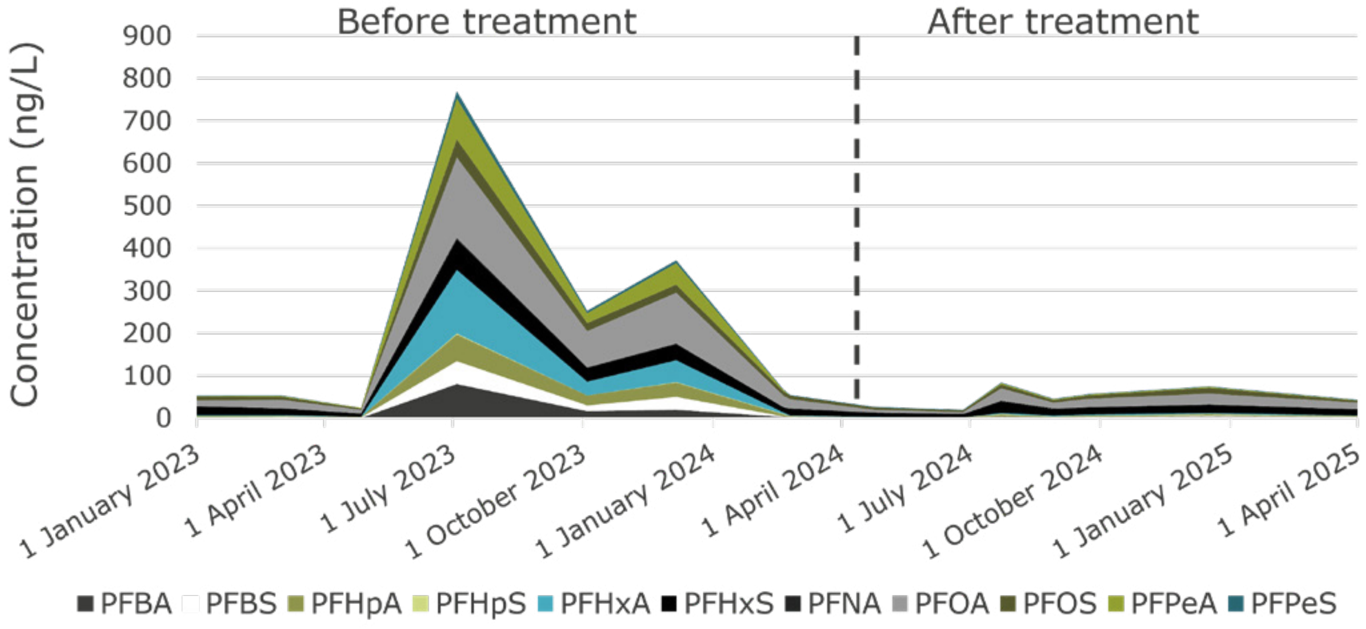
Future challenges

PFAS contamination remains a long-term challenge due to the extreme persistence of these substances and the presence of ongoing pollution sources. From a technical perspective, future efforts should focus on scaling up cost-effective and sustainable regeneration methods for anion exchange resins, which are particularly important for the removal of short-chain PFAS. In addition, the use of additives (surfactants) in the SAFF process, tested at full scale within LIFE SOuRCE, has shown potential to further enhance the removal of short-chain PFAS. This approach should be further evaluated in future studies for large scale application.

One practical limitation is that PFAS plumes can be spatially extensive, requiring very large volumes of groundwater to be extracted and treated. As a result, pump and treat solutions are generally most cost efficient when applied close to the contamination source, while treatment of large downstream plumes may be less economically feasible.

A general challenge when it comes to PFAS remediation is associated with analytical methods for PFAS, as current methods cannot yet fully detect and quantify the wide range of known PFAS, their precursors, and emerging compounds.

Finally, technical solutions must be aligned with evolving regulatory and management frameworks, which vary between regions and place additional demands on monitoring strategies, treatment targets, and implementation timelines.



PFAS concentration in groundwater downstream the implemented treatment train.

Dissemination activities

Project results have been widely disseminated to raise awareness of PFAS contamination and available remediation solutions. More than 2,000 people were reached through the project website, social media, and dissemination networks. Stakeholders were also actively engaged through webinars, meetings, and on-site events in Spain and Sweden.

One of LIFE SOuRCE one-site events at the Swedish site.

Key findings from the sites:

- **SAFF + PHYTO** achieved almost 100% removal of long-chain PFAS(≥C7) and 61% of short-chain PFAS (<C7). Additional tests with co-foaming surfactants revealed a substantial potential to increase the removal efficiency of short-chain PFAS.
- **SAFF + AEX** removed 99% of long-chain PFAS and 92% of short-chain PFAS and offers a more viable approach than SAFF + PHYTO, as resins can be regenerated, and EO can treat both SAFF concentrate and eluates from AEX regeneration.
- **EO** achieved up to 88% degradation during the deployed treatment time. Fluorine mass balance showed nearly complete recovery (97–99%), confirming that degraded PFAS were mineralized.
- **Treatment costs** for the full process are comparable to granular activated carbon (GAC), around 0.15 $€/m^3$ of treated water.

The project partners

Fundació Eurecat (project coordinator)

Envytech Solutions AB

ESOLVE Consultoría e Ingeniería Medioambiental S.L.

Laqua Treatment AB

Nova Diamant AB

Swedish Geotechnical Institute (SGI)

Swedish University of Agricultural Sciences (SLU)

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