# intersoil'2026

International Conference on Soils, Sediments and Water



**October 7 & 8, 2026**
**Barcelona Spain**

## Innovative Soil Remediation Solutions & PFAS Challenges

### Innovative Soil Remediation Solutions

• Regulatory framework - Characterisation - Risk assessment • Appropriate remediation strategies • Innovative solutions - Nature-based - Bioremediation • Existing and Emerging technologies

### PFAS Challenges

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**October 7, 2026**

**Innovative Soil Remediation Solutions**

08:00
Welcoming participants

08:45
**Chairman introduction**
The State of Soil Contamination in Catalonia and Challenges for the Future
*Lídia Ferran i Ubach, Technical Officer, Soil Contamination Management Department - ARC, Catalonia Waste Agency (Spain)*

**Moderators:**
- *Lluïsa Nadal Jaume, ARC (Catalonia Waste Agency, Spain)*
- *Joan Bartoll Navas, ARC (Catalonia Waste Agency, Spain)*

**Regulatory framework - Characterisation - Risk assessment**

09:00
From soil monitoring to remediation: Contributions and limitations of the EU Soil Monitoring Law
*Elsa Edynak, Lecturer-researcher, Coordinator for the UNESCO Chair "Soils, Biodiversity and Future Generations" - UniLaSalle (France)*

09:20
Integrating soil health into contaminated site and soil management compliant with French national methodology and the NF X31-620 series of French standards
*Virginie Derycke, Research Engineer - French Geological Survey, BRGM (France)*

09:40
Field Comparison of Contaminant and Water Mass Flux in CVOCs- and PFAS-Contaminated Sites to Effectively Build Conceptual Site Models and Design Permeable Reactive Barriers
*Dr. Janis Patiño, Remediation Solutions Specialist - Regenesis (Italy)*

10:00
Rough estimate of the soil protection potential of the CAP (Common Agricultural Policy) - Strategic Plans over the 2023-2027 period
*Adrien de Pierrepont, Director of the Sustainable Agriculture unit - Oréade-Brèche (France)*

10:20
A probabilistic model for evaluating human health and environmental risks of chemicals in advanced treated water: the Montornès case study
*Hèctor de Buen Lapena, Advanced Researcher - Fundació Eurecat (Spain)*

10:40
Coffee break

**Appropriate remediation strategies**

11:10
What monitoring data really tell us: Lessons learned from ISCO, ERD and ISCR field applications
*Lionel Counet, Project Engineer - Injectis (Belgium)*

11:30
Polymeric gel injection: A scalable solution for the in-situ degradation of Lindane
• *Arnau March i Roca, Technical Director - Geoambient-Serfim Environnement (Spain)*
• *Julien Maire, R&D and Lab Manager - Serpol-Serfim Environnement (France)*

11:50
Biogeochemical technology application for the full-scale treatment of an aquifer impacted with chlorocarbons near a salt pond ecosystem in Sardinia, Italy
*Alberto Leombruni, Technical Business Manager Europe - Evonik Operations (Italy)*

12:10
Beyond pump & treat: Aggressive in situ remediation of a historical chlorinated solvent source zone using Groundwater Circulation Wells (GCWs) at Bussi sul Tirino, Italy
*Marco Petrangeli Papini, CEO - Trireme (Italy)*

12:30
The local soil loop, a Marseille case study: Integrating soil security and robustness into climate-resilient land rehabilitation
*Hugo Maurer, Head of Regional Projects and R&D Strategy - Neo-Eco (France)*

12:50
Lunch

**Moderators:**
• *Roberto Sainz Gutiérrez, AECAS (Association of Environmental Consultancy Firms specialising in Soil and Groundwater, Spain)*
• *Carme Bosch Suades, EURECAT (Research and Technology Organization in Catalonia, Spain)*

**Innovative solutions - Nature-based - Bioremediation**

14:00
Risk based and sustainable redevelopment of a contaminated industrial site using an integrated bioremediation design
*Andrea Bianchini, Country Manager Iberia - GreenSoil International (The Netherlands)*

14:20
Selection of the best available technology for the reduction of chlorinated solvents in groundwater, based on a thorough understanding of the site, complementing remediation works with targeted monitoring
*Unai Reyes, Chemical Engineer in the Contaminated Soil - AFESA Medio Ambiente (Spain)*

14:40
LIFE InBioSoil: In-situ advanced biological treatment of the unsaturated soil zone
*Carmen Lázaro Sánchez, Researcher - Fundació Eurecat (Spain)*

15:00
Advances in the characterisation and remediation of LNAPL-contaminated sites: insights from a collaborative effort
*Jonás García-Rincón, Principal Consultant - Kepler (Spain)*

15:20
Combining whey injection and isotope verification for robust nitrate removal in polluted aquifers
*Rosanna Margalef Marti, Postdoc Researcher - Universitat de Barcelona (Spain)*

15:40
Coffee break

**Existing and emerging technologies**

16:10
New technology for monitoring the efficiency of in situ chemical oxidation (ISCO) treatments with persulfate
*Sara Herrero Martín, Scientific Project Manager & Innovation Promoter - Universitat de Barcelona (Spain)*

16:30
RED4SOLS – Short-time electrodialytic remediation of Walloon polluted soils
*Mathieu Henry, Senior Researcher and Project Manager - CTP (Belgium)*

16:50
In-situ reductive dechlorination by direct push injection of groundwater contaminated with perchloroethylene
*Rosa Enrique Márquez, Consultant - Kepler (Spain)*

17:10
Reduction of air activated carbon consumption by on-site regeneration
*Guillaume Morel, Head of Business Development, Environmental Remediation - Aircovery-Dessica (France)*

17:30
End of the first day

# From Soil Monitoring to Remediation:
# Contributions and Limitations of the EU Soil Monitoring Law

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Coordinator of the UNESCO Chair “Soils, Biodiversity and futures generations” (hosted by UniLaSalle)

The adoption of the EU Soil Monitoring Directive marks a significant step for European soil policy. For the first time, Member States are bound by a harmonised framework for assessing soil health and identifying contaminated sites. But a directive voted in Brussels is not, on its own, a guarantee that it will work on the ground, and it is this gap that this paper sets out to examine, adopting a positivist reading of the text to assess both its weaknesses and its genuine contributions to a European soil culture.

The first set of weaknesses is structural, and has little to do with soil as such. As a directive rather than a regulation, the text only binds Member States as to the result to be achieved; the form and means are left to national governments, in line with the principle of subsidiarity in environmental matters (Article 191(4) TFEU). This opens the door to the usual risks that come with transposition: it can arrive late, be reduced to a bare minimum, or remain formally compliant while practically empty – each of which chips away at the harmonisation the directive was meant to deliver.

A second, more substantive set of weaknesses lies in the text itself. Remediation goals, thresholds and technologies are left unspecified, so much of the real decision-making power falls back on national governments and local stakeholders. This is particularly striking when it comes to persistent or complex contaminants such as PFAS, where the absence of common benchmarks is keenly felt.

That said, the directive is not without merit, and this is where the paper turns to what it calls the emergence of a "soil culture" in Europe. Alongside the more familiar tools of EU environmental law, the directive breaks new ground by making awareness-raising, training and advisory obligations a structural part of its architecture, rather than the optional afterthought they were in earlier environmental texts. The work of the UNESCO Chair "Soils, Biodiversity and Future Generations" hosted by UniLaSalle offers a concrete illustration of this shift: bringing together science, training and awareness-raising across seven countries and four continents, it embodies the kind of cultural work the directive calls for but cannot, in substance, impose.

Taken together, these observations suggest that soil remediation – and soil governance more broadly – should be understood as a systemic, governance-dependent process, not simply a technical or technological one.

# Integrating Soil Health into Contaminated Site and Soil Management compliant with French National Methodology and the NF X31-620 series of French standards

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**Innovation aspect:** The originality of this work lies in adapting the soil health concept to contaminated site management, through the development of a coherent terminology and operational framework. It delivers an integrated workflow from site surveys to management decisions, explicitly designed to be compliant with detailed French regulatory standards (NF X31-620)

**Key words**: soil function, contaminated land management, soil health, operational framework, terminology and concepts adaptation

**Objective:** practical integration of soil health concepts into contaminated land management practices

**Authors:** Virginie Derycke, BRGM / Maha Chalhoub, BRGM / Maïwenn Lothodé, BRGM / Jennifer Harris, BRGM / Guillaume Grignard, EDF-TEGG / Hubert Leprond, EDF-TEGG / Catherine Baumgartner, EDF

**Abstract:**

BRGM (French Geological Survey) and EDF conducted research to integrate soil health considerations into the French national methodology for managing contaminated sites and soils, which is formalized in the NF X31-620 series of standards. This work responds to the 2021 French Climate and Resilience Law and the 2025 European Directive on Soil Monitoring and Resilience.

The adapted methodology maintains the management plan (Plan de Gestion) as the core decision-making framework while integrating soil health at three critical stages: definition of soil management objectives, scenario selection within cost-benefit analysis, and post-remediation monitoring decisions. A specialized glossary was developed to bridge soil health concepts with contaminated site terminology, introducing key terms such as pedological trajectories, key ecological functions, and soil health objectives.

The methodology proposes complementary information requirements at each study stage, following an iterative and proportionate approach. Early-stage studies include agro-pedological field observations and identification of key functions, while advanced studies incorporate detailed diagnostics and mapping of multifunctional pedological coverage zones. The enhanced cost-benefit analysis framework now evaluates remediation technique impacts on soil ecological functions.

The structured approach includes selection of key functions based on site-specific issues and regulatory frameworks, definition of pedological trajectories through historical land use analysis, and establishment of quantifiable soil health objectives with monitoring indicators. This research provides the first operational framework for integrating soil health compliant with the NF X31-620 standardized contaminated site management methodology in France.

# Field Comparison of Contaminant and Water Mass Flux in CVOCs- and PFAS-Contaminated Sites to Effectively Build Conceptual Site Models and Design Permeable Reactive Barriers

**Dr. Janis Patiño**
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**Background/Objectives**. Contaminant mass flux is increasingly recognized as a critical metric for risk assessment of contaminant migration and effective remedial designs, becoming a critical component of conceptual site models (CSMs). Traditional point measurements of contaminant concentrations are key to delineating plumes and defining the compliance of specific monitoring wells, making this data available at most sites. Consequently, first estimations of mass flux are usually obtained when multiplying the concentration by the Darcy velocity (derived from slug/pump test and hydraulic gradients). While this approach is acceptable for hydraulically homogeneous aquifers, it has been shown that even in homogeneous aquifers (conductivity variations lower than 1.5 orders of magnitude) up to 80% of the contaminant mass can move in 20% of a cross-section area.

These findings reexamine the resolution of mass flux required to construct a CSM and design an effective permeable reactive barrier (PRB). The objectives of the present study were to: (1) evaluate the relationship between groundwater flux and contaminant mass flux; (2) identify lithological characteristics associated with elevated mass flux intervals; and (3) assess the implications of high-resolution mass flux measurements for PRB design and amendment dosing.

**Approach/Activities.** Over the years, numerous methods to measure mass flux have been proposed, each with advantages and limitations. Passive mass flux devices have been evaluated in multiple studies, becoming a reliable method for providing high spatial and temporal resolution in capturing water and contaminant mass flux variations across an entire screened section of monitoring wells. In this study, passive flux meters were deployed at multiple sites impacted by CVOCs and PFAS. The resulting data were analyzed to evaluate vertical distributions of groundwater flux, contaminant mass flux, and lithology at 30 to 60 cm resolution. Two CVOC case studies were further evaluated to assess the influence of mass flux heterogeneity on CSM development and permeable reactive barrier design.

**Results/Lessons Learned.** Results demonstrate that contaminant mass flux variability can substantially exceed groundwater flux variability. Variations in Darcy velocity were generally less than one order of magnitude, while contaminant mass flux varied by up to two orders of magnitude. In several cases, more than half of the contaminant mass migrated through less than 30% of the screened interval. High mass flux zones were commonly associated with sandy units bounded by finer-grained layers, highlighting the influence of lithologic variations on contaminant migration pathways. These results were crucial in the design and final tuning of PRBs to effectively treat the contaminants of concern. More importantly, these findings suggest that even in relatively homogeneous aquifers slight variations in Darcy flux can be linked to maxima peaks of contaminant mass flux that pose a risk to the performance of PRB if not properly measured and included in design calculations.

# Rough estimate of the soil protection potential of the CAP (common agricultural policy) Strategic Plans over the 2023-2027 period

Adrien de Pierrepont, Director of the sustainable agriculture unit - Oréade-Brèche (France)

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This study presents an innovative, policy-oriented methodology to quantify the potential contribution of the EU Common Agricultural Policy (CAP) to soil health improvement over the 2023–2027 programming period. Developed within the EU CAP Network and applied to 13 CAP Strategic Plans representing a wide range of European pedoclimatic contexts, the analysis establishes a systematic link between CAP instruments (GAEC standards and interventions) and six key soil health indicators, including soil organic carbon, soil nitrogen stocks, water retention, compaction, erosion, and nitrogen losses. By combining programming data with quantitative effect coefficients from the Joint Research Centre's Farming Practices Evidence Library and national soil baselines, the study provides rough but comparable estimates of the maximum potential soil protection effects of policy measures. The results highlight the differentiated contribution of soil management, crop rotation, landscape features and organic farming practices, as well as the added value of the current GAEC framework. Beyond its findings, the study offers a transferable assessment tool for managing authorities and policymakers, supporting evidence-based decision-making and the design of more effective soil protection strategies at scale.

# A probabilistic model for evaluating human health and environmental risks of chemicals in advanced treated water: the Montornès case study

Hèctor de Buen Lapena, Advanced Researcher - Fundació Eurecat (Spain)

**Keywords:** Probabilistic risk assessment; exposure assessment; Bayesian inference; water treatment; PFAS; iPMT chemicals; human health; circular economy

**Objective:** Providing a quantitative tool to support decision-making on treated water use, accounting for performance variability along treatment trains.

**Abstract:**

Per- and polyfluoroalkyl substances (PFAS) and industrial persistent, mobile, and toxic (iPMT) compounds pose increasing risks to water quality, particularly in water reuse systems. Existing quantitative models for prioritizing contaminants and assessing exposure are largely deterministic, often overlooking variability in treatment performance across multi-barrier water treatment trains. In this work, we present a probabilistic model that integrates literature-derived parameters with site-specific data to explicitly account for uncertainty and enable flexible scenario analysis.

The framework was applied to the municipal wastewater treatment plant (WWTP) in Montornès, where effluent undergoes advanced oxidation (E-peroxone) followed by constructed wetlands before water reuse for crop irrigation. A total of 10 PFAS and 4 iPMT compounds were evaluated. Results showed that six substances consistently exceeded human health and ecosystems concentration thresholds, highlighting potential risks despite treatment.

Scenario analyses focusing on PFOS and PFOA revealed distinct controlling factors. For PFOA, inlet concentration variability had a greater influence on risk uncertainty than treatment variability. In contrast, PFOS risk remained above acceptable levels even under improved treatment conditions, driven by its low concentration thresholds. These findings underline the importance of understanding how uncertainty propagates from the treatment inlet to the outlet for reuse.

The developed model serves as a practical decision-support tool for utilities and regulators, enabling more informed management of emerging contaminants. By explicitly incorporating uncertainty, it helps identify key risk drivers, prioritize monitoring and treatment actions, and evaluate alternative scenarios, ultimately supporting more robust and transparent decision-making in water reuse systems.

# What Monitoring Data Really Tell Us: Lessons Learned from ISCO, ERD and ISCR Field Applications

Lionel Counet[2.1], Jeroen Vandenbruwane[1,] Steven De Clerk[1]

Remediation projects are often evaluated based on the evolution of contaminant concentrations. However, field experience consistently shows that concentration trends alone rarely tell the full story. Behind every dataset lies a complex interplay of chemical reactions, biological processes, and site-specific constraints that ultimately control treatment performance.

This presentation is based on four remediation projects targeting chlorinated solvents, combining in situ chemical oxidation (ISCO), enhanced reductive dechlorination (ERD), and in situ chemical reduction (ISCR) using zero-valent iron (ZVI). Rather than focusing solely on results, the objective is to explore what monitoring data truly reveal about subsurface processes—and how these insights can improve remediation strategies.

Across these projects, monitoring data highlight recurring patterns. In reductive treatments, decreases in parent compounds such as TCE are frequently accompanied by the temporary accumulation of intermediate products, reflecting active but incomplete degradation pathways. The gradual appearance of ethene confirms that complete dechlorination can be achieved, although often later than expected. At the same time, the data reveal limiting factors that are not always visible at the design stage, such as the persistence of competing electron acceptors like sulfate, which can significantly influence treatment efficiency.

In ISCR applications using zero-valent iron, the monitoring results illustrate the coexistence of abiotic and biotic processes, creating conditions that both directly reduce contaminants and stimulate biological activity. This dual behavior adds complexity to data interpretation but also opens opportunities for more robust treatment strategies.

ISCO projects, on the other hand, demonstrate the ability to achieve rapid concentration reductions, particularly in well-contacted zones. However, monitoring data also reveal the limitations of oxidation-based approaches, especially in heterogeneous formations where distribution and oxidant demand strongly control performance. Changes in pH, redox conditions, and by-products provide valuable clues to understand these dynamics.

A key lesson emerging from these case studies is that the presence of injected reagents does not necessarily translate into effective treatment. Distinguishing between what is injected, what is accessible, and what is actually reactive in the subsurface is essential. Monitoring parameters such as DOC, VFA, redox indicators, and degradation products provide a much more reliable picture of ongoing processes than concentrations alone.

Ultimately, these projects highlight that successful remediation relies not only on selecting the appropriate technology, but also on the ability to interpret field data and adapt strategies accordingly. Monitoring is not just a validation tool—it is a decision-making tool that helps bridge the gap between design assumptions and field reality.

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# Polymeric Gel Injection: A Scalable Solution for the In-Situ Degradation of Lindane

**Authors:**
**Arnau March i Roca**: Technical Director at Geoambient, SL (Serfim Environnement)
**Julien Maire:** R+D and Lab Manager at SERPOL (Serfim Environnement).

**Abstract:**

The application of polymeric gels has emerged as a frontier in environmental engineering, offering a uniform and predictable methodology for treating persistent organic soil pollutants. Unlike traditional aqueous remediation fluids, gel-based systems provide higher viscosity and shear-thinning behavior allowing them to be less sensitive to soil anisotropy and gravity, ensuring homogeneous in-situ delivery and prolonged contact time.

An on-site pilot study is being conducted in Spain, focusing on the structural design and optimization of these hydrogel carriers, specifically regarding their ability to degrade persistent organic pollutants. The efficacy of these engineered gels in the degradation of Lindane (γ-HCH) mobilization and degradation is carried out in a heterogeneous, non-saturated soil.

Despite high static viscosity, the shear-thinning behavior of the gel allows for injection at very low pressures. Furthermore, the gel propagated evenly in all directions, with radii of influence exceeding several meters. Gel propagation can be accurately monitored and predicted using electrical resistance tomography (ERT).

Injecting the reagent in a single application as a gel enables homogeneous distribution and sustains its presence for several months, ensuring the contact time required to degrade 90+% of the adsorbed pollution within only one month, as confirmed by core sampling. Soil vapor extraction is also integrated into the pilot to assess the elimination of formed chlorobenzenes by vacuuming the affected zone.

