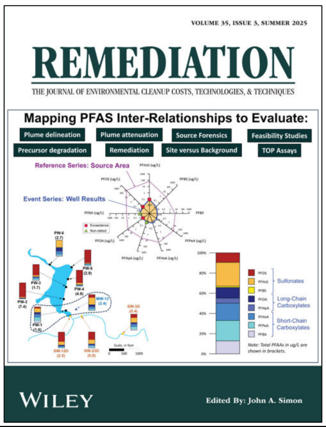
PFAS Visualization Case Studies: Site Characterization, Remediation, and Forensics



By Grant Carey, Ph.D.
Porewater Solutions
Email: gcarey@porewater.com

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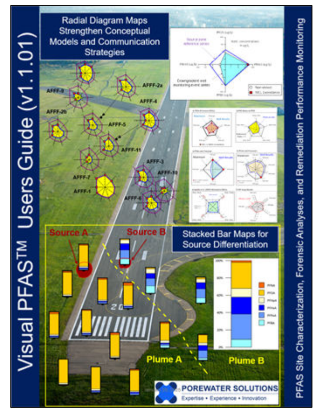


January 14, 2026

 1

1

Porewater Solutions Involvement In SERDP-ESTCP PFAS Projects

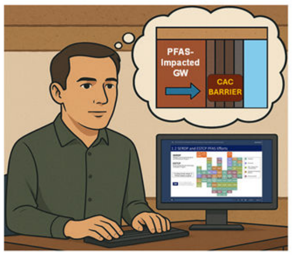
SERDP ESTCP

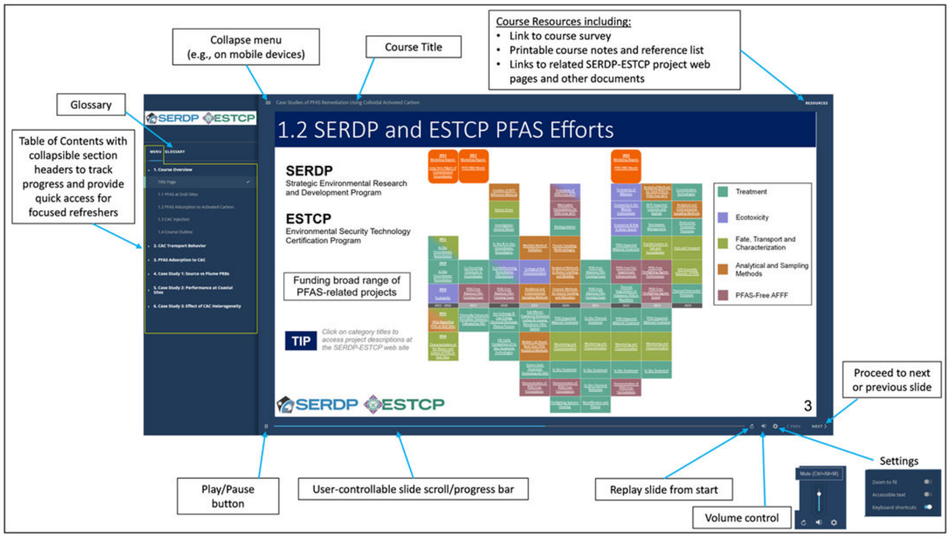
1. SERDP ER21-3959	An Investigation of Factors Affecting **In Situ PFAS Immobilization** by Activated Carbon
2. SERDP ER21-1070	Hydraulic, Chemical, and Microbiological Effects on the Performance of **In Situ Activated Carbon Sorptive Barriers** for PFAS Remediation at Coastal Sites
3. ESTCP ER20-5182	Validation of **Colloidal Activated Carbon** for Preventing the Migration of PFAS in Groundwater
4. ESTCP ER24-8200	**Two PFAS Remediation Models** for Understanding and Managing PFAS in the Saturated Zone
5. ESTCP ER25-8624	Colloidal Activated Carbon for **In Situ PFAS Remediation at Coastal Sites**: Field Assessment and Modeling of Long-Term Efficacy
6. ESTCP ER25-8483	Demonstrating the **SERDP-ESTCP e-Learning Platform** for Enhancing Technology Transition
7. ESTCP ER25-8875	Evaluation of an **Injected Surface Modified Clay Permeable Adsorptive Barrier** for PFAS Sequestration