We can conclude that gels serve as highly effective vehicles for the in-situ delivery of reagents. The synthesis of these findings demonstrates that the strategic use of gels provides a predictable, scalable framework for addressing Lindane. This approach—refining material science to enable superior chemical degradation—represents a significant shift toward sustainable and controlled in-situ soil restoration.

The keynote will also feature returns of experience of gel on other pilots with similar strategies (reagent delivery) or to serve other purposes (organic phase mobilization and extraction).

**Keywords:**

Lindane, Polymeric Gels, In-situ Remediation

# Biogeochemical Technology Application for the full-scale treatment of an Aquifer Impacted with Chlorocarbons near a salt pond ecosystem in Sardinia, Italy

**Alberto Leombruni** (alberto.leombruni@evonik.com)
(Technical Business Manager, Evonik Operations GmbH Filiale Italiana, Assago Italy)

**Background/Objectives.** The site is in a highly and historical industrialized area of Italy where groundwater is contaminated with a large dilute plume including tetrachloroethylene (PCE; >10 ppb), trichloroethylene (TCE; >10 ppb) and, to a lesser extent, dichloroethylene and vinyl chloride (<1 ppb). The target area is up to 14000 $m^2$ with a typical vertical interval of approximately 13 m bgl. The aquifer presented challenges in terms of contaminant distribution and permeability due to the presence of silty-clay layers that made the saturated soil very heterogenous. Little DHC microbial activity has been detected occurring naturally in groundwater along with a high natural content of sulphate in solution. Moreover, low remedial goals along with a rapid treatment timeline made this site a challenge. After a detailed assessment, the ELS™ Microemulsion technology (ELS®) was selected as the preferred remedy. ELS® deploys Enhanced Reductive Dichlorination (ERD) mechanisms for treatment of impacted groundwater and, it is comprised of a controlled-release food-grade carbon in the form of lecithin. ELS® is specially designed for easy on-site handling and addition to the subsurface via existing wells, hydraulic injection networks, or direct push technology.

**Approach/Activities.** In 2024, full-scale was successfully performed in the contaminated aquifer showing rapid and full treatment of the chlorinated mass. Application of the ELS™ Microemulsion remedial reagent was performed via direct push DPT injection system in approximately 500 injection points distributed in a triangular grid mode in the most impacted areas nearby a salt pond ecosystem. Treatment interval was in the shallow aquifer between 2 m and 15 m b.g.l. where a grey clay layer represents the bottom.

**Results/Lessons Learned.** Less than 24 months after injection into the main contaminated areas, concentrations of PCE and TCE contaminants were rapidly reduced up to 95% in the main monitoring locations compared to pre-treatment levels. Main field parameters in the ERD treatment areas included: i) increase of Mn & Fe(II) in solution as anaerobic cometabolites, ii) decrease of DO (mg/L) and sulphate (mg/L) – competing electron acceptors pH stable in the neutral range, and iii) negative Redox around -150 mV. These conditions along with black precipitates as FeS confirmed also ongoing biogeochemical treatment. Consequently, no substantial accumulation of daughter products such as DCE and VC has been observed. Site-specific remedial target values were reached in most of the main monitoring piezometers of the treatment areas.

# Beyond Pump & Treat: Aggressive *in situ* Remediation of a Historical Chlorinated Solvent Source Zone Using Groundwater Circulation Wells (GCWs) at Bussi sul Tirino, Italy

Marco Petrangeli Papini, Paolo Ciampi, Bruna Matturro, Simona Rossetti – Trireme Srl
Ernst Bartsch, Eduard Alesi, Damiano Feriaud – IEG Technology GmbH
Andrea Del Frate, Giuseppe Giuva – Edison Regea

Historical chlorinated solvent contamination often remains trapped for decades within heterogeneous aquifers, where conventional Pump & Treat systems mainly provide hydraulic containment while leaving secondary source zones substantially untouched. The former chloromethanes production area at the Bussi sul Tirino National Priority Site (Italy) exemplifies this challenge, with persistent high concentrations of chlorinated solvents distributed across a complex alluvial aquifer impacted by more than 100 years of industrial activity.

This work presents the design and implementation of an innovative pilot-scale remediation system based on Groundwater Circulation Wells (GCWs), conceived not simply as a containment measure, but as an aggressive in situ source-zone remediation strategy. The approach is specifically aimed at mobilizing and removing contaminant mass from low-permeability domains and vertically distributed residual source areas through induced groundwater recirculation.

The pilot was developed through the integration of high-resolution site characterization tools, including long-term hydrochemical datasets, detailed geological reconstruction, GIS-based 4D geodatabase development, and Membrane Interface Probe (MIP) investigations used to identify the geometry and intensity of persistent chlorinated solvent accumulations. The resulting conceptual site model supported the data-driven design of a seven-well GCW hexagonal array capable of generating overlapping circulation cells across the most contaminated portion of the aquifer.

Each GCW is configured with multiple screened intervals to allow adaptive manipulation of vertical hydraulic gradients and optimization of contaminant flushing during operation. External treatment combines compact vacuum stripping and activated carbon adsorption prior to groundwater reinjection. The pilot also integrates multilevel groundwater monitoring and borehole ERT imaging to assess hydraulic performance and contaminant mobilization dynamics.

The project highlights the potential of GCW systems as a sustainable and scalable alternative to traditional containment-oriented remediation approaches for complex chlorinated solvent source zones, particularly in historically contaminated industrial sites characterized by strong geological heterogeneity and persistent secondary contamination sources.

The pilot test is currently under construction, and completion and start-up of the system are expected by mid-October 2026. During the conference first result from base line will be presented along with information on the realization of the plants.

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**The Local Soil Loop, a Marseille Case Study:**
**Integrating Soil Security and Robustness into Climate-Resilient Land Rehabilitation**

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**Innovation:** This contribution introduces the Local Soil Loop (LSL), an operational paradigm developed and field-tested in Marseille that closes the gap between soil security science and the procurement, regulatory and large-scale logistics realities of brownfield rehabilitation. Its novelty lies in combining three building blocks rarely articulated together in remediation practice. The first block is the operationalization of the five-dimensional soil security framework, encompassing capability, condition, capital, connectivity and codification, inside a real urban regeneration program. The second block is a territorial-metabolism-based approach that turns excavated materials, mineral by-products and composts into engineered functional soils through short circular loops. The third block is an adaptive governance scheme structured as a Living Lab connecting public authorities, industry and civil society. The approach reframes remediation as a regenerative process embedded in long-term territorial strategies, rather than a stand-alone end-of-pipe operation.

**Keywords:** Soil security; Local Soil Loop; circular economy; pedological engineering; Living Lab; robustness; brownfield rehabilitation; Mediterranean climate.

**Objectives:** The work pursues four objectives. The first is to establish soil security as a central objective in brownfield rehabilitation and climate-resilient planning. The second is to address paradigm gaps that prevent the translation of multidimensional soil knowledge into decision frameworks, currently constrained by siloed diagnostics and conventional procurement practices. The third is to propose the LSL as a practical paradigm to shorten material loops, minimize rebound effects and embed soil regeneration in long-term territorial strategies. The fourth is to identify four work streams that turn this paradigm into practice, namely robustness-first planning, territorial metabolism to map stocks and flows, pedological engineering of stratified technosoils and amended in situ soils, and governance innovation through Living Lab mechanisms and adaptive contractual tools.

**Targeted tracks:** The contribution targets two tracks of the conference. Track 1 on Regulatory and Institutional Frameworks for Soil Remediation is addressed by the way the Local Soil Loop reshapes procurement practices and regulatory dialogue around urban soils. Track 7 on Strategies for Complex, Deep or Large-Scale Remediation Projects is addressed by the technical, logistical and economic lessons drawn from a coordinated, metropolitan-scale rehabilitation program.

## Introduction

Degraded urban land and climate extremes expose a persistent blind spot in remediation and planning, namely the lack of operational frameworks for soil security. Soils are nested socio-ecological systems, where human and ecological dynamics co-evolve through feedbacks across scales. Yet current remediation practices still treat soils as inert media, separating contamination management, geotechnics and landscape design. This fragmentation generates rebound effects that undermine climate benefits. The Local Soil Loop (LSL) is proposed as an operational paradigm to restore soils through short, circular and context-driven material cycles. Inspired by integrated water-cycle policies, the LSL is research-based and couples pedological engineering, circular resource management and adaptive governance. Rooted in ongoing projects in Marseille (France), the case study demonstrates through pilot testing how soil robustness can be designed as a precondition for resilience, aligning remediation strategies with climate adaptation, ecosystem restoration and territorial circularity. The project shows how Living Lab methods, funded by the European Commission and national agencies, can accelerate implementation by fostering collaboration across pilot sites and stakeholder networks. The relevance for Intersoil Barcelona is twofold. The work directly informs Track 1 by demonstrating how regulatory and institutional frameworks for soil remediation can evolve to recognize soil

functions and circular sourcing. It also informs Track 7 by documenting the technical, logistical and economic challenges of complex, large-scale rehabilitation projects coordinated across multiple urban sites.

## Methods

Robustness forms the keystone of the LSL methodology, guiding all technical and organizational decisions. Rather than seeking fixed optima, the approach defines dynamic ranges of soil functionality resilient to climatic and logistical variability. Two main methodological pillars support this paradigm. The first pillar is territorial metabolism, which quantifies and spatially organizes local material and energy flows to design short, circular loops, supported by an upstream metropolitan survey of excavated soils, sediments, mineral by-products and composts available for formulation. The second pillar is the Living Lab method, which creates transdisciplinary spaces where scientists, engineers and practitioners co-develop soil formulations and governance tools. Together, these frameworks operationalize a systemic, context-driven approach to soil regeneration and climate-resilient land rehabilitation, articulating site-scale remediation decisions with metropolitan-scale material strategies. This integration challenge is precisely the focus of Track 7 on complex and large-scale projects.

## Results

Preliminary results from the Marseille Living Lab demonstrate that implementing the Local Soil Loop generates significant operational and ecological benefits. The approach reduces logistics intensity and carbon footprint by promoting local reuse of excavated materials and minimizing off-site transport, while maintaining full regulatory compliance through controlled on-site formulation and targeted pre-amendment, an outcome of direct relevance to Track 1 on regulatory and institutional frameworks. Functional soils have been successfully established under Mediterranean drought to deluge regimes, showing measurable gains in unsaturated hydraulic conductivity, available water capacity and structural stability without inducing hydromorphy. The inclusion of reactive clays, in particular rich smectitic and illitic fines, has accelerated organo-mineral bonding and carbon stabilization, enhancing early microbial activity and aggregate resilience. These outcomes validate the potential of circular-economy sourcing strategies that prioritize locally available sediments, mineral by-products and composts within controlled quality ranges. Beyond technical results, the LSL has strengthened project governance by fostering collaboration across soil, water and remediation disciplines through shared clausebooks and adaptive design reviews. Although rooted in the Mediterranean and European institutional context, the Marseille experience provides a transferable methodological framework for other territories seeking to couple soil regeneration and climate resilience. These results have also been shared with the international remediation community at the NICOLE Spring Workshop 2026, entitled "Strategic revitalisation of megasites: innovative soil reuse and adaptive land transformation" (Bagnoli, Italy, April 2026), and at the Battelle 14th International Conference on Remediation of Chlorinated and Recalcitrant Compounds, session "Climate Resilience and Site Remediation" (Fort Worth, USA, May and June 2026). Both events were explicitly framed by the entry into force of the European Soil Monitoring Law on 16 December 2025. Ongoing research continues to refine performance indicators, monitoring protocols and governance tools to support broader replication of this approach.

## Conclusions

Integrating soil security through the Local Soil Loop reframes remediation as a regenerative process where robustness precedes resilience. The four operational axes, namely robust planning, territorial metabolism, pedological engineering and adaptive governance, translate soil science into decisions that reduce environmental rebounds and co-optimize soil and water functions. The Marseille Living Lab illustrates that collaborative, circular and context-driven soil rehabilitation can restore ecosystem

services, reduce carbon intensity and build territorial capacity. Scaling this approach across Mediterranean cities will require expanded monitoring, refinement of functional thresholds and formal integration into public procurement frameworks, ensuring that urban soils are recognized and governed as living infrastructures for climate-resilient regeneration. The contribution to Intersoil Barcelona aims to bring this experience into dialogue with Spanish and European peers facing comparable challenges of complex, deep or large-scale remediation in dense, climate-stressed urban contexts.

## Partners and funding

The Marseille Living Lab is structured around two complementary research programs co-funded by the French Environment and Energy Management Agency (ADEME), which also provides scientific and technical advisory support throughout the program. The first program is FrichEco, supported by ADEME under the GESIPOL call for proposals, focused on the formulation of constructed soils through circular economy methods. The second is APPLLEX, supported by ADEME under the GRAINE call for proposals as part of the France 2030 plan, structuring an inter-territorial Living Lab on soil health between the Lorraine and Aix-Marseille-Provence regions.

**Academic laboratories.** The consortium mobilizes Aix-Marseille University with the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE) for pedology and mineralogy, the BRGM (French Geological Survey) for applied geosciences and excavated soil management, the Groupement d'Intérêt Scientifique sur les Friches Industrielles (GISFI) and the University of Lorraine for technosol research, and the INRAE Laboratoire Sols et Environnement (LSE) for soil functioning and trajectories of constructed soils.

**Institutional stakeholders.** EPA Euroméditerranée as the public project owner of the pilot site at the Aygalades Park, the Aix-Marseille-Provence Metropolis, the City of Marseille, the SOLEAM as urban developer, the Sud Region for regional anchoring and environmental policies, and the Marseille Major Sea Port as a key territorial stakeholder.

**Industrial partners.** Bronzo Perasso, a quarry and concrete operator hosting the ex situ pilot platform in Aubagne, the Société des Eaux de Marseille (SEMM) supplying potabilization silts from the Durance River as a source of reactive clays and organic matter, Poterie Ravel providing pure clay fines from production offcuts, and local green waste composting operators.

**Civil society.** Engagement is structured through the Association du Talus, an organization developing urban agriculture on brownfield sites, and through the network historically built around the Cité de l'Agriculture initiative.

## Author

***Long version***

Hugo Maurer is Director of Strategy at Neo-Eco, a French engineering and consulting company specialized in circular economy solutions, where he leads interdisciplinary R&D and innovation projects connecting soil restoration, circular economy and urban resilience. He is currently pursuing a PhD with Neo-Eco and Aix-Marseille University, focusing on the development of the Marseille Living Lab and the deployment of the Local Soil Loop paradigm for regenerating degraded urban lands. Holding a Master's degree from Sciences Po Paris (School of International Affairs), Hugo combines technical expertise with a deep understanding of political and institutional dynamics. His career bridges science and practice, both in France and abroad, to design integrative solutions for sustainable territorial transformation. At the European level, he serves as a leader within the NICOLE Emerging Talent Group (ETG) and SuRF France network. He is also a co-founder of the "Circular Economy and Sustainable Remediation" working group under NICOLE Latin America, fostering international collaboration on soil circularity and environmental innovation.

***Short version***

Hugo Maurer is Director of Strategy at Neo-Eco and PhD researcher leading the Marseille Living Lab on soil regeneration. His work develops the Local Soil Loop paradigm linking circular economy and soil resilience. He is also a leader within NICOLE Europe's Emerging Talent Group and co-founder of the "Circular Economy and Sustainable Remediation" initiative under NICOLE Latin America.

# Risk based and sustainable redevelopment of a contaminated industrial site using an integrated bioremediation design

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**Background/Objectives**
Historical activities of a multinational automotive company in Venray (The Netherlands) resulted in significant soil and groundwater contamination across an 8-ha site. Two main source zones containing chlorinated solvents (cVOCs) and TPH were identified, alongside more widespread heavy metal contamination. Approximately 125,000 $m^3$ of soil was impacted by cVOCs, with concentrations exceeding 10% of PER solubility.
A pump-and-treat (P&T) system had operated for years as a hydraulic containment barrier but removed little contaminant mass, as source areas beneath buildings remained untreated. Monitoring indicated potential lateral plume spreading within site boundaries.
Redevelopment plans were stalled due to regulatory concerns about off-site migration, uncertainties regarding subsurface conditions, and significant liability risks. Remediation had to be integrated with building demolition and asbestos removal, further increasing complexity.

**Approach/Activities**
To break the deadlock, GreenSoil assumed full environmental liability under a lump-sum contract covering demolition, asbestos removal, and comprehensive soil and groundwater remediation.
Source areas were excavated to 4 m below ground level and treated off-site. An in-situ groundwater remediation system was then installed, based on recirculation filters (extraction and injection wells), designed to function beneath future buildings. Extracted groundwater was amended with GreenSoil's carbon substrate (Dehalo GS™) and reinjected to stimulate enhanced anaerobic biodegradation, effectively creating a large in-situ bioreactor.
A bio-barrier was installed along the site boundary to prevent plume migration. The entire remediation infrastructure was constructed underground, allowing rapid site preparation and uninterrupted redevelopment.
Liabilities were partially transferred to Bodem Beheer Nederland after achieving predefined remediation targets, ensuring long-term plume monitoring and risk control.

**Results / Lessons Learned**
Through proactive risk transfer, integrated design, and LEAN planning, the site was redeveloped quickly and cost-effectively. The property was handed back to the client within five months, enabling immediate construction activities. Active remediation was completed in three years, and subsequent monitoring confirmed long-term performance. The full remediation process was finalized in 2025.
This case demonstrates how combining risk management, technical innovation, and redevelopment planning can transform a complex contaminated site into a successful and sustainable remediation project.

Our case strongly demonstrates how the planned redevelopment of the site drove the remediation strategy:

- The remediation was fully integrated with demolition and new construction.
- An underground remediation design was developed specifically to allow new warehouses to be built during in-situ treatment.

- Risk transfer and liability management were structured to enable rapid site sale and redevelopment.
- The solution balanced regulatory concerns, plume control, and commercial redevelopment needs.

The project is essentially a redevelopment-driven remediation design

# Selection of the best available technology for the reduction of chlorinated solvents in groundwater, based on a thorough understanding of the site, complementing remediation works with targeted monitoring

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The technical approach to reducing chlorinated compounds in water has evolved in the recent past, and traditional mechanical extraction methods (e.g., pump & treat or MPE) have been totally or partially replaced by more innovative approaches with lower environmental impact. In particular, many conventional environmental issues are currently being addressed using biological methods.

From the point of view of their behaviour in the aquatic environment, chlorinated solvents are classified as DNAPL (Dense Non-Aqueous Phase Liquids), as their densities are higher than that of water (1 kg/L). They form fluids denser than water that tend to sink until reaching an impermeable lithological layer, which prevents further vertical migration due to gravity, creating zones of free-phase accumulation (where present).

On the other hand, environments characterized by fractured rock present complex approaches for removing groundwater contamination, often reducing the likelihood of success.

In this context, a hydrogeological study of the site was carried out with the aim of gaining a deeper understanding of the medium through specific tests, in order to adapt the remediation technique to the site's complexity. Fieldwork included a topographic survey of all site piezometers, sampling and analysis of soil samples, and a series of in situ tests (Lefranc, Lugeon, and slug tests, as well as pumping and recovery tests). This analysis made it possible to determine the differing hydrogeological behaviour of the identified layers and to confirm the key role of the fractured basal limestones, where contamination is concentrated and through whose fractures the main groundwater flow occurs.

Based on the above, ISCR + EAD was considered the best viable alternative to improve the site's environmental condition, through the injection of the selected products into newly constructed piezometers. TCE and DCE can be degraded both biologically and abiotically; however, the abiotic (chemical) process does not produce chlorinated by-products (particularly VC) and is faster than the biological pathway. VC, on the other hand, can only be degraded biologically. Based on these considerations, an integrated treatment (chemical and biological) was proposed, as it would reduce TCE and DCE concentrations while minimizing VC production, and simultaneously enable the biological degradation of VC.

For the injection works, 83 piezometric wells were installed, into which the products were injected. Biochemical processes occur in groundwater that temporarily modify its biological and chemical characteristics. Therefore, in order to gain a better understanding of the biochemical reactions occurring during the intervention, and to verify that the appropriate processes are taking place, in addition to the biannual groundwater sampling and laboratory analysis of target compounds, further monitoring is being conducted for nitrates, sulphates, Fe, Mn, organic matter, redox potential, pH, and bacterial populations. The latter is assessed through NGS 16S metagenomic analysis in the laboratory.

The detailed understanding of lithology and hydrogeology has made it possible to design the project to ensure that the entire contaminated saturated zone is effectively treated. Furthermore, 18 months after reagent injection, data obtained from post-injection monitoring

and control have provided indirect information that helps to better understand the chemical and biological processes occurring in the subsurface. This strong monitoring has recently been improved by applying compound-specific isotope analysis at selected wells.

Thanks to these insights, the remediation is achieving target values that are even more stringent than those initially proposed, with degradation rates in some cases exceeding 95%.

# LIFE InBioSoil: In-situ Advanced Biological Treatment of the Unsaturated Soil Zone

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**Keywords:** In-situ bioremediation, injection, biostimulation, bioaugmentation, petroleum hydrocarbons, vadose sone.

Petroleum hydrocarbon soil contamination represents one of the major environmental challenges in Europe, since soil is considered a non-renewable resource. Traditional remediation approaches, such as landfilling, thermal desorption and in-situ chemical oxidation, are often costly, energy-intensive, and disruptive to soil functioning. In situ bioremediation, which relies on microbial abilities to degrade contaminants, offers a low-cost and environmentally sustainable alternative. Compared to ex-situ strategies, this approach avoids the need for excavation and transportation, reducing both environmental and economic impact, while preserving soil structure and safeguarding the integrity and functionality of soil ecosystem services throughout and after the remediation process.

In this context, the LIFE InBioSoil project proposes an in-situ advanced biological treatment of the unsaturated soil zone through bioaugmentation and/or biostimulation, carried out via low-pressure slurry injection. The slurry composition, comprising biostimulants and/or fungal enrichments, is selected and validated through in-house assays and laboratory feasibility studies under predicted optimal conditions. The effectiveness of the amendments in petroleum hydrocarbons degradation is evaluated through a multi-parametric approach based on detailed characterization of the contaminated site and matrix. At laboratory scale, residual TPH (Total Petroleum Hydrocarbon) concentrations are monitored alongside microbial community evolution, assessed through community characterization and quantification of fungal and bacterial hydrocarbonoclastic activity.

The results obtained from the laboratory scale test will allow the on-site implementation of the treatment through low-pressure injection of the selected amendments and/or inocula in the vadose zone. Overall, through the presented activities, the LIFE InBioSoil project aims to demonstrate the scalability and feasibility of site-specific in-situ bioremediation treatments.

# Advances in the characterisation and remediation of LNAPL-contaminated sites: insights from a collaborative effort

Jonás García-Rincón, Evangelos Gatsios, Robert Lenhard, Estella Atekwana, Ravi Naidu

Keywords: Entrapped and Residual LNAPL; LNAPL Transmissivity; Multiphase Flow Modelling; Natural Source Zone Depletion; Petroleum Hydrocarbons.

## INTRODUCTION

Understanding of the fate and transport of light non-aqueous phase liquids (LNAPLs) has improved over the years. Numerous site investigation and remediation technologies have been developed to overcome limitations associated with conventional approaches and manage LNAPL sites in a more efficient and sustainable way. Nevertheless, it often takes a long time for novel concepts and strategies to be incorporated into regulatory frameworks and the standard practice of contaminated land professionals. The authors were engaged by the imprint Springer to complete a book giving visibility to advances in the characterisation and remediation of petroleum-impacted systems, as well as pertinent concepts and methods that may still not be broadly acknowledged by the remediation industry internationally.

## METHODS

The open access book entitled 'Advances in the Characterisation and Remediation of Sites Contaminated with Petroleum Hydrocarbons' was prepared as a contributed volume involving the participation of more than 100 global experts. Chapters 1–6 analysed the fate and transport of petroleum hydrocarbons in the subsurface, chapters 7–11 focused on site characterisation tools, and chapters 12–18 discussed site management strategies. Potential future lines of research and development as well as best practices providing guidance to contaminated land practitioners were presented throughout the book. An analysis of the book contents yielded general insights into the state of the art regarding the investigation and in-situ remediation of LNAPL-contaminated sites.

## RESULTS AND DISCUSSION

LNAPL fate and transport were determined to be largely controlled by multiphase flow mechanics intrinsically linked to natural source zone depletion (NSZD) phenomena and other biological processes as well as the spatial and temporal variability of multiple subsurface properties. Most site characterisation methods presented in the book (from direct sensing technology and biogeophysics to molecular biological tools or compound specific isotope analysis), as well as the management strategies described (including monitored NSZD, bioremediation, high-energy injection of carbon-based amendments, or implementation of low-temperature thermal systems), addressed factors sometimes overlooked in conventional investigation and remediation projects such as: (i) the presence of residual and entrapped LNAPL, (ii) the role of biodegradation processes, and (iii) subsurface heterogeneity.

## CONCLUSIONS

Despite the numerous advances observed in the field of contaminated site characterisation and in-situ remediation, many practitioners still rely on conventional methods that cannot adequately delineate subsurface contaminant distributions nor capture the spatial variability of hydrogeological and contaminant properties. Improved understanding of aspects like multiphase flow mechanics, microbiological processes, and subsurface heterogeneity effects have contributed to more confidently assess and manage LNAPL-impacted sites. However, methodologies often recognised as best practice by government agencies (e.g., sequence stratigraphy or high-resolution site characterisation) are still seldom implemented within the contaminated land industry. Further research and adoption of up-to-date concepts and methods are encouraged to ensure best practices are implemented and LNAPL risks are managed sustainably and responsibly.

# Combining Whey Injection and Isotope Verification for Robust Nitrate Removal in Polluted Aquifers

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**Technologies for treating nitrate pollution in groundwater and monitoring remediation efficiency**

Keywords: nitrate pollution, groundwater, bioremediation, isotopic fractionation

Groundwater nitrate pollution remains a costly and persistent problem across Europe, driving regulatory pressure, environmental damage, and growing demand for practical remediation solutions. Although denitrification enables the reduction of nitrate to innocuous dinitrogen gas, it is often limited by the availability of suitable electron donors in aquifers. Stimulating denitrification through the addition of external organic carbon is therefore a promising strategy. In particular, the use of carbon-rich agro-industrial by-products could also contribute to a circular economy.

This study showcases a scalable and cost-efficient remediation solution based on the use of whey, a widely available agro-industrial by-product, as an organic carbon source to stimulate denitrification directly within the aquifer. The approach was validated through a pilot-scale implementation in the Campo de Cartagena Quaternary aquifer (southeastern Spain), a nitrate-impacted system with direct discharge into the Mar Menor lagoon, an environmentally and socio-economically sensitive area affected by recurrent eutrophication events.

The pilot system comprised four wells and operated through controlled weekly whey injections. Within two months, nitrate concentrations in the treatment well dropped from 200–260 mg/L to below 25 mg/L. Operational parameters were subsequently optimized to consistently meet regulatory standards (<37.5 mg/L) while avoiding common side effects such as ammonium accumulation, hydrogen sulfide formation, and excessive biomass growth. Monitoring data confirmed a broader decreasing trend across the site, despite natural groundwater variability.

A key challenge in field implementation is distinguishing true contaminant removal from concentration decreases caused by dilution or mixing. To address this, stable isotope monitoring was integrated as a performance verification tool. This allowed clear differentiation between true nitrate removal through biological denitrification and apparent reductions caused by dilution, providing decision-ready evidence of treatment effectiveness.

Overall, the results highlight whey-based carbon amendment as a scalable, cost-effective, and circular-economy solution for groundwater nitrate remediation. The study also illustrates how combining operational control with isotope-based verification can support robust performance assessment, optimize treatment strategies, and reduce uncertainty in full-scale deployment. This work was developed in the context of the projects REMEDIATE (TED2021-131005B) and ISOTRACE (PID2022-139911OB-C41).

# New technology for monitoring the efficiency of in situ chemical oxidation (ISCO) treatments with persulfate

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Persulfate ($S_2O_8^{2-}$, PS) is an oxidizing species increasingly used for In Situ Chemical Oxidation (ISCO) treatments, applied for the remediation of organic contaminants in soil and groundwater. Because the reaction of PS with common contaminants is relatively slow, PS is typically activated to enhance contaminant degradation rates through the formation of highly reactive radical species such as the sulfate radical anion ($SO_4\bullet^-$) and the hydroxyl radical ($HO\bullet$). Several PS activation methods exist, including thermal and alkaline activation (Ike et al., 2018).

At present, the progress of PS activation in groundwater is typically monitored by measuring the remaining PS concentration and/or the sulfate produced during activation. However, these parameters can be significantly influenced by processes such as dilution and dispersion, as well as by elevated background sulfate concentrations, thereby limiting their reliability. Therefore, concentration-based monitoring alone does not allow an accurate determination of the extent of PS activation.

In this context, the methodology proposed in this work provides complementary information to improve conventional monitoring approaches. A novel multi-isotopic technique has been developed within the MAiMA research group to determine both the degree of PS activation and the spatial extent affected by the oxidant.

The results illustrate the potential of this approach to optimize subsequent oxidant injections, including dosage as well as spatial and temporal injection strategies, ultimately leading to more efficient remediation processes and reduced operational costs. This methodology enables a more robust assessment of ISCO performance, thereby reducing uncertainty and improving decision-making.

In this presentation, the potential of this new multi-isotopic methodology will be discussed, together with its validation through laboratory-scale experiments and pilot tests for field-scale application.

Keywords: In Situ Chemical Oxidation (ISCO); persulfate activation; multi-isotopic analysis; groundwater remediation; oxidation efficiency; environmental monitoring.

# RED4SOLS – Short-time electrodialytic remediation of Walloon polluted soils

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Due to its history of heavy industry, Wallonia homes a high number of old industrial sites (brownfields), where are located highly contaminated soils, notably in heavy metals: 1,800 proven sites and 21,000 potential sites, representing surface area of 7,000 and 42,000 hectares, respectively.
For these highly polluted sites with heavy metals, solutions are missing. In fact, mineral processing techniques (combining size fractionation and densimetric separations), although simple and cheap, are not adapted to these heavily contaminated soils. Concerning soil washing with agents (acid, chelatant, etc.), high amounts of reactants, sometimes expensive, are necessary to extract all metals, and this technique generates a great amount of wastewater. Moreover, Walloon decree of March 1st, 2018, on soil management and remediation, only defines threshold values on raw materials (see Table 1), not on leachates, limiting the use of pollutants stabilisation techniques; these must therefore be accompanied by a risk analysis.
Due to the lack of remediation solutions for highly contaminated soils, the current practice is soil confinement, combined with environmental monitoring, which could become expensive with time.
This is in this context that the RED4SOLS project is involved, with the aim of remediating these highly contaminated sites, using an innovative remediation technique, named electrodialytic remediation. This choice is justified by the fact that this technique can be applied on the soil fine fraction, which concentrates the pollutants and, on the other hand, could be integrated in a global process of soil washing, already available in the main Walloon soil remediation companies. Figure 1 presents the principle scheme of a combined process "soil washing + electrodialysis". Nevertheless, to be integrated in an industrial line with profitability, the electrodialytic remediation step must last 5 hours at maximum, without consuming more than 100 kWh/ton$_{dry\ matter}$.

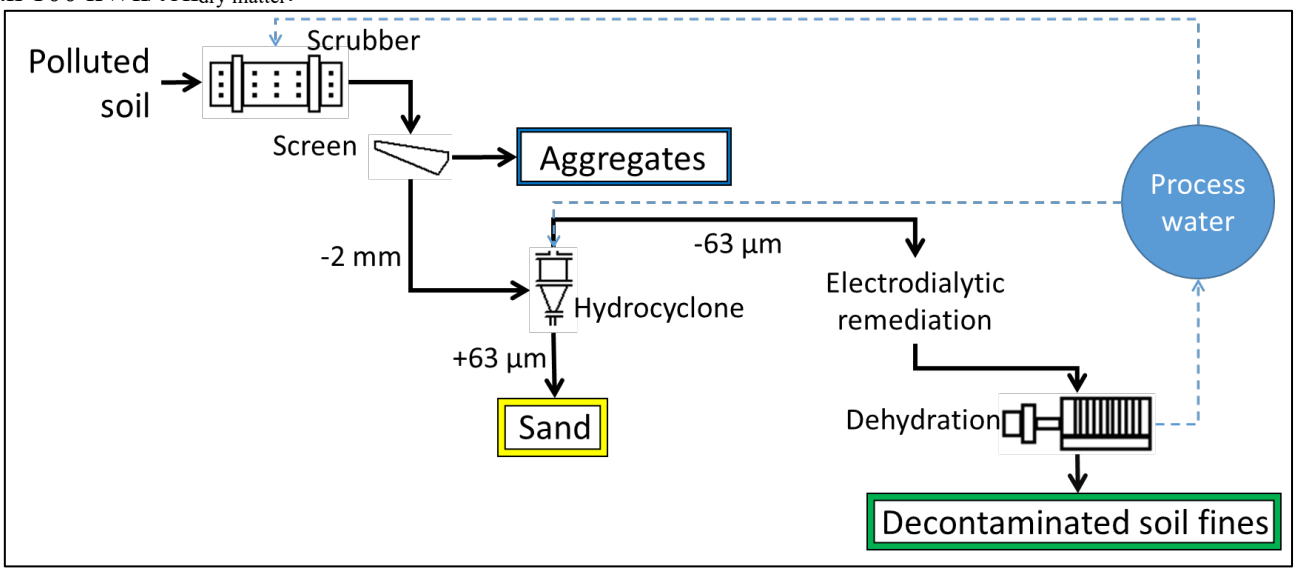



*Figure 1 : Contaminated soil washing process, including electrodialytic remediation step.*

In terms of concept, electrodialytic remediation is an improvement of the electrokinetic remediation, by using ion exchange membranes. It allows to extract ionic species by using an electric field induced by two electrodes (anode and cathode). This field goes through a soil slurry, and the ions are extracted by electromigration through one or more ion exchange membrane. The placement of membranes between the soil slurry and the electrolyte allows to compartment the solutions, avoiding mixing between solutions. Literature indicates that the electrodialytic remediation lasts about 48 h in batch mode and the energetic consumption is about 340 kWh/ton$_{dry\ matter}$, demonstrating that project objectives are ambitious.
After a batch cell design and several trials using different experimental setup and cell designs, the two-compartments cell was favoured (Figure 2). The soil slurry is in direct contact with the anode in this cell design, generating directly $H^+$ ions in the slurry. The acidification is therefore direct, allowing fast

mobilization of heavy metals and inorganic elements, faster than 5 hours. The electromigration of cations through the cation exchange membrane also lasts during the time limit, but more slowly than the ion mobilization.

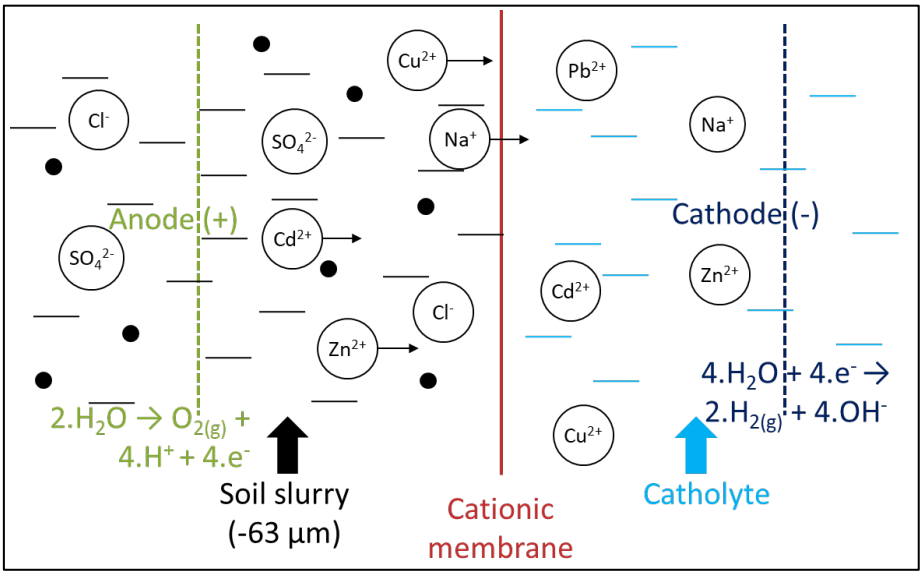



*Figure 2 : Schematic diagram of electrodialytic remediation in a two-compartment cell.*

The current results, presented in Table 1, show a great reduction in heavy metals levels, overall for the more concentrated ones (Cd and Zn), for a remediation time from 2 to 3 hours and an electric consumption of 150 kWh/ton$_{dry\ matter}$. The objective in term of remediation time is achieved and the objective in term of energy consumption is closed to the threshold for the economic profitability. To maintain the remediation performances, the adding of 60 kg$_{H2SO4}$/ton$_{dry\ matter}$ (to keep pH values low and stable in the catholyte) and of 10 kg$_{NaCl}$/ton$_{dry\ matter}$ (to keep high conductivity values inside the soil slurry) are necessary. An operating cost of around 100 €/ton$_{dry\ matter}$ was calculated for a soil washing process including an electrodialytic remediation step of soil fines.

*Table 1: Remediation performances of electrodialysis over polluted soil fines.*

| **Parameters** | | **Untreated** | **Batch** | **Mini pilot close to continue** | **Walloon decree thresholds (type V)** |
|---|---|---|---|---|---|
| **Mean time-on-steam (h)** | | - | 5 | 2 | - |
| **Energy (kWh/ton$_{dry\ matter}$)** | | | 441.1 | 149.1 | |
| **$H_2SO_4$ (kg/ton$_{dry\ matter}$)** | | | 96.7 | 60 | |
| **NaCl (kg/ton$_{dry\ matter}$)** | | | 100 | 10 | |
| **Levels (mg/kg$_{dry\ matter}$)** | **As** | 46.1 | 45.7 (-0.9%) | 43.2 (-6.3%) | 65 |
| | **Cd** | **84.2** | 8.7 (**-89.7%**) | **21.9** (**-74.0%**) | 20 |
| | **Cr** | 229.1 | 183.7 (-19.8%) | 235.4 (+2.8%) | 288 |
| | **Cu** | 219.9 | 77.1 (-64.9%) | 165.2 (-24.9%) | 600 |
| | **Ni** | 116.3 | 82.5 (-29.1%) | 69.8 (-39.9%) | 350 |
| | **Pb** | 876.1 | 467.4 (-46.6%) | 738.9 (-15.7%) | 1,840 |
| | **Zn** | **3,957.8** | 566.1 (**-85.7%**) | 966.4 (**-75.6%**) | 3,000 |

Following the electrodialytic treatment, the remediated fine fraction could be mixed with coarser fractions, and the mix can be reused on the initial site, allowing the reassignment of the field to economic activities. The soil fines were characterized in terms of agronomic parameters: remediated soil presents delayed germination and slow plant growth. Nevertheless, these harmful behaviours are mitigated by reducing remediation time. Recovery of valuable metals (e.g. Zn) is possible using several techniques.
Despite good technical performances, this process remains slightly high in terms of economics, and future research about this technique must use electrodes with correct cost/performance balance.

# *IN-SITU* REDUCTIVE DECHLORINATION BY DIRECT PUSH INJECTION OF GROUNDWATER CONTAMINATED WITH PERCHLOROETHYLENE

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## ABSTRACT

*In situ* chemical reduction enables the removal of organochlorine compounds through reductive dechlorination. This treatment was applied to remediate an aquifer located beneath a supermarket, where groundwater was initially contaminated with perchloroethylene (PCE) at concentrations of up to 16,000 µg/L. During the process, PCE is transformed into intermediate compounds such as trichloroethylene (TCE), cis-dichloroethylene (cis-DCE), and vinyl chloride (VC), and is ultimately degraded to ethylene, the harmless end product of the dechlorination metabolic pathway.

Reducing conditions were established by injecting a microemulsion into the aquifer using the Direct Push technique, which allows the controlled delivery of long-lasting hydrogen-releasing substrates and zero-valent iron particles throughout the saturated zone, thereby promoting a reductive environment for the degradation of organochlorinated compounds. Once reducing conditions were achieved, bioaugmentation was performed using an inoculum of anaerobic bacteria (*Dehalococcoides* sp.), capable of degrading halogenated organic compounds, to ensure complete contaminant removal. In this way, both chemical and biological degradation processes were combined.

Throughout the treatment, groundwater (using a peristaltic pump system) and soil gas (using Vapor Pin® samplers) were monitored every three months to assess both the remediation progress and the potential for vapor intrusion into the supermarket from degradation by-products. A quantitative risk assessment (QRA) was conducted based on soil gas data collected over 12 months to evaluate the potential impact of vapor intrusion of TCE and VC, which are more toxic than the parent compound (PCE).

The QRA results indicated that concentrations of PCE, TCE, cis-DCE, and VC in the soil gas phase posed acceptable risks to human health for all receptors considered throughout the treatment period.

After 34 months from reagent injection, PCE and its metabolites are below target values in 19 out of 23 monitoring wells across the site. Vinyl chloride is still detected in initial hotspot areas, confirming the proper progression of PCE reductive dechlorination pathway in groundwater.

Keywords: Dehalococcoides sp., Direct Push injection, *in-situ* reductive dichlorination, perchloroethylene, QRA, soil gas.

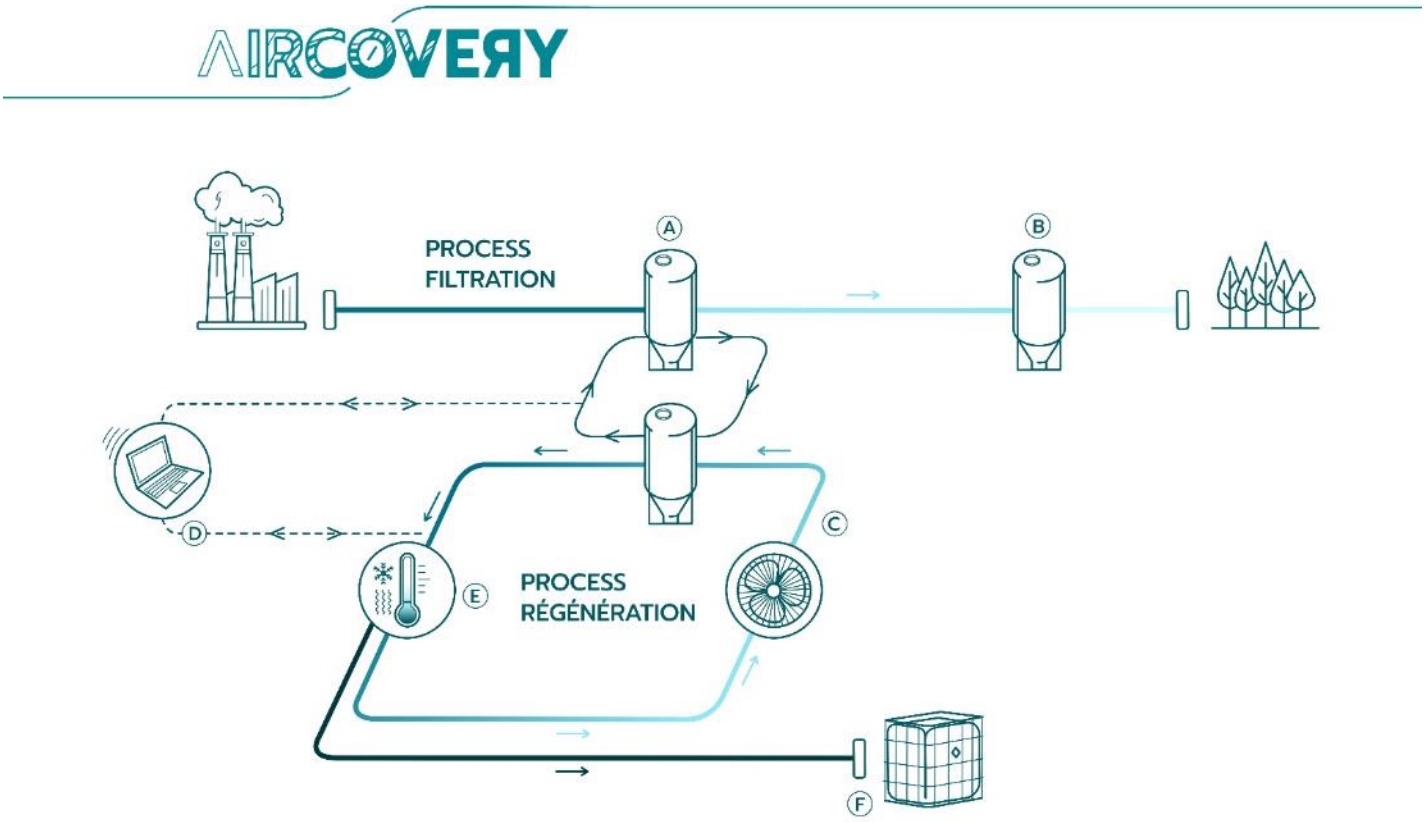
**Reduction of air activated carbon consumption by on-site regeneration**

Guillaume MOREL – 06 63 19 58 56 – guillaume.morel@aircovery.fr

AIRCOVERY-DESSICA – 605, allée des filiéristes 01600 Trévoux - France

In soils remediation project, a very common and effective way of VOC catching in the air is using activated carbon filters. Moreover ready-to-use solutions developed in recent years have facilitated site remediation work. Even if it is reactivated in dedicated plants, it is transported and there is a loss at each reactivation. But what about the impact? And what would you say if no transportation was necessary?

Projects realized in France for six years show that recycling AC on-site is possible when VOC concentration are high enough and especially with HVOC. The regeneration enables activated carbon to recover its adsorbent capacity instead of using a new load of AC. Different configuration of activated carbon regeneration process allows to work with different contaminants and handle ignition hazard: steam regeneration / nitrogen regeneration. Each one requires specific sizing.




We propose to explain principles, give costs ideas and clarify requirements of the technique.

Then examples of projects with common pollutions will be detailed to show classic applications.

After that, we will carry out an assessment of greenhouse gas emissions for a typical project in order to give a comparison of carbon footprint between several techniques of remediation and one of them, the on-site activated carbon regeneration.

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**October 8, 2026**

**PFAS Challenges**

08:00
Welcoming participants

08:45
**Chairman introduction**
Overview of Groundwater Contamination by PFAS in Catalonia
*Montse Toribio, ACA - Catalan Water Agency (Spain)*

**Moderator:**
*Emilio Orejudo Ramírez, ACA - Catalan Water Agency (Spain)*

**Regulations - Sources & Identification**

09:00
PFAS in Spain: Between the current regulatory framework and the legal horizons ahead - Challenges, difficulties and perspectives
*Noemi Blázquez Alonso, Lawyer - URÍA (Spain)*

09:20
PFAS management under the emerging EU water and wastewater framework: From WWTP monitoring to conceptual site models
*Ana Jiménez Muñecas, Hydrogeologist - IDOM (Spain)*

09:40
PFAS released by our buried waste: how effective are the treatments currently in place?
*Alice Senet, CIFRE Doctoral Student - Serpol & INSA (France)*

10:00
PFAS in fire-fighting foams: Regulation and analytical approaches
*Ariadna Macip, Country Manager Iberia - SGS Nederland (Spain)*

10:20
PFAS site characterization and source identification: Analytical challenges and investigation methodologies for groundwater and soil matrices
*Mónica Berrios, Environmental Laboratory Director - AGQ Labs (Spain)*

10:40
Coffee break

**Advanced characterisation - Fate & Transport - Risk Assessment**

11:10
Influence of macropores on PFAS transport in low-permeability media: From experimental setup to modelling
*Léonard Botella, Ph.D. Candidate in PFAS - WSP (France)*

11:30
Feedbacks on PFAS site characterization
*Juliette Chastanet, R&D Project Manager - Burgeap (France)*

11:50
Measuring the success of PFAS remediation: Integrating human health risk assessment and mass flux assessments to inform PFAS management
*Angela Ruthenberg, Senior Risk Assessor and Managing Consultant - Ramboll Iberia (Spain)*

12:10
Quantitative human health risk assessment for PFAS: Toxicology, environmental fate, and critical challenges
*Domingo Espinosa Pulido, Expert Consultant - Kepler (Spain)*

12:30
European Benchmark of remediation technologies for soil and groundwater polluted by PFAS
*Jesús Casado León, Technical Director Remediation - Veolia, Sarpi Remediation (Spain)*

12:50
Lunch

**Moderators:**
• *Sara Herrero Martin, MAiMA (Research group at the University of Barcelona, Spain)*
• *Víctor Carnicero Fabregat, AECAS (Association of Environmental Consultancy Firms specialising in Soil and Groundwater, Spain)*

**Physico-chemical and thermal treatments**

14:00
Restoring PFAS-contaminated soils to their pristine state: thermal treatment of source zones and pathways to full-scale remediation with Krysalis®
*Erwan Goulian, Account Manager - Haemers Technologies (Belgium)*

14:20
Technologies for treating PFAS-contaminated water – an analysis based on our own experience, including an economic assessment
*Thomas Meyer, International Manager - Züblin Umwelttechnik (Germany)*

14:40
Managing the legacy of PFAS-containing foams: from fire suppression systems to soil and groundwater
*Jonás García-Rincón, Principal Consultant - Kepler (Spain)*

15:00
Pilot-scale evaluation of a novel PFAS-selective adsorbent matrix as a sustainable alternative to granular activated carbon in groundwater remediation
*Matteo Dei, General Manager - Geostream Iberica (Spain)*

15:20
Capturing what others overlook - Lewatit ion exchange resins remove short-chain PFAS from drinking water and wastewater
*Jaime Alemany, Country Sales Manager - Lanxess Chemicals (Spain)*

15:40
Coffee break

**Biological and Emerging Treatments**

16:10
An advanced biological treatment for PFAS removal from landfill leachate
*Claudio Di Iaconi, Research Director - Water Research Institute, C.N.R (Italy)*

16:30
Innovative tools for fighting PFAS
*Dr. Alexander Stefan, Director Operations & Technology - Cornelsen Group (Germany)*

16:50
Scaling fungal biofiltration for the remediation of concentrated PFAS streams: From site-specific bioprospecting to full-scale on-site pilot demonstration in Willebroek (Belgium)
*Caroline Zaoui, Scientific Director - Novobiom (Belgium)*

17:10
Conclusions and closing of the conference

17:30
End of the conference

# “Overview of Groundwater Contamination by PFAS in Catalonia”

Emilio Orejudo, **Montse Toribio,** Roberto Espinola and Joan Sánchez. Catalan Water Agency

In recent years, PFAS have become one of the main substances of concern due to their potential impacts on human health and their persistence in the environment. These compounds appear to be ubiquitous, meaning that groundwater is affected to some extent by their presence. However, what do we currently know about PFAS in groundwater?

The Catalan Water Agency (ACA) is the public authority of the Generalitat responsible for planning and managing water resources in Catalonia. Its objective is to guarantee the supply and quality of water, both now and in the future, while protecting aquatic ecosystems.

This presentation provides an overview of the current state of knowledge on PFAS in groundwater in Catalonia. The main sources of information are the following:

a) **Drinking water monitoring:**
Information provided by companies responsible for monitoring and assessing drinking water quality to comply with the Drinking Water Directive. In this context, the detection of PFAS in wells is of particular importance.

b) **Industrial emissions monitoring:**
Certain facilities are required to monitor soil, and groundwater in order to comply with the Industrial Emissions Directive. Currently, the administration is incorporating PFAS analysis into groundwater monitoring at facilities that may have used or handled PFAS-containing substances in the past.

c) **ACA monitoring and control programme:**
The monitoring and control programme carried out by ACA provides a consistent and comprehensive view of the status of water bodies. This programme not only includes information on PFAS, but also provides concentration levels for a wide range of other contaminants.

In summary, obtaining a comprehensive understanding of PFAS contamination in groundwater requires integrating information from multiple sources. ACA is currently expanding its monitoring programmes to obtain more detailed and accurate data on PFAS in water.

# PFAS in Spain: Between the Current Regulatory Framework and the Legal Horizons Ahead: Challenges, Difficulties and Perspectives

Noemi Blázquez Alonso, Lawyer – URÍA (Spain)
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PFAS, widely known as "forever chemicals," have long remained a secondary issue in Spanish environmental law, yet their persistence in the environment and the growing regulatory concern surrounding them have brought them firmly into focus. There is currently no single, comprehensive EU instrument governing PFAS; instead, a fragmented framework of chemicals, persistent organic pollutants, food safety, drinking water and packaging legislation applies concurrently, each covering these substances from a different angle and across their full life cycle — from manufacture and use to their presence in the environment and in drinking water — meaning limits set in one regulatory area cannot automatically be transposed to another.

The most significant recent development is Directive (EU) 2026/805, amending the Water Framework, Groundwater and Environmental Quality Standards Directives, which regulates PFAS as a group rather than substance by substance, broadens the concept of "chemical status" of water bodies, introduces effects-based monitoring, and strengthens public access to justice; it must be transposed by Member States by 21 December 2027. Other relevant EU instruments include Regulation (EU) 2025/40 on packaging and packaging waste, which restricts PFAS in food-contact packaging from 12 August 2026, Directive (EU) 2024/3019 on urban wastewater treatment, which applies extended producer responsibility to PFAS, and Directive (EU) 2020/2184 on the quality of water intended for human consumption, which introduced the first binding EU parametric values for PFAS in drinking water, applicable since 12 January 2026. At the national level, Spain still lacks specific PFAS legislation, relying instead on the transposition of EU instruments, most notably Royal Decree 3/2023 on drinking water quality, which sets binding parametric values for PFAS.

Looking ahead, the most far-reaching change under discussion is a general restriction on PFAS under REACH, proposed by Germany, Denmark, the Netherlands, Norway and Sweden, aimed at limiting the manufacture, marketing and use of a very broad group of substances so that restricting one specific PFAS cannot be circumvented by substituting it with another compound from the same family carrying similar risks. This restriction is not yet in force: ECHA's Risk Assessment Committee has already adopted a final opinion favourable to an EU-wide restriction, while its Socio-Economic Analysis Committee is still assessing the input received during the public consultation that closed on 25 May 2026, with a final opinion expected by the end of 2026, after which the European Commission must prepare the definitive legislative proposal. Key aspects such as scope, exemptions and transitional periods therefore remain to be defined.

This presentation examines the practical implications for businesses, including the need to strengthen supply-chain information and due diligence — requesting PFAS presence/absence declarations, composition data and compliance guarantees from suppliers — investing in advanced filtration and substitution technologies such as activated carbon, and managing exposure to administrative, civil and criminal liability, including under Spain's Environmental Liability Act (Ley 26/2007) and, in the most serious cases, the environmental offence under Article 325.1 of the Criminal Code.

The central message is that PFAS regulation is no longer a matter for the future: concrete obligations already apply in areas such as drinking water and food-contact packaging, while a much broader

regulatory framework is being built that is expected to have a growing impact across numerous sectors in the coming years. From a business perspective, this translates into an increasing need to know which PFAS are present in products and processes, control the supply chain, anticipate regulatory change and be able to demonstrate compliance — companies should focus not merely on adapting once new restrictions take effect, but on anticipating them.

# PFAS Management Under the Emerging EU Water and Wastewater Framework: From WWTP Monitoring to Conceptual Site Models

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The introduction of Directive (EU) 2024/3019 on Urban Wastewater Treatment and Directive (EU) 2026/805 updating the European water quality framework is strengthening the role of PFAS monitoring within wastewater systems and increasing attention on the implications of PFAS releases for surface water and groundwater quality.

A key consequence of this evolving framework is that the detection of PFAS at a wastewater treatment plant (WWTP) is increasingly becoming the starting point, rather than the end point, of an environmental investigation. When PFAS are identified in WWTP influents, questions immediately arise regarding their origin, including potential industrial, commercial or historical contamination sources within the catchment conversely, when PFAS are detected in treated effluents, such as sludge or other treatment residuals, attention shifts to their subsequent environmental pathways and potential impacts on receiving waters, groundwater resources and other receptors. In both cases, understanding these linkages requires the development of robust Conceptual Site Models (CSMs) that integrate sources, pathways and receptors across interconnected environmental systems. In the context of PFAS, this often extends beyond traditional site-scale assessments to include groundwater, surface water, sewer networks, wastewater infrastructure and catchment-scale processes. Monitoring data generated within WWTPs then can therefore provide valuable information for identifying contaminant sources, understanding contaminant transport mechanisms and evaluating associated environmental risks.

In this presentation I explore how PFAS monitoring and emerging European regulatory requirements are driving the need for integrated conceptual site models. I emphasize particularly the relationship between wastewater systems, contaminated land, hydrogeology and water-body protection, and how source-pathway-receptor frameworks can support the investigation and management of PFAS within complex environmental settings.

# PFAS released by landfill waste: how effective are the treatments currently in place?

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Alice SENET, Doctorante CIFRE – Phone : 06 65 43 29 83 – Email : alice.senet@serpol.fr

## Introduction

Per- and polyfluoroalkyl substances (PFAS) are chemicals that have been incorporated into many products such as fire-fighting foams and surface treatment agents. The widespread use and disposal of consumer products containing PFAS, coupled with the physical and chemical stability of these chemicals, has led to increased concentrations in municipal landfill leachate. PFAS concentrations in landfill leachate vary from 100 to over 100 000 ng/L, with 5:3 FTCA and other short-chain PFAS dominating across studies. Source analyses show major PFAS inputs from consumer products, especially carpets, textiles, paper, and food-contact materials.

## Material and methods

ATOLIX (Ecotoxicological Analyses and Advanced Oxidation Treatment of PFAS in Leachate from Municipal Landfills) is a project partially funded by The French Agency for Ecological Transition (ADEME), aimed at studying PFAS in landfill leachate and developing a technology to destroy PFAS in leachate. For this project, samples will be collected on 8 French landfills. All sites have different storage capacities as well as different ages. Samples included raw leachate, leachate undergoing treatment, and treated leachate. Samples were collected at the discharge valve in the leachate treatment plants or using Eurobailer® single-use polypropylene samplers in the ponds and/or lifts stations. Raw and treated leachates were sampled on the same day, which facilitates data analysis. Flasks and analysis were commissioned to an external laboratory. In this study, all concentration values identified under the limit of quantification have been considered equal to the limit of quantification.

## Results & discussion

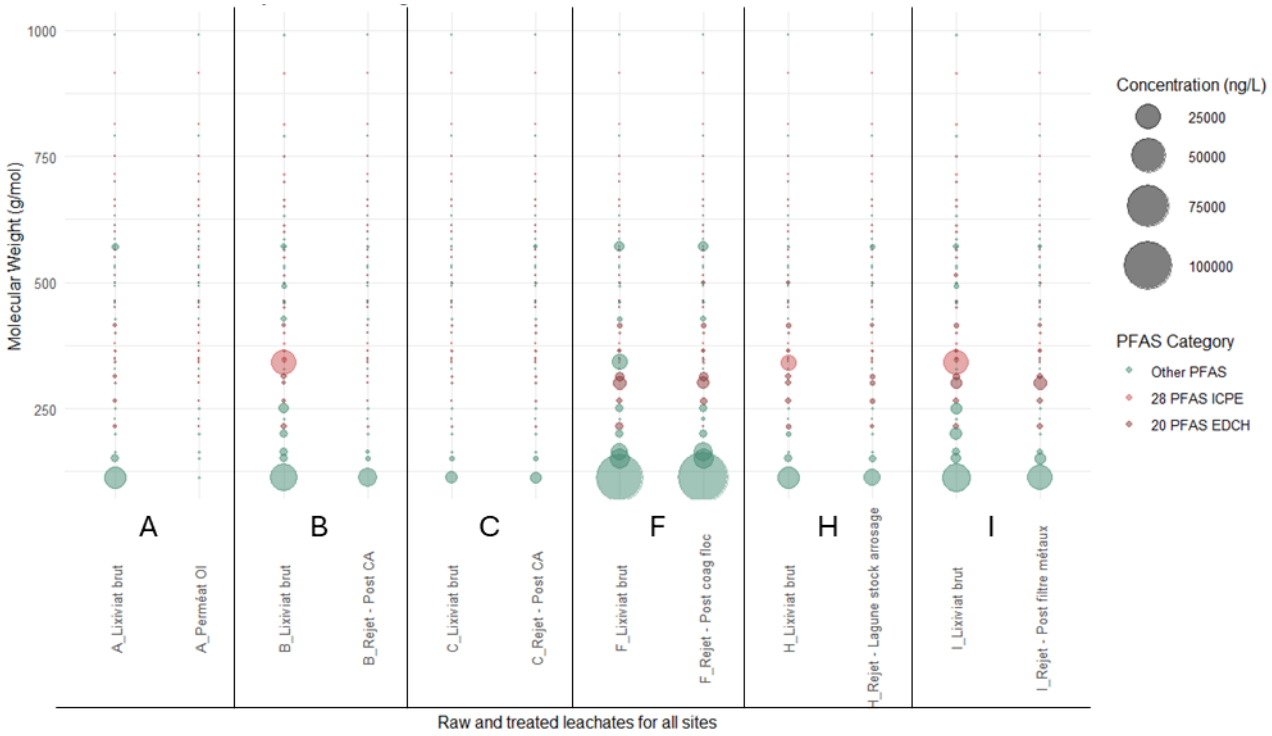



*Figure 1: PFAS concentration by molecular weight in raw and treated leachates at all sites*

## Raw leachates

"All PFAS" in the ATOLIX project refers to the sum of 49 PFAS. In those 49 PFAS are perfluoro carboxylic and sulfonic acids, fluorotelomer based substances, per- and polyfluoroalkyl ether acids, etc. Overall concentrations of PFAS differ greatly across all sites as highlighted in Figure 1 by the differences in disks sizes. The lowest concentration for the sum of 49 PFAS being 8 623 ng/L and the highest 153 179 ng/L. That is, more than ten times higher. The five PFAS with the highest concentrations in raw leachates are: trifluoro acetic acid (TFA), perfluoro ([5-methoxy-1,3-dioxolan-4-yl]oxy) acetic acid ($C_6O_4$), trifluoromethanesulfonic acid (PFMeS), pentafluoropropionic acid (PFPrA) and perfluorobutane sulfonic acid (PFBS). The highest contributors to the overall PFAS concentration are "Ultra Short Chain" (USC) PFAS, i.e. those with the lowest molecular weight. TFA is the most important PFAS in raw leachate and yet it is not included in neither the European directive for drinking water (**dark red disks** in the Figure 1) nor the French "facilities classified for environmental protection" lists (**light red disks** in the Figure 1). Therefore, adding USC PFAS to monitoring lists would help grasp the overall concentration of PFAS in leachates. In May 2026, the EU has indeed updated its list of water pollutants to include newly identified substances that harm the environment and human health, such as TFA. For ATOLIX project, Extractible Organic Fluor (EOF) was analyzed for raw and treated leachate. For several sampling points the EOF value was lower than the sum of 49 PFAS. It appears that, for leachates, EOF is not a suitable method for estimating total PFAS concentration.

As part of the interministerial plan on PFAS, all French "facilities classified for environmental protection", including landfills, have published data on PFAS concentrations in their effluent. In compliance with current regulations, only 28 PFAS were analyzed. USC compounds were not included. Average PFAS concentrations range from 41 to 3 923 ng/L in raw leachate. When selecting the same PFAS, the average for ATOLIX sites is 1 601 ng/L. For 8 landfills that published according to the interministerial plan, data on both raw and treated leachate were published, allowing for an estimation of the efficiency of the existing treatments in reducing PFAS levels, even though they were not designed with this purpose in mind. Indeed, more than 90% of PFAS present in raw leachate were removed. However, no information is available regarding the type of treatment in place and USC were not included.

## Treatment efficiency

The different treatment techniques implemented on ATOLIX sites are treatment wetland, reverse osmosis (RO), ultra- (UF) and nanofiltration (NF), activated carbon (AC), granular ferric hydroxide filter, coagulation-flocculation, filter micron and denitrification / nitrification. In order to establish the efficiency of treatment wetland, other sampling campaigns will have to be carried out (sites B, C and H in Figure 1). Coagulation-flocculation with $FeCl_3$ + sodium hydroxide solution + cationic flocculant, has seemingly no impact on the concentration of PFAS overall (see site F in the Figure 1). The efficiency of AC is highly dependent on the filter saturation. Even though landfill leachate has high organic matter concentrations, AC efficiency is still relatively high, up to 73% for site B. In agreement with the literature, RO is the most efficient treatment included in the ATOLIX project: 98 to 99,95% removal efficiency for the sum of PFAS, with USC (see site A in Figure 1). NF is less efficient with 77% removal efficiency for the sum of PFAS, without USC (see site I in Figure 1).

## Treated leachates

In treated leachate, USC PFAS remain the primary contributors to the overall PFAS concentration. At the leachate treatment plant discharge point, TFA accounts for between 59% and 85% of the total flow, depending on the site. The PFAS flow at the treatment plant discharge point ranges from 3 to 2 246 g/year for the 49 PFAS analyzed as part of the ATOLIX project. In the event of direct discharge into surface waters, PFAS released from landfills contribute to their dispersion in the environment

## Conclusion

All techniques studied in this project are separation techniques that produce highly concentrated PFAS waste. PFAS molecules are not degraded. To that end, concentrated effluent (RO, NF, UF) and/or contaminated matrices (AC, sludge) will have to be further degraded, generating extra costs for the landfill owner.

# PFAS in Fire-Fighting Foams: Regulation and Analytical Approaches

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**Context:**

PFAS are known as Poly and Per Fluorinated Alkyl Substances. It consists of a large group of estimated 10,000 compounds of which only a few are well studied (type PFOA/PFOS). Current approaches provide a limited view of existing PFAS pollution. Nevertheless, these compounds have been used in different fields and especially in fire-fighting foams. Several studies have demonstrated the impact and widespread use of PFAS in these products. Fire-fighting foams have become a priority topic due to their recent regulatory requirements and analytical complexities.

**Target:**

To contribute to the development of analytical techniques for PFAS analysis, including fire-fighting foams, by combining complementary detection methods to provide all relevant stakeholders (consultants, site owners, remediation companies, and regulatory authorities) with accurate data for PFAS risk assessment.

**Innovation to be presented:**

In recent years, an increasing number of PFAS have been regulated at the European level across multiple sectors, with particular emphasis on fire-fighting foams. These regulatory frameworks address not only individual target PFAS but also the related compounds, thereby requiring the application of the TOP assay. The TOP assay, through an oxidative conversion step, enables the transformation of precursor PFAS present in fire-fighting foams into terminal perfluoroalkyl acids. In this work, the TOP assay was specifically adapted to the fire-fighting foam matrix to ensure compliance with current regulatory requirements.



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# PFAS SITE CHARACTERIZATION AND SOURCE IDENTIFICATION: ANALYTICAL CHALLENGES AND INVESTIGATION METHODOLOGIES FOR GROUNDWATER AND SOIL MATRICES

*Berrios Caballero, Mónica, AGQ Labs*

## SUMMARY

The reliable identification of PFAS sources and the comprehensive characterization of contaminated sites have become priority activities within the European environmental management framework. Groundwater and soils represent the most relevant compartments for evaluating site impact, given their role as long-term reservoirs of PFAS and as key vectors for both human and ecological exposure. This paper addresses the main analytical challenges associated with PFAS site characterization in groundwater and soil matrices, the current source identification approaches based on congener fingerprinting, diagnostic ratios and precursor assessment, and the integration of analytical results into structured investigation methodologies. Special attention is given to the EPA 1633A method as the current reference framework and to the role of accredited laboratories in delivering robust data to support risk-based decision-making.

## KEYWORDS

PFAS; site characterization; source identification; groundwater; soils; EPA 1633A; LC-MS/MS; ENAC accreditation; conceptual site model

## INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a broad family of synthetic compounds whose extreme persistence, mobility in aqueous systems and potential toxicity have positioned them as priority emerging contaminants. Their widespread historical use in aqueous film-forming foams (AFFF), metal plating, textile and paper manufacturing, fluoropolymer production and a wide range of industrial processes has resulted in extensive contamination of soils and aquifers across Europe.

Within the framework of the European Union strategy on PFAS, including the proposed universal PFAS restriction under REACH, the revised Drinking Water Directive (EU 2020/2184) and the recent updates to the Industrial Emissions Directive, the demand for reliable site characterization data has grown substantially. Public administrations, industrial site owners and environmental consultants increasingly require analytical results that not only quantify PFAS concentrations but also support source identification, exposure assessment and remediation strategy design.

This work focuses on the analytical and methodological challenges of PFAS site characterization in groundwater and soil matrices, presenting current investigation approaches, the role of the EPA 1633A method and the contribution of accredited laboratories to robust environmental decision-making.

## PFAS BEHAVIOR IN GROUNDWATER AND SOILS

The environmental behavior of PFAS in subsurface systems is governed by their amphiphilic nature, low volatility and high resistance to abiotic and biotic degradation. In soils, PFAS distribution is strongly influenced by chain length and functional group: long-chain compounds (PFOS, PFOA, PFNA) tend to bind preferentially to organic matter and clay fractions, whereas short-chain analogues (PFBA, PFBS, PFHxA) exhibit higher mobility and migrate readily into groundwater.

In aquifer systems, PFAS plumes can extend hundreds of meters or even kilometers from source areas due to the limited retardation of short-chain compounds. Air–water interface partitioning, particularly relevant in the vadose zone, contributes additional accumulation patterns that complicate plume delineation and remediation design.

The presence of polyfluorinated precursors—compounds that can transform into terminal PFAS through biotic or abiotic processes—introduces a further dimension to site characterization. Conventional targeted analysis may significantly underestimate the total PFAS load, since many precursors are not included in standard analytical panels.

*Table 1: PFAS distribution patterns in soil and groundwater compartments*

| Matrix | Predominant PFAS | Key behavior | Implications |
|---|---|---|---|
| Surface soils | Long-chain (PFOS, PFOA, PFNA) | Adsorption to organic matter and clays | Source areas, residual contamination |
| Vadose zone | Mixed congeners and precursors | Air–water interface retention | Continued source of leachate |
| Groundwater | Short-chain (PFBA, PFBS, PFHxA) | High mobility, plume extension | Drinking water risk, delineation challenges |

**ANALYTICAL CHALLENGES IN SITE CHARACTERIZATION**

PFAS analysis at the low ng/L and ng/g concentration ranges required for site characterization presents specific challenges that distinguish it from most other environmental analytes:

- Cross-contamination control: PFAS are present in many laboratory consumables, sampling materials and personal protective equipment. Strict protocols on the selection of PFAS-free materials, the use of field, equipment and method blanks, and adequate decontamination procedures are essential to ensure data integrity.
- Matrix effects: Soils and groundwater present highly variable composition. Dissolved organic matter, metal ions, lipids and inorganic salts can interfere with both extraction efficiency and ionization in LC-MS/MS, making isotope dilution quantification with mass-labeled standards a methodological requirement.
- Analytical scope: The number of PFAS detected depends critically on the analytical panel. Restricted lists may exclude relevant emerging compounds, leading to incomplete characterization. Comprehensive panels covering at least 40 compounds, supplemented by precursor assessment when relevant, are required for site characterization purposes.
- Sampling representativeness: Soil heterogeneity, plume stratification and seasonal variation in groundwater levels strongly influence the quality of the conceptual site model. Investigation strategies must align analytical capability with field design to deliver representative results.

*Table 2: Main analytical challenges by matrix and mitigation strategies*

| Matrix | Critical issues | Mitigation strategies |
|---|---|---|
| Groundwater | Cross-contamination, low LOQ requirements | PFAS-free materials, isotope dilution, field blanks |
| Surface and subsurface soils | Heterogeneity, matrix effects | Composite sampling design, SPE clean-up |
| Vadose zone soils | Precursor presence, retention at interfaces | Targeted analysis combined with TOP assay |

## THE EPA 1633A METHOD AS REFERENCE FRAMEWORK

The EPA 1633A method, published in 2024, has become the international reference for PFAS analysis in environmental matrices, including aqueous samples, soils, sediments and biosolids. It establishes a validated procedure for the determination of 40 PFAS using LC-MS/MS with isotopically labeled standards, ensuring traceability and inter-laboratory comparability.

For groundwater applications, the method requires controlled solid-phase extraction (SPE), strict blank monitoring and the use of field replicates. For soil matrices, sample preparation involves solvent extraction followed by anion-exchange clean-up. Implementation under accreditation schemes (ISO/IEC 17025) provides the legal and technical robustness required by regulatory frameworks and tender specifications.

The application of EPA 1633A within an accredited environment also supports the comparability of results across investigation phases—from preliminary characterization to remediation monitoring—facilitating consistent decision-making throughout site management.

## SOURCE IDENTIFICATION APPROACHES

Source identification is one of the most demanding components of PFAS site characterization, particularly when multiple potential sources coexist within an investigation area. Several complementary approaches are currently applied:

- Congener fingerprinting: distinct PFAS profiles are associated with different source types. AFFF-impacted sites typically show high concentrations of PFOS, PFHxS and 6:2 FTS, often accompanied by zwitterionic and cationic precursors. Industrial sites associated with fluoropolymer manufacturing may present PFOA and short-chain perfluorocarboxylic acids. Landfill leachate impacts produce mixed profiles with elevated short-chain compounds and 5:3 FTCA.
- Diagnostic ratios: ratios such as PFHxS/PFOS or PFOA/PFNA are used as indicators of source origin and weathering, although they must be interpreted in light of site-specific conditions and the historical evolution of PFAS formulations.
- Precursor assessment (TOP assay): the Total Oxidizable Precursor assay enables an indirect estimation of the precursor load through oxidative conversion to terminal PFAS. This approach is particularly valuable in AFFF-impacted sites and landfill leachate investigations, where targeted analysis alone may significantly underestimate total PFAS mass.
- High-resolution mass spectrometry (HRMS): non-target and suspect screening based on Orbitrap or QTOF instrumentation allow the identification of PFAS not included in standard panels. Although HRMS is not yet routinely accredited, it is increasingly used as a complementary tool in complex source attribution scenarios.

*Table 3: Characteristic PFAS profiles by source type*

| Source type | Characteristic PFAS profile | Diagnostic indicators |
|---|---|---|
| AFFF-impacted sites (airports, military, fire training) | PFOS, PFHxS, 6:2 FTS, zwitterionic precursors | High PFHxS/PFOS ratio, significant TOP assay response |
| Fluoropolymer manufacturing | PFOA, PFNA, short-chain PFCA | Dominance of PFOA, GenX presence |

| Source type | Characteristic PFAS profile | Diagnostic indicators |
|---|---|---|
| Landfill leachate impact | Mixed profile, 5:3 FTCA, short-chain PFAS | Elevated short-chain compounds, organic load |
| Industrial discharge (metal plating, textiles) | PFOS, 6:2 FTSA, sulfonamide precursors | Sector-specific congener distribution |

**INVESTIGATION METHODOLOGIES**

Robust PFAS site characterization requires the integration of analytical results into a phased investigation strategy aligned with national and European guidance. Key elements include:

- Conceptual Site Model (CSM): iterative development of a CSM that integrates PFAS sources, transport pathways and potential receptors. The CSM should explicitly consider precursor transformation, vadose zone retention and air–water interface effects.
- Phased investigation: preliminary screening with broad analytical panels followed by targeted investigation in identified hotspots. Adaptive sampling strategies allow optimization of analytical resources without compromising data quality.
- Risk-based assessment: alignment of analytical limits of quantification with relevant regulatory thresholds, ensuring that data are fit-for-purpose for the intended decision-making framework.
- Long-term monitoring: continuous monitoring programs to evaluate plume stability, remediation efficiency and emerging regulatory compliance, with consistent analytical scope over time.

**IMPLICATIONS AND FUTURE PERSPECTIVES**

The progressive tightening of PFAS regulation in Europe, including drinking water thresholds, soil quality standards and the proposed restriction of the entire PFAS class under REACH, will substantially increase the demand for accredited PFAS analytical services in soil and groundwater investigations. Public administrations, infrastructure managers (airports, military sites, industrial estates) and brownfield developers are expected to require systematic PFAS characterization as a standard component of site investigation programs.

In this context, accredited laboratories play a strategic role in supporting environmental consultants, public authorities and industrial operators with analytical data of legal and technical robustness. AGQ Labs offers ENAC-accredited PFAS analysis in groundwater following EPA 1633A and provides analytical capability for soil matrices, contributing to comprehensive site characterization programs and to the consistent generation of data for regulatory and risk-based decisions.

**CONCLUSION**

PFAS site characterization in groundwater and soils represents one of the main analytical and methodological challenges currently faced by the European environmental sector. The reliable identification of PFAS sources and the assessment of contaminated sites depend on the integration of robust analytical methods—particularly EPA 1633A applied under accredited frameworks—with structured investigation strategies and well-developed conceptual site models. The contribution of accredited laboratories with proven capability across both aqueous and solid matrices is essential to support consultants, public administrations and site owners in the implementation of effective and defensible PFAS management strategies.

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# Influence of Macropores on PFAS Transport in Low-Permeability Media: From Experimental Setup to Modeling

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Per- and polyfluoroalkyl substances (PFAS) are highly mobile compounds in water and exhibit surfactant properties. Their transport in saturated zones can generally be assimilated to that of conservative tracers. In contrast, in the vadose zone, their behavior is strongly influenced by adsorption at air-water interfaces, which constitutes a major retention mechanism.

The transport of PFAS in low-permeability media, such as clays, remains a challenge for understanding their fate in the vadose zone. Field studies have reported contrasting observations: some indicate facilitated PFAS transport through low-permeability layers[1], while others report accumulation of these compounds within or around such zones[2]. These observations raise questions regarding the mechanisms controlling PFAS transfer. Accounting for soil heterogeneity and episodic rainfall events is necessary to better describe PFAS transport processes.

Current PFAS transport models in the vadose zone generally consider low-permeability layers as regions with high water content, where adsorption at air-water interfaces is limited. Under this assumption, PFAS transport is often treated similarly to that of conservative tracers[3]. This approach is based on the premise that the elevated water content reduces the extent of air-water interfaces, despite their recognized role as a major PFAS retention mechanism.

In this context, the objective of this study is to better understand PFAS transport mechanisms within low-permeability soil layers, with particular emphasis on the role of capillary structures in controlling transport processes. The study investigates surfactant retention within capillary films as well as diffusive exchanges between capillaries and the surrounding soil matrix.

The study combines an original experimental setup with breakthrough curve analyses based on the analytical solutions proposed by Rahman et al[4] to investigate and model PFAS transport, retention, and diffusive exchange between macropores and the adjacent soil matrix. The experimental device consists of a sand-filled trench crossed by a cylindrical macropore 3 mm in diameter. The macropore walls are made of a clay-xanthan mixture (xanthan being a polysaccharide), which ensures pore stability during successive wetting and drying cycles. Transport experiments were performed using an anionic

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surfactant, sodium dodecylbenzene sulfonate (SDBS), commonly used as a tracer for air-water interfacial areas in column studies[5].

Figure 1 presents a schematic view of the experimental setup (left) and a conceptual representation of half of the system (right), illustrating surfactant adsorption at air-water interfaces within capillary films, diffusion into the surrounding matrix, and remobilization through water flushing.

The experiments consist of injecting a pulse of tracer or surfactant solution, followed by an air pulse and finally a water-flushing phase. Water flushing disrupts the air-water interfaces formed within the system, thereby remobilizing both the surfactant molecules adsorbed at these interfaces and those that have diffused into the surrounding matrix. The study evaluates the respective contributions of adsorption at capillary air-water interfaces and diffusion into the matrix.

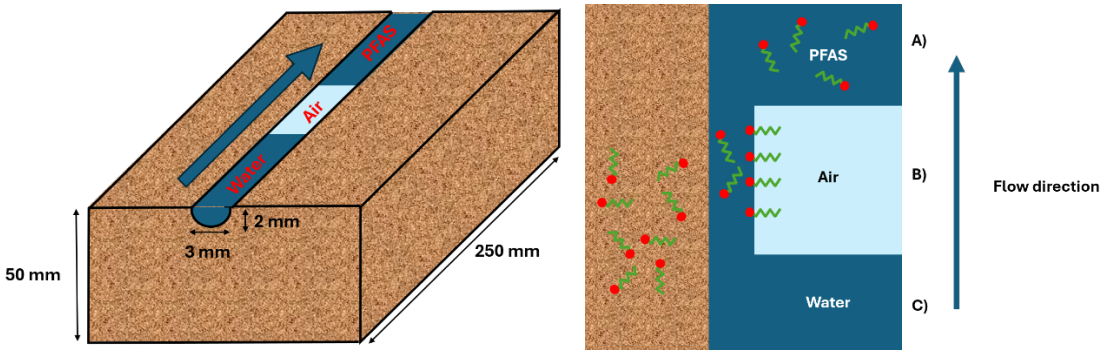



*Figure 1 : Schematic of the experimental setup (left) and conceptual representation of the experimental procedure (right): A) injection of a surfactant solution (SDBS), B) air pulse injection into the system, C) water injection to flush the macropore*

Figure 2 shows the breakthrough curves obtained for a tracer and for SDBS. Surfactant remobilization is both less extensive and more prolonged than that observed for the tracer.

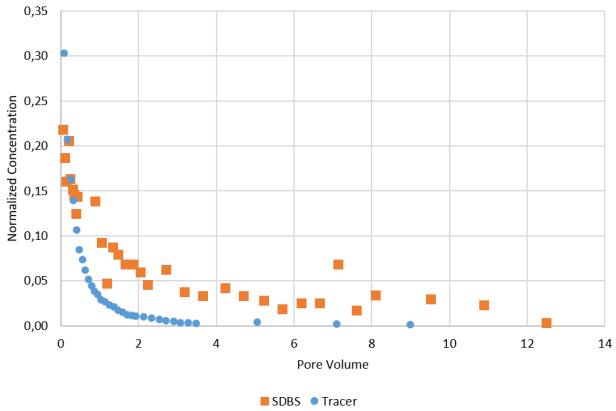



*Figure 2 : Breakthrough curves of a tracer (fluorescein) and a surfactant (SDBS) through the experimental system*

[5] Heonki Kim, P. Suresh C. Rao, and Michael D. Annable, 'Determination of Effective Air-Water Interfacial Area in Partially Saturated Porous Media Using Surfactant Adsorption', *Water Resources Research*, 33.12 (1997), pp. 2705–11, doi:10.1029/97WR02227.

The analytical solutions proposed by Rahman et al. describe concentration evolution within the macropore and the surrounding matrix:

$$C_m(z,t) = C_0 erfc \frac{\frac{2}{a}\frac{n_{im}R_{im}}{n_m R_m}\sqrt{D_a}\frac{zR_m}{v_a}}{\sqrt{4(t-\frac{zR_m}{v_a})}} \quad (1)$$

$$C_{im}(z,x,t) = C_0 erfc \frac{\frac{x-a}{\sqrt{D_a}}+\frac{2}{a}\frac{n_{im}R_{im}}{n_m R_m}\sqrt{D_a}\frac{zR_m}{v_a}}{\sqrt{4(t-\frac{zR_m}{v_a})}} \quad (2)$$

where $C_m$and $C_{im}$are the concentrations in the macropore and matrix, respectively, as functions of $z$ (distance from the inlet), $x$ (distance perpendicular to the macropore), and time $t$. $C_0$ is the injected concentration, erfc denotes the complementary error function, $R_m$and $R_{im}$ are retardation factors in the macropore and matrix, $n_m$and $n_{im}$ are the porosities of the macropore and matrix, $a$ is the macropore radius, $v_a$is the average pore water velocity within the macropore, and $D_a$is the apparent diffusion coefficient.

The experiments are designed to support the development of a model derived from these equations and adapted to account for PFAS sorption mechanisms. The model is calibrated using the experimental data and incorporates processes such as adsorption at air-water interfaces and sorption kinetics.

Theresults from the tests suggest that macropores may contribute to enhanced PFAS retention in the vadose zone of low-permeability media. Further investigations are required to better quantify the role of macropores in PFAS transport, particularly by examining adsorption kinetics at air-water interfaces within soil capillaries, in order to improve our understanding of retention mechanisms in such enironment.

# Feedbacks on PFAS site characterization

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**Summary**

PFAS are persistent, synthetic chemicals widely used in industrial and consumer products that have become ubiquitous environmental contaminants. Whereas more than 10,000 distinct PFAS compounds have been identified, several dozen compounds are commonly quantified at the industrial site scale. As their transfer in the subsurface is driven by many mechanisms (dissolution, adsorption, biotic or abiotic degradation, …), their distribution can be very different according to the considered matrix (soil, groundwater, soil gas), their location (source zone versus plume) and the in situ physico-chemical conditions. In order to improve the understanding of PFAS distribution in the subsurface, all field data collected by GINGER BURGEAP on PFAS-contaminated sites have been compiled into a database. A detailed analysis of this data has been conducted including comparison of field data with theoretical distribution (based on the principle of thermodynamic equilibrium) and statistical analysis. The feedbacks of this meta-analysis result in a better understanding of the fate and behaviour of PFAS from the source zone to the groundwater plume, and operational recommendations for PFAS site characterization and source identification.

**Key words**

PFAS site characterization, source identification, multi-matrix équilibrium

**Presenter Name:** Angela Ruthenberg

**Title:** Independent Contractor for Ramboll

**Title of the Presentation: Measuring the Success of PFAS Remediation: Integrating Human Health Risk Assessment and Mass Flux Assessments to Inform PFAS Management**

PFAS remediation programs are increasingly being implemented yet a fundamental question remains: **how do we define and measure remediation success?** While reductions in PFAS concentrations are often reported as a key performance indicator, concentration data alone may not fully reflect whether human health risks have been reduced, contaminant migration has been controlled, or remediation objectives have been achieved. This presentation explores two complementary assessment approaches, **Human Health Risk Assessment (HHRA)** and **mass flux assessments**, and demonstrates how each can be used to evaluate and communicate PFAS remediation outcomes.

Drawing on practical experience the presentation focuses on how these tools can inform site-specific decision making, stakeholder engagement and remediation strategy development. A key theme throughout the presentation is that successful PFAS management relies on **multidisciplinary collaboration**, bringing together geologists, hydrogeologists, chemists, toxicologists, risk assessors, remediation specialists, communications professionals, and other key stakeholders.

The HHRA component of the presentation demonstrates how risk assessments can be used to identify the exposure pathways, receptors and contaminants of concern that should drive remediation objectives. Using practical examples involving consumption of home-grown produce, eggs, milk and meat, the presentation highlights how different data selection approaches, including maximum concentrations, averages and upper confidence limits, can significantly influence calculated risk estimates and the interpretation of remediation success. The presentation further explores the value of **sensitivity assessments**, showing how variations in consumption rates, exposure frequency, source contribution assumptions and statistical treatment of datasets can identify dominant risk drivers and support more transparent communication with regulators, landholders and other stakeholders.

The second part of the presentation focuses on **mass flux assessments** as an additional line of evidence for evaluating remediation performance. Unlike concentration-based monitoring, which provides a snapshot of contamination at individual locations, mass flux assessments quantify contaminant loading and migration through groundwater and surface water systems. The presentation outlines the data requirements for undertaking mass flux assessments and discusses how these data can be used to assess source control effectiveness and off-site migration. Practical lessons learned from field implementation are also discussed, including challenges associated with plume delineation, hydrogeological uncertainty, monitoring network design, temporal variability and data interpretation.

HHRA and mass flux assessments provide different but complementary lines of evidence for evaluating remediation progress. The presentation emphasises that the true value of these approaches lies not simply in the numerical outputs they generate, but in how multidisciplinary teams use those data to understand site conditions, inform remediation strategies

Ultimately, the presentation argues that successful PFAS remediation is generally not measured by achieving a single concentration target or producing a single model output. However, success can be evaluated through a combination of risk-based assessment and contaminant migration evaluation, as part of a multiple lines of evidence approach that allows consultants to clearly communicate remediation success to site owners, affected communities, regulators, and other stakeholders.



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# QUANTITATIVE HUMAN HEALTH RISK ASSESSMENT FOR PFAS: TOXICOLOGY, ENVIRONMENTAL FATE, AND CRITICAL CHALLENGES

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## ABSTRACT

Per- and Polyfluoroalkyl Substances (PFAS) constitute a vast family of thousands of synthetic organofluorine compounds characterised by exceptional chemical and environmental persistence. This presentation addresses the integration of PFAS toxicology and physicochemical properties, which differ substantially from those of conventional regulated contaminants, into quantitative human health risk assessments (QRA) for contaminated soil and groundwater sites.

PFAS classification by chain length and functional group (carboxylates, sulfonates, sulfonamides, and fluorotelomers among others) largely determines environmental behavior and toxicological profile. From a toxicological perspective, PFAS differ markedly from classic lipophilic pollutants, as they bind preferentially to proteins and accumulate in liver, kidneys, and blood. Long-chain variants ($C \geq 8$), including PFOS (banned since 2009) and PFOA (banned since 2020), exhibit high log $K_{oc}$ values and human biological half-lives ranging from 2 to 35 years, complicating species-to-species dose extrapolation. Short-chain variants ($C < 7$), by contrast, present minimal soil retention, extreme aqueous mobility, and resistance to removal by conventional activated carbon treatment, making them particularly problematic in drinking water protection contexts.

Toxicological reference values for PFAS are substantially more restrictive than those applied to widely regulated chlorinated compounds. The oral reference dose for PFOA ($3\times10^{-8}$ mg/kg-d) and the cancer slope factor (29,300 $(mg/kg\text{-}d)^{-1}$), both sourced from DWSHA, exceed by several orders of magnitude the equivalent parameters for trichloroethylene or vinyl chloride. PFOA is classified as a confirmed human carcinogen (IARC Group 1), while PFOS is categorized as possibly carcinogenic (Group 2B).

The presentation highlights critical gaps in current risk assessment frameworks: the absence of inhalation toxicity reference values for vapor-forming PFAS such as FTOHs and FOSAs, marked interspecies differences in elimination kinetics that limit animal-to-human dose extrapolation, and the ongoing transformation of polyfluorinated precursors into terminal perfluoroalkyl acids (PFAAs) through both biotic and abiotic pathways. These factors must be incorporated into site-specific QRA involving PFAS-contaminated matrices.

Keywords: Partitioning, PFAS fate in the environment, PFAS toxicology, Regulatory Challenges.

# European Benchmark of remediation technologies for soil and groundwater polluted by PFAS

**VEOLIA |Remediation SPAIN**

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**HAZARDOUS WASTE EUROPE**

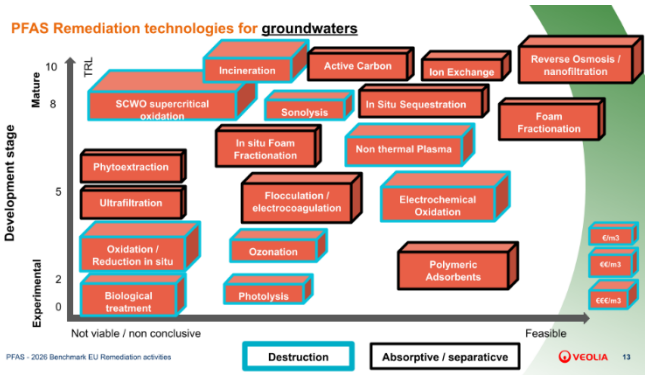
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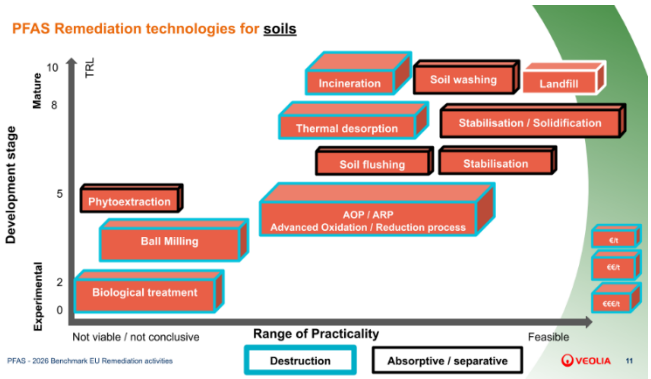
**Speaker:** Jesús Casado León. Sarpi Remediation Spain

In the management of contaminated sites and soils, interventions remain rare in countries without soil threshold values. This is particularly true in France and Spain, which differ from other European countries.

The existence of regulatory values for soil recovery, as in Belgium and the Netherlands, allows for the regulation of treatment methods for soils contaminated with PFAS by washing, defining an acceptable technical entry threshold to ensure their treatment and final disposal or reuse. For the soil-washing process, PFAS are largely transferred into water, and their treatment is carried out by concentration on filter media (activated carbon, resins). These widely used techniques remain quite expensive in terms of filter media, which do not have very high loading rates, especially for short chains, and are practically ineffective for ultrashort chains.

Following a critical review of the maturity of various PFAS treatment technologies in both soil and water matrices, initial field feedback will be presented: foam fractionation, in-situ thermal desorption or solidification stabilization will be discussed. Finally, future technologies such as Non-Thermal Plasma, Sonolysis and those being considered for groundwater management using reactive permeable barriers, with and without pollutant extraction, will be addressed.



# Restoring PFAS-Contaminated Soils to Their Pristine State — Thermal Treatment of Source Zones and Pathways to Full-Scale Remediation with Krysalis®

Presenting author : Erwan Goulian, erwan.goulian@haemers-tech.com

## 1. Background and Problem Statement

Contaminated soils represent the primary long-term reservoir of per- and polyfluoroalkyl substances (PFAS) in the environment, sustaining diffuse contamination of groundwater and surface water long after the original emission source has ceased. This recognition is now embedded in European policy, through the proposed group-wide PFAS restriction under REACH and the EU Soil Monitoring Law (Directive (EU) 2025/2360). Priority source zones — including PFAS manufacturing facilities, downstream industrial sites, airports, firefighting training areas, and military or defence installations — concentrate the largest contaminant mass within a manageable treatment volume.

The scale difference between soil and water treatment underlines the importance of source-zone intervention. One cubic metre of soil contaminated at 50 mg/kg total PFAS contains approximately 90 g of PFAS mass. At the Belgian regulatory threshold of 100 ng/L, the same mass dispersed into groundwater would correspond to approximately 900,000 m³ of water requiring treatment. Downstream water treatment cannot therefore serve as the primary remediation strategy while the source remains active.

Current soil management practices — containment, stabilization, excavation and landfill, or conventional incineration at 900–1,100°C — typically result in partial degradation, pollutant transfer between environmental compartments, or indefinite storage rather than permanent elimination. Complete mineralization of PFAS requires temperatures exceeding 1,400°C to reliably cleave the carbon–fluorine bond.

## 2. Technology Description — Krysalis®

Krysalis® is an ex situ containerised thermal treatment system developed by Haemers Technologies for the complete on-site destruction of PFAS-contaminated soil. The technology is protected by 60+ patents and has been validated at Technology Readiness Level 7+ (TRL 7+). It operates through two sequential stages within a single integrated unit.

In the first stage, Thermal Conductive Heating (TCH), excavated soil is loaded into sealed containers maintained under constant negative pressure. Heated plates powered by Smart Burners™ heat the soil by direct conduction to 350–400°C. At these temperatures, PFAS compounds desorb from the soil matrix and transfer to the vapour phase, with a demonstrated removal efficiency exceeding 99.98%. The soil mineral matrix is preserved throughout this stage.

In the second stage, extracted vapours are injected into a reburn chamber operating at temperatures exceeding 1,400°C, with a minimum residence time of one second in the presence of excess oxygen and steam. Under these conditions, PFAS compounds are completely mineralised into $CO_2$, HF and water. This destruction stage is integrated directly into the heating unit; no separate off-gas treatment facility is required. Because the soil itself is never subjected to destruction temperatures, it retains its structural and mineral integrity and can be reused on site following treatment. No contaminated material leaves the treatment perimeter and no secondary waste is generated.

## 3. Field Validation — Korsør, Denmark (2025)

The technology was validated at full scale at the PKOR site in Korsør, Denmark, in partnership with the five Danish regions and Arkil. Approximately 60 tonnes of highly PFAS-contaminated, clay-rich soil from a former firefighter training area were treated in a containerised system operating at 350–400°C. Clay-rich matrices represent a particularly demanding test environment due to the low permeability that impedes contaminant extraction. Results confirmed strong reductions in PFAS concentrations in treated soil, a significant decrease in leachability, 99.98% PFAS destruction, and no detectable PFAS in monitored

emissions. The Korsør demonstration represents the first full-scale validation of complete PFAS destruction in excavated soil.

## 4. Development Outlook and Scale-Up Pathway

The Korsør demonstration validated the process at 60 tonnes in a single containerised unit. The current development programme addresses the transition to industrial-scale deployment across the large PFAS source zones that constitute the primary remediation need across Europe.

The full-scale Krysalis system is based on a modular, plate-based architecture. Individual heated plates are assembled into treatment cells of approximately 100 $m^3$ each, which are grouped into multi-cell units: a 10-cell configuration processes 1,000 $m^3$ per batch; a 20-cell unit scales to 2,000 $m^3$. Treatment capacity is increased by adding cells in parallel, with no modification to the underlying process. This plate-based modularity represents the core architectural evolution from the Korsør demonstration toward large-scale source-zone remediation: site volume becomes a function of unit configuration rather than a constraint on technology applicability. As an illustration of this pathway, projects currently in preliminary design involve volumes of 22,000 $m^3$ or more, across multiple parallel treatment cells.

A next-generation pilot system is currently under development with a specific focus on energy optimisation. As treatment volumes increase, energy efficiency per tonne of treated soil becomes a critical determinant of economic viability. The deployment roadmap targets 65 operational Krysalis units in the base case, corresponding to a treatment capacity of 130 kt/yr, scaling to 160 units and 320 kt/yr under the accelerated scenario. These development programmes, combined with a partner-based licensing model for international deployment, define the pathway from the Korsør proof of concept toward the systematic remediation of PFAS-contaminated source zones at the scale that European environmental regulation now demands.

**October 7 & 8, 2026 Barcelona, Spain**

**PFAS challenges**

# Technologies for treating PFAS-contaminated water – an analysis based on our own experience, including an economic assessment

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**Züblin Umwelttechnik GmbH**

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**Technical summary**

Over the past 17 years, ZÜBLIN Umwelttechnik GmbH has designed, built and operated over 80 plants for the treatment of PFAS-contaminated water. The flow rates of these plants are ranging from 1 m³/h to 400 m³/h.

Furthermore, ZÜBLIN has designed and operated two soil washing plants for PFAS-contaminated soil with a capacity of up to 2,000 tons per day, together with the associated systems for the treatment of PFAS-containing process water and sludge dewatering.

These interventions were carried out at various sites: decommissioned and active industrial areas (chemical and petrochemical industries), where contamination is attributable to the manufacture or direct use of PFAS; civil and military airports, where contamination is mainly attributable to the use of foams in firefighting exercises; and other sites subject to indirect sources of contamination. Similarly, significant variability in the types and levels of PFAS concentrations present in the water (ranging from less than 1 µg/l to over 600 µg/l) was considered.





*Figures 1&2: Full-scale washing plant for PFAS-contaminated soil and process water (Germany)*

The management of these facilities made it possible to collect a representative set of operational data, which was used to compare the effectiveness and evaluate the technologies potentially best

suited for the treatment of PFAS-contaminated water. Specifically, the use of the following technologies was assessed:

- Adsorption on granulated activate carbon (GAC)
- Removal of PFAS-molecules using ion-exchange resins (IEX)
- Foam fractionation (FF)
- Adsorption on surface-modified clay mineral

During the lecture, several case studies will be presented.

Analysis of data collected during the implementation of a considerable number of water treatment projects involving PFC contamination has shown that the choice of an effective method for treating water containing these compounds depends primarily on their concentrations.

- At low concentrations in the range of 0.1–10 µg/L, adsorption onto activated carbon has proven to be the most effective and cost-efficient purification method.
- At particularly high concentrations in the range of 50–600 µg/L or more, adsorption onto activated carbon alone is not the most cost-effective due to the high consumption of the filter medium.
- With presence of short chain-PFAS (≤ 4 C atoms), a combination of activated carbon and ion exchange resin seems to be a good option.
- Based on our tests, the adsorption capacity of surface-modified clay mineral seems to be muss less than GAC and/or IEX.
- In the case of high concentrations, the most efficient solution was establishing a treatment train, including foam fractionation as the first treatment stage, followed by further treatment via filtration using activated carbon or ion-exchange resin.

For selected cases, the economic assessment will be presented during the lecture, showing treatment costs in EUR / m³.

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# Managing the legacy of PFAS-containing foams: from fire suppression systems to soil and groundwater

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Keywords: Aqueous film-forming foams (AFFF), Flux-based risk management, High resolution site characterization (HRSC), Per- and polyfluoroalkyl substances (PFAS), Post-remediation rebound.

Per- and polyfluoroalkyl substances (PFAS) historically used in Class B firefighting foams have left a persistent legacy of contamination at sites with fire suppression facilities worldwide. If not contained properly, even using compliant firefighting concentrate can push large volumes of groundwater above current regulatory limits. This explains why regulatory pressure on PFAS is intensifying: the EU's POPs Regulation (EU) 2019/1021 already restricts PFOA, PFOS and PFHxS, with most of the remaining exemptions for existing foams due to expire in August 2028, while under REACH (Regulation (EC) No 1907/2006), the use of PFAS-containing foams for training and testing purposes will be banned from April 2027. These requirements sit alongside environmental liability, occupational safety and contaminated land legislation, meaning site owners are answering to a complex regulatory framework. Yet PFAS behave very differently from the contaminants most site investigations have been designed around, and conventional approaches, based on a few soil and groundwater samples for routine laboratory analysis, repeatedly fail to capture the PFAS distribution encountered in industrial sites, leading to both under- and overestimation of risk. This presentation will illustrate the importance of approaching PFAS-impacted sites holistically: from supporting the safe transition to fluorine-free foams by carefully cleaning fire suppression assets and responsibly managing the resulting waste to addressing secondary, long-term sources of PFAS such as concrete surfaces, drainage systems, clayey low-permeability zones, or air-water interfaces, which can result in re-contamination of cleaned-up areas. We will also showcase the application of high-resolution site characterisation (HRSC) methods to investigate PFAS preferential migration pathways in groundwater systems, supporting flux-based decisions and better identification of high- and low-risk conditions. These approaches can inform the selection and optimisation of cost-effective site management strategies, ensuring regulatory obligations are met defensibly across the site's full lifecycle, from foam to aquifer and receiving ecosystems.

# PFAS Removal from a Highly Contaminated Groundwater Site: Pilot-Scale Performance of a Novel Adsorption Media Compared with Activated Carbon

Matteo Dei[1*], Silvia Cattarino[2], Jamie Dawson[3], Raul Mucciolella[2], Paolo Renoldi[2]
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**Abstract**
Granular activated carbon is currently the most widely used treatment media for PFAS-contaminated groundwater; however, its environmental footprint — associated with production, transport and thermal regeneration or disposal — raises growing sustainability concerns. In this context, Geostream, in collaboration with Puraffinity, conducted pilot-scale trials to evaluate the performance of an innovative treatment media for PFAS removal (G400) from contaminated groundwater in North-Eastern Italy, comparing its effectiveness with a conventional activated carbon blend under real operating conditions. The G400 can operate at Empty-Bed-Contact-Times (EBCT) as low as 30 seconds, enabling PFAS treatment systems with significantly reduced media volumes and footprint compared with activated carbon. The pilot test was performed by diverting a continuous groundwater flow upstream of an existing treatment plant into a dedicated filtration unit consisting of two filters installed in series. Following treatment, the water was returned to the main process to ensure compliance with discharge requirements and operational continuity.
Although the trial is still ongoing, its first phase was completed in April 2026, and this paper presents the results obtained and the analyses carried out to date. Preliminary data show >99.8% removal of PFAS4 and >92% removal of PFAS20 after two months of operation: influent concentrations of 3.9–9.3 µg/L (Sum of PFAS 20, dominated by PFOA) were reduced to <0.10–0.32 µg/L in the effluent, with the four priority PFAS consistently below quantification limits. Short-chain compounds (primarily PFBA) showed the earliest breakthrough, a limitation common to adsorption-based technologies.
These findings are particularly relevant in light of the evolving European regulatory framework. Directive (EU) 2020/2184 sets harmonised sum-based parameters for PFAS in drinking water ("Sum of PFAS": 0.10 µg/L; "PFAS Total": 0.50 µg/L, binding since January 2026), but national transpositions differ significantly across Member States. Spain, under "Real Decreto 3/2023, de 10 de enero, por el que se establecen los criterios técnico-sanitarios de la calidad del agua de consumo", monitors the sum of the 20 PFAS defined by the Directive, in line with several other European countries. Italy, driven by some of the most severe contamination cases in Europe, has adopted a multi-layered approach (D.Lgs. 102/2025): an extended "Sum of PFAS" list of 30 compounds, an additional limit of 20 ng/L for the sum of four priority PFAS (PFOA, PFOS, PFNA, PFHxS), a dedicated limit for TFA, an ultrashort-chain PFAS whose 10 ng/L limit will enter into force in 2027, and individual threshold values for groundwater within the site-remediation framework. This regulatory heterogeneity means that the performance requirements for treatment technologies — including which compounds must be targeted and to what levels — vary substantially across Europe, reinforcing the need for flexible, sustainable and effective alternatives to activated carbon for groundwater remediation.

## Industrial Origins of PFAS Contamination

Northern Italy has historically been one of Europe's most industrialised regions, and its textile sector has played a central role in the widespread use of per- and polyfluoroalkyl substances (PFAS). For decades, these synthetic chemicals were valued in textile manufacturing for their exceptional water, stain, and oil repellency, making them a staple in the finishing processes of fabrics, technical garments, and industrial coatings. However, their persistence, mobility in water, and resistance to natural degradation have led to significant and long-lasting environmental contamination. There are many documented cases where industrial discharges from textile and chemical manufacturing facilities contaminated groundwater and drinking water supplies across a vast area affecting hundreds of thousands of residents, prompting major public health investigations and regulatory action. This situation reflects a broader pattern across Northern Italy's industrial corridors, where legacy

pollutants from textile finishing, tanning, and chemical production have left soils and aquifers burdened with persistent contaminants, underscoring the urgent need for targeted remediation strategies, stricter substance controls, and long-term monitoring of affected sites.

**Groundwater Treatment Plant**

The site hosts a groundwater treatment plant that has been in continuous operation for several years, designed to handle a nominal capacity of 5 $m^3$/h, although the current inlet flowrate from the wells is around 2 $m^3$/h. Treatment relies on activated carbon adsorption, with the water first passing through an equalisation tank and then through three filters in series (1 m diameter each), each loaded with 250 kg of fine mineral activated carbon plus 250 kg of fine vegetal activated carbon.

The plant effectively treats a range of chlorinated contaminants present in the inlet water — PCE (up to 36 µg/L), TCE (up to 230 µg/L), VCM (up to 0.2 µg/L), trichloroethane (up to 0.1 µg/L), and 1,2-dichloroethylene — consistently complying with discharge/reinjection limits.

PFAS micropollutants are also present and generally well treated, though performance is not consistently satisfactory for the short-chain compound PFBA, which is subject to a restrictive on-site limit of 10 ng/L. Inlet concentrations fluctuate significantly: according to historical data, Sum of PFAS ranges from 17,000 to 37,000 ng/L, PFOA from 12,000 to 26,000 ng/L, and PFBA from 100 to 1,200 ng/L. At the outlet, Sum of PFAS and PFOA remain below their respective limits (500 ng/L), while PFBA stays below its 10 ng/L limit but not on a stable, long-term basis.

**New Filtering Media Trial**

To address this PFBA limitation, a dedicated test system was installed inside the existing plant to trial a new filtering media supplied by Puraffinity (G400, a granular functionalised activated alumina designed specifically for the removal of per- and polyfluoroalkyl substances (PFAS) from water).

The trial treats 0.5 $m^3$/h of the total flow i.e. roughly 1/10 of the plant's nominal 5 $m^3$/h capacity (field-measured values are sometimes even lower than this).

The test skid consists of two filters in series (WCF-804/1 and WCF-804/2), each a composite fibreglass cylinder with a PE inner lining, holding approximately 11.5 kg (12.5 L) of G400 media, operating at an EBCT of 1.5 minutes at 0.5 $m^3$/h.

Three sampling points are provided to track performance across the trial: IN-MIX, upstream of the first filter, capturing the water diverted from the main plant before treatment; OUT-PUR1, between the two filters, isolating the removal performance of the first filter alone; and OUT-PUR2, downstream of the second filter, showing the final polished result after both stages. The second filter thus acts as a safety/polishing stage, capturing any residual PFAS breakthrough — particularly short-chain compounds like PFBA — that the first filter fails to retain. After passing through both filters, the treated water is returned to the main plant's line, rejoining the flow through the three existing carbon filters before final discharge, so the trial operates as a closed loop that does not bypass the plant's normal compliance path.

**Results**

The results of the Phase 1 campaign are presented in the charts and tables below. The figure 1 shows the characterisation of the water to be treated, expressed as weight % and referring to PFAS only. PFAS4 are shown in grey and are predominant, with PFOA as the dominant compound.

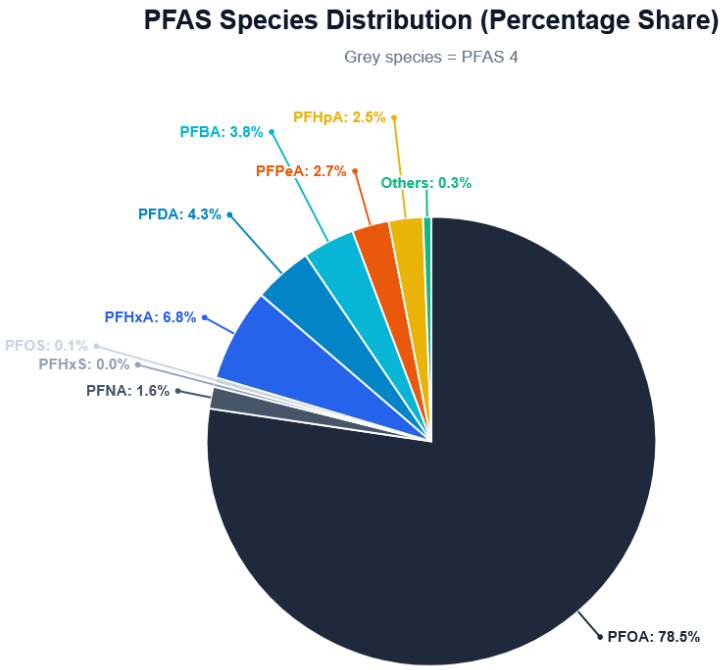



Figure 1

The performance of the system with the two G400 filters is shown in the following figures 2 & 3. The Sum of PFAS concentration at the system inlet was consistently below 10,000 ng/L, though fairly variable over time. Outlet values from the tested system remained consistently low and is even below the limit set by the most recent drinking water regulation leaving the plant (Sum of PFAS < 100 ng/L).




Figure 2

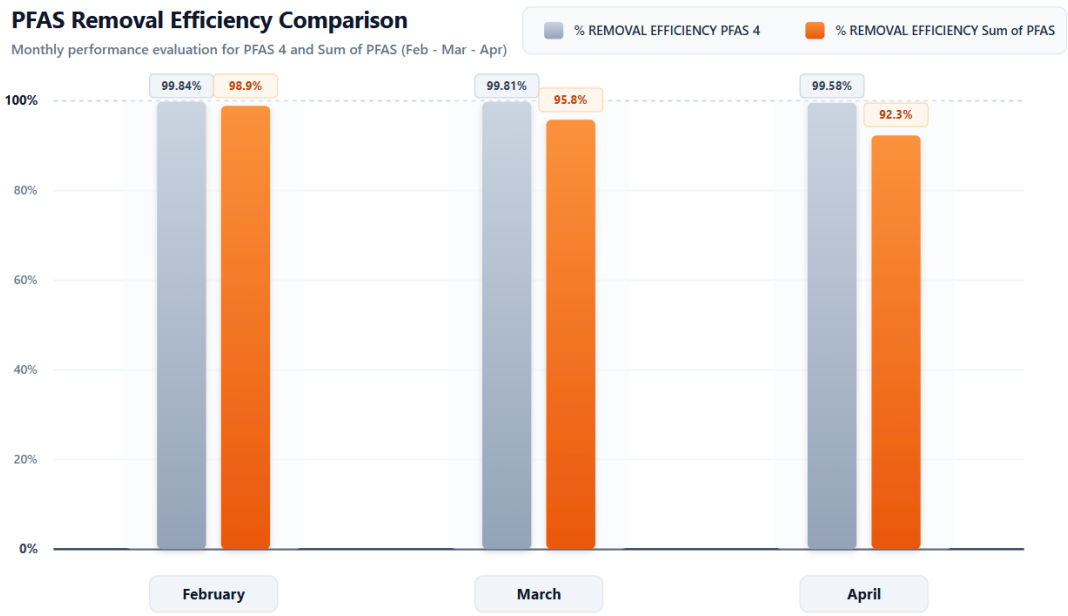



Figure 3

Removal efficiency was already very high downstream of the first G400 filter, for both PFAS4 and Sum of PFAS. The detailed results in the tables below 1,2 & 3, covering approximately two months of trial, show that saturation was reached for the short-chain compound PFBA. On this basis, Phase 1 of the pilot project was considered complete.

**Table 1**

| February 2026 | IN MIX | OUT PUR 1 | OUT PUR 2 | Plant Discharge |
|---|---|---|---|---|
| PFBA (perfluorobutanoic acid) (ng/l) | 350 | 110 | 11 | < 2 |
| PFPeA (perfluoropentanoic acid) (ng/l) | 250 | < 2 | < 2 | < 2 |
| PFHxA (perfluorohexanoic acid) (ng/l) | 630 | < 2 | < 2 | < 2 |
| PFHpA (perfluoroheptanoic acid) (ng/l) | 230 | < 2 | < 2 | < 2 |
| PFOA (sum of linear and branched isomers) (ng/l) | 7300 | < 4 | < 4 | < 4 |
| PFNA (perfluorononanoic acid) (ng/l) | 150 | < 2 | < 2 | < 2 |
| PFDA (perfluorodecanoic acid) (ng/l) | 400 | < 2 | < 2 | < 2 |
| PFUnDA (perfluoroundecanoic acid) (ng/l) | 7,5 | < 2 | < 2 | < 2 |
| PFDoA (perfluorododecanoic acid) (ng/l) | 10 | < 2 | < 2 | < 2 |
| PFBS (perfluorobutanesulfonic acid) (ng/l) | 3,9 | < 2 | < 2 | < 2 |
| PFPeS (perfluoropentanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFHxS (perfluorohexanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFHpS (perfluoroheptanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFOS (sum of linear and branched isomers) (ng/l) | 5,5 | < 4 | < 4 | < 4 |
| GenX (HFPO dimer) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| ADONA (dodecafluoro-3H-4,8-dioxanonanoic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| cC6O4/S ammonium salt (ng/l) | < 10 | < 10 | < 10 | < 10 |
| 4:2-FTS (ng/l) | < 2 | < 2 | < 2 | < 2 |
| 6:2-FTS (ng/l) | 6,7 | < 2 | < 2 | < 2 |
| 8:2-FTS (ng/l) | 2,3 | < 2 | < 2 | < 2 |
| Sum of PFAS (= PFAS 20) (ng/l) | 9300 | 110 | < 100 | < 100 |
| % REMOVAL EFFICIENCY Sum of PFAS | | | 98,9% | |
| PFAS 4 (ng/L) | 7455,5 | <12 | <12 | <12 |
| % REMOVAL EFFICIENCY PFAS 4 | | | 99,8% | |
| Samples taken approximately 15 days after start-up | | | | |

**Table 2**

| **March 2026** | **IN MIX** | **OUT PUR 1** | **OUT PUR 2** | **Plant Discharge** |
|---|---|---|---|---|
| PFBA (perfluorobutanoic acid) (ng/l) | 280 | 330 | 310 | < 2 |
| PFPeA (perfluoropentanoic acid) (ng/l) | 190 | 95 | 7 | < 2 |
| PFHxA (perfluorohexanoic acid) (ng/l) | 380 | < 2 | < 2 | < 2 |
| PFHpA (perfluoroheptanoic acid) (ng/l) | 130 | < 2 | < 2 | < 2 |
| PFOA (linear isomer) (ng/l) | 4700 | < 2 | < 2 | < 2 |
| PFOA (branched isomers) (ng/l) | 1400 | < 2 | < 2 | < 2 |
| PFOA (sum of linear and branched isomers) (ng/l) | 6100 | < 4 | < 4 | < 4 |
| PFNA (perfluorononanoic acid) (ng/l) | 150 | < 2 | < 2 | < 2 |
| PFDA (perfluorodecanoic acid) (ng/l) | 480 | < 2 | < 2 | < 2 |
| PFUnDA (perfluoroundecanoic acid) (ng/l) | 11 | < 2 | < 2 | < 2 |
| PFDoA (perfluorododecanoic acid) (ng/l) | 18 | < 2 | < 2 | < 2 |
| PFTrDA (perfluorotridecanoic acid) (ng/l) | < 10 | < 10 | < 10 | < 10 |
| PFBS (perfluorobutanesulfonic acid) (ng/l) | 3,8 | < 2 | < 2 | < 2 |
| PFPeS (perfluoropentanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFHxS (perfluorohexanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFHpS (perfluoroheptanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFOS (linear isomer) (ng/l) | 3,2 | < 2 | < 2 | < 2 |
| PFOS (branched isomers) (ng/l) | 2 | < 2 | < 2 | < 2 |
| PFOS (sum of linear and branched isomers) (ng/l) | 5,2 | < 4 | < 4 | < 4 |
| PFNS (perfluorononanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFDS (perfluorodecanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| perfluoroundecanesulfonic acid (ng/l) | < 10 | < 10 | **< 10** | < 10 |
| perfluorododecanesulfonic acid (ng/l) | < 10 | < 10 | < 10 | < 10 |
| perfluorotridecanesulfonic acid (ng/l) | < 10 | < 10 | < 10 | < 10 |
| GenX (HFPO dimer) (ng/l) | < 2 | < 2 | **< 2** | < 2 |
| ADONA (dodecafluoro-3H-4,8-dioxanonanoic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| cC6O4/S ammonium salt (ng/l) | < 10 | < 10 | < 10 | < 10 |
| 4:2-FTS (ng/l) | < 2 | < 2 | < 2 | < 2 |
| 6:2-FTS (ng/l) | 5,3 | < 2 | < 2 | < 2 |
| 8:2-FTS (ng/l) | 2,4 | < 2 | < 2 | < 2 |
| Sum of PFAS (ng/l) | 7700 | 430 | 320 | < 100 |
| % REMOVAL EFFICIENCY Sum of PFAS | | | 95,8% | |
| PFAS 4 (ng/L) | 6255,2 | <12 | <12 | <12 |
| % REMOVAL EFFICIENCY PFAS 4 | | | 99,8% | |
| $m^3$ treated | 151,9 | | | |
| flow rate (m3/h) | 0,44 | | | |

**Table 3**

| April 2026 | IN MIX | OUT PUR 1 | OUT PUR 2 | plant discharge |
|---|---|---|---|---|
| PFBA (perfluorobutanoic acid) (ng/l) | 240 | 240 | 270 | < 2 |
| PFPeA (perfluoropentanoic acid) (ng/l) | 130 | 130 | 34 | < 2 |
| PFHxA (perfluorohexanoic acid) (ng/l) | 310 | 10 | < 2 | < 2 |
| PFHpA (perfluoroheptanoic acid) (ng/l) | 91 | < 2 | < 2 | < 2 |
| PFOA (linear isomer) (ng/l) | 2200 | < 2 | < 2 | < 2 |
| PFOA (branched isomers) (ng/l) | 620 | < 2 | < 2 | < 2 |
| PFOA (sum of linear and branched isomers) (ng/l) | 2800 | < 4 | < 4 | < 4 |
| PFNA (perfluorononanoic acid) (ng/l) | 77 | < 2 | < 2 | < 2 |
| PFDA (perfluorodecanoic acid) (ng/l) | 190 | < 2 | < 2 | < 2 |
| PFUnDA (perfluoroundecanoic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFDoA (perfluorododecanoic acid) (ng/l) | 3,7 | < 2 | < 2 | < 2 |
| PFTrDA (perfluorotridecanoic acid) (ng/l) | < 10 | < 10 | < 10 | < 10 |
| PFBS (perfluorobutanesulfonic acid) (ng/l) | 2,6 | < 2 | < 2 | < 2 |
| PFPeS (perfluoropentanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFHxS (perfluorohexanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFHpS (perfluoroheptanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFOS (linear isomer) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFOS (branched isomers) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFOS (sum of linear and branched isomers) (ng/l) | < 4 | < 4 | < 4 | < 4 |
| PFNS (perfluorononanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| PFDS (perfluorodecanesulfonic acid) (ng/l) | < 2 | < 2 | < 2 | < 2 |
| perfluoroundecanesulfonic acid (ng/l) | < 10 | < 10 | < 10 | < 10 |
| perfluorododecanesulfonic acid (ng/l) | < 10 | < 10 | < 10 | < 10 |
| perfluorotridecanesulfonic acid (ng/l) | < 10 | < 10 | < 10 | < 10 |
| HFPO-DA (ng/l) | < 10 | < 10 | < 10 | < 2 |
| ADONA (ng/l) | < 10 | < 10 | < 10 | < 2 |
| C6O4 (ng/l) | < 10 | < 10 | < 10 | < 10 |
| 1H,1H,2H,2H-perfluorohexanesulfonic acid (4:2 FTS) (ng/l) | < 10 | < 10 | < 10 | < 2 |
| 1H,1H,2H,2H-perfluorooctanesulfonic acid (6:2 FTS) (ng/l) | < 10 | < 10 | < 10 | < 2 |
| 1H,1H,2H,2H-perfluorodecanesulfonic acid (8:2 FTS) (ng/l) | < 10 | < 10 | < 10 | < 2 |
| Sum of PFAS (ng/l) | 3900 | 380 | 300 | < 100 |
| % REMOVAL EFFICIENCY Sum of PFAS | | | 92,3% | |
| PFAS 4 (ng/L) | 2877 | <12 | <12 | <12 |
| % REMOVAL EFFICIENCY PFAS 4 | | | 99,6% | |
| $m^3$ treated | 270,8 | | | |
| flow rate (m3/h) | 0,425 | | | |

Activated Carbon versus G400 for the Test Site. The performance comparison indicated that PFBA — present at inlet concentrations of around 300 ng/L, against a discharge limit of 10 ng/L — represents the main area for further improvement, consistent with the short-chain breakthrough already noted above. The comparison with activated carbon for this specific site can be summarised as follows:

- To maintain the Sum of PFAS discharge limit (< 500 ng/L), activated carbon consumption is conservatively estimated at around 2,000 kg per year, of which 500 kg is required to

keep PFOA below its limit (with the third filter replaced more frequently than the first two).

- After 5 months of operation (data not presented in this report), the two Puraffinity vessels are still maintaining total PFAS to <500ng/L. On a conservative estimate of a replacement at 6 months of the lead vessel, this equates to a full-scale annual consumption of 250L of G400 (around 8 x less mass and 16 x less volume vs GAC). This provides significant footprint, disposal, logistics and OPEX advantages for bulk PFAS removal.
- The site has a particularly low discharge limit for PFBA of 10 ng/L and the effluent for G400 exceeded this limit within this trial period. For this particular application, either a longer EBCT or a polishing step would be recommended to maintain PFBA compliance for longer. Despite reaching saturation for PFBA, G400 maintained excellent removal for PFAS 4 and PFAS 20. This showcases G400 as a low footprint complete solution for sites with lower PFBA concentrations and/or higher discharge limits, such as the EU sum of PFAS 20 regulation.

The three-stage activated carbon solution, refined over time through extensive testing, remains the most established option for this specific site to date. At the same time, the substantially smaller footprint and lower media volumes required by G400 (which bulk density is around 850 kg/m3 vs the 500 kg/m3 of the activated carbons) make it a promising direction for further development, particularly as complementary short-chain media become available or for sites with lower short-chain presence and/or less stringent short-chain discharge requirements. (see Conclusions).

**Conclusions**

The Phase 1 results indicate that further optimisation is needed to improve removal of the short-chain compound PFBA. The trial is nonetheless continuing into Phase 2, to monitor the system's PFAS removal performance over the longer term. At the end of this phase, it will be possible to determine the overall PFAS loading capacity of the media (g PFAS/kg media).

G400 appears well suited to drinking water applications targeting PFAS. As highlighted above, regulation is increasingly focused on Sum of PFAS and PFAS4, with markedly stringent limits — targets that remain achievable with this media.

Puraffinity has also recently proposed the addition of a further media dedicated to short-chain compounds, since this remains one of the more challenging aspects within the PFAS family. This media will be trialled from the coming months as a polishing stage downstream of G400 at the same site, thanks to its availability and to the coordination of Geostream as manufacturer and supplier of water treatment plants.

**Keywords**

Geostream; Puraffinity; per- and polyfluoroalkyl substances; groundwater remediation; granular activated carbon; short-chain PFAS; EU Drinking Water Directive; pilot-scale trial

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# Capturing what others overlook - Lewatit ion exchange resins remove short-chain PFAS from drinking water and wastewater

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Innovative technologies and materials are needed to comply with increasingly stringent regulatory requirements regarding PFAS emissions into the environment. Removing short- and ultra-short-chain per- and polyfluoroalkyl substances (PFAS) from wastewater is a particular challenge because they often bind only poorly to adsorbent materials. Here we highlight our case study at Chemours in Dordrecht, in which a novel selective ion exchange (IEX) resin with groundbreaking performance is used.

Lewatit® MDS TP 108 used to remove short-chain PFAS is significantly superior to conventional selective resins, which is reflected in a 4-6 times longer service life and thus lower resin consumption. The disposal costs for the loaded resin and the carbon footprint from thermal utilization are correspondingly lower. In addition, a very compact design of ion exchange filter is possible. More than 99.9% of all fluorinated organic compounds from the wastewater remain on the adsorbent materials.

INTERNAL

# An advanced biological treatment for PFAS removal from landfill leachate

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In the last decades, the solid waste generation is continuously rising due to socioeconomic and demographic factors increase. Despite efforts to increase the recycling of urban waste, landfilling is still a widely used disposal technique in many countries. Within landfills, waste undergoes a number of physical, chemical and biological processes and releases a variety of pollutants within the landfill leachate, making this matrix one of the most difficult to treat. Recently, in landfill leachate perfluoroalkyl substances (PFAS) have also been found. These substances are widely used in various manufacturing, commercial, and consumer products, due to their unique properties such as hydrophobicity, oleophobicity, and chemical stability. However, at the end of their life cycle, these products often end up in landfills where they release fluorinated compounds into leachate. The percolation of water through the landfill matrix can facilitate the mobilization of PFAS from disposed materials into the leachate. Therefore, the latter is an important source of PFAS release into the environment since it is usually disposed at municipal wastewater treatment plants, which are not designed to remove PFAS.

The treatment of medium-age landfill leachates containing different PFAS concentrations was investigated for three years by employing an advanced biological system (SBBGR-Sequencing Batch Biofilter Granular Reactor). The SBBGR is an innovative technique that takes advantage of the presence of a new structure and composition of biomass featured by very long retention times (longer than a year). The latter enables enrichment of slow growing microorganisms and forces biomass to use unusual substrates (e.g., PFAS). Furthermore, the particular structure and properties of the biomass (i.e., a mixture of biofilm and granules showing high hydrophobicity) and the dynamic conditions (arising from the sequential operation) favour absorption of hydrophobic micropollutants on the biomass, which works at very long retention times with concrete possibilities of potential destruction

After a long acclimatization time of the biomass, SBBGR was able to completely remove long-chain PFASs and to ensure a moderate removal of the short-chain ones. Furthermore, the system was characterized by a negligible excess sludge production. Given the considerable interest in biological PFAS removal, particularly in light of their well-known persistence and resistance to degradation, particular attention was devoted to characterizing the SBBGR biomass to identify the key microbial components and elucidate the potential catabolic pathways involved.

Based on these promising results, recently, the technological transfer of SBBGR-based leachate treatment will be carried out in the Italian Ministry of Environment and Energy Security (MASE) project on PFAS research and monitoring.

Keywords: Landfill leachate, PFAS removal, SBBGR, granular biomass

# Innovative tools for fighting PFAS

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**Background**

PFAS contamination now appears to be ubiquitous whenever investigations are carried out. This applies to both soil and aqueous solutions. These liquids may include, amongst other things, premixes in fire-suppression systems, landfill leachate or groundwater. All these PFAS contaminations can have an impact on water bodies and drinking water supplies.

Due to growing evidence regarding the health effects of PFAS, legislative bodies are constantly tightening limit or target values for PFAS concentrations in soil and water. This can mean that technical solutions previously in use are no longer effective enough. In other cases, PFAS contamination is too high and/or too complex for traditional treatment techniques.

**PFAS contamination in water**

PFAS contamination in fire-fighting systems (premix), in industrial wastewater or in landfill leachate is often characterised by the presence of other water constituents such as DOC, other pollutants or elevated levels of dissolved iron alongside the PFAS. This complicates the removal of PFAS using conventional techniques, as other water constituents are preferentially adsorbed onto activated carbon, for example. One solution to this challenge involves incorporating a specialised process upstream of the main treatment.

This involves adding an environmentally friendly solution to the contaminated water and mixing it thoroughly. The substance is based on organic material and is biodegradable.

After a reaction time of a few minutes, a bond forms between the added solution and the dissolved PFAS. This bond is based on the difference in charge between the PFAS and the added substance. The resulting compound is large enough to be visible in the water and thus amenable to filtration for the removal of particles (flocs).

Examples in the groundwater sector show that, depending on the composition of the PFAS contamination, up to 98.1% of the PFAS present can be removed as flocs by filtration when this method is applied. An example involving landfill leachate yields a PFAS removal rate of 93.7%. Furthermore, the examples demonstrate that the treatment step is not hindered by water constituents such as DOC or dissolved divalent iron.

**PFAS contamination in soil**

PFAS contamination in soil is often soluble and can affect groundwater. Excavated soil can remove the contamination, but a solution must be found for the contaminated soil. Landfilling requires transport routes to a suitable landfill site. Soil washing requires a certain minimum quantity of soil to be economically viable.

A technically innovative solution involves adding a special powder to the soil using conventional mixing methods. This powder consists of environmentally friendly ingredients and, when used in the appropriate dosage, prevents the PFAS from continuing to dissolve. Different binding forces contribute to the fixation (sorption) of the PFAS. The soil itself shows no change.

The dosage rate can be adjusted on a project-by-project basis and is often in the range of one to two per cent by weight. It can be determined in advance by means of a test. Treated soil can sometimes be reused on site.

**Conclusion**

Practical applications show that when contaminated water is treated with the special solution, the majority of PFAS is removed in the form of particles. This results in a significantly reduced amount of PFAS-containing residue. Following this pre-treatment, the removal of PFAS remaining in the water is technically simplified, and the significantly reduced concentration of PFAS lowers the consumption of activated carbon and thus the volume of PFAS-containing residues.

The treatment of PFAS in soil using the special powder is widely used (USA, B, S, AUS, NZ,…) and has proven to be an easy-to-use technique that can also be successfully applied to fine-grained soil. Studies have shown that neither organic-rich solutions nor freeze-thaw cycles nor dry-wet phases can cause the release of the sorbed PFAS.

# Scaling fungal biofiltration for the remediation of concentrated PFAS streams: from site-specific bioprospecting to onsite pilot demonstration in Willebroek (Belgium)

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The working premise is that an organism able to operate in a PFAS stream is more likely to be found in contaminated ground than in a culture collection.

Sampling at Willebroek, a Belgian site carrying a decades-old fluorochemical burden, yielded 79 fungal isolates, recovered and stabilised for industrial use. Identification placed them across a wide taxonomic range. Isolates were tracked over fourteen days on minimal medium and in the presence of PFPeA for an in vitro assessment of tolerance to PFAS and detection of potential PFPeA oxidation. Laccase, an enzyme that has been reported to be involved in PFAS compound breakdown, was then assayed on ABTS-containing medium at days 4, 7, 11 and 14, with and without PFPeA. Apiotrichum sporotrichoides and Trichoderma crassum displayed laccase expression consistently from day 4 and peaked at day 11. The presence of PFPeA in the culture medium did not alter growth rate nor laccase expression, which hinted at a potential use of the selected strains to implement a biological treatment on PFAS polluted streams.

We then performed batch flasks experiments combining fungi and biochar using a PFAS charged foamate carrying approximately 180 µg/L sum PFAS, with 6:2 FTS accounting for roughly 78% of that mass. Adsorption onto biochar was observed, and in bottles pairing biochar with the fungal strain U151 two short-chain PFAS increased over the run — a signal expected if precursors are being transformed. This observation is treated as a lead rather than a result: no transformation claim will be made without products confirmed by LC-MS/MS and a mass balance closed across water, carrier and biomass.

Two mineral carriers were then run as separate columns on this foamate. Biochar is a porous organic carrier offering a large surface for fungal colonisation, and potential retention ability on long-chain PFAS. An in-house mineral granulate was developed as a polisher acting across both long and short chains. The biochar column (300 mL bed, downflow, four-hour empty bed contact time at 75 mL/h, 128 hours across 32 bed volumes) removed better than 99% over the first two bed volumes, reached 10% breakthrough near 8 hours and 50% near 20 hours, and gave a working capacity of approximately 6.5 µg PFAS per gram dry biochar.

To effectively combine the potential of fungal metabolism and mineral carrier ability to sorb PFAS, we ran colonisation tests on the carriers using the model fungal organisms Trametes versicolor, as well as Fusarium oxysporum. T. versicolor colonised fully within ten days from a 2.5% inoculum, while Fusarium oxysporum grew within three to four days.

Consequently, three constraints govern application: the bed must hold its structure through wetting and drainage without compacting; enough biomass must survive exposure to be re-isolated and scored; and adsorption, passive biosorption by dead biomass and any living contribution must be told apart. A six-column matrix is currently running to distinguish the impact of those parameters.

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