 2

2

ESTCP ER25-8483: PFAS e-Learning Modules





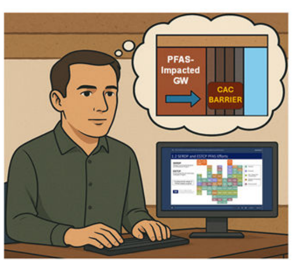
Online quizzes available for licensed professionals needing Certificates of Completion

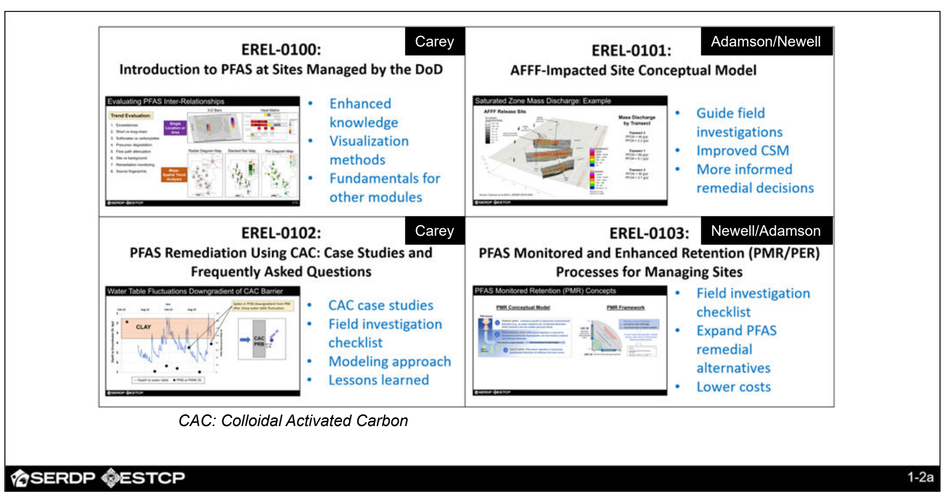
 3

3

ESTCP ER25-8483: PFAS e-Learning Modules

Interested Reviewers:
Please contact
gcarey@porewater.com





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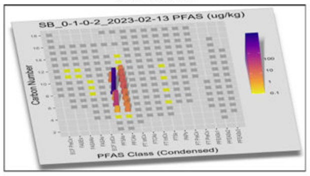
4

ENSAFE | POREWATER SOLUTIONS Expertise • Experience • Innovation

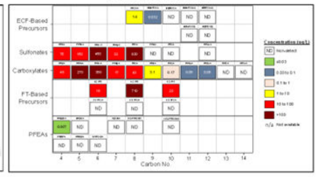
Specialized PFAS Services

Visualization / Forensics

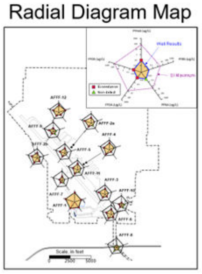
3-D Bars



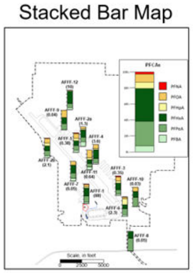
Heat Matrix



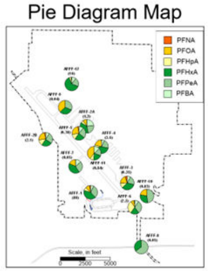
Radial Diagram Map



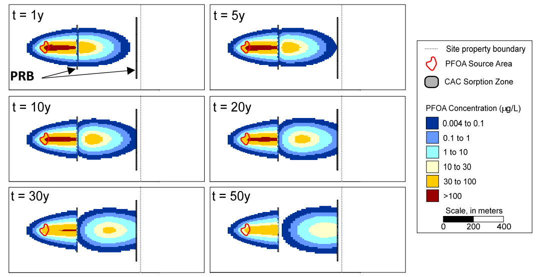
Stacked Bar Map



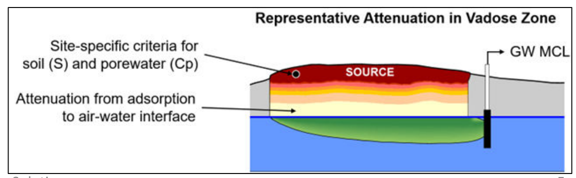
Pie Diagram Map



Feasibility Studies / Remedial Design



Soil Screening Levels



Agenda

1. Quick PFAS Primer
2. PFAS Visualization Methods
3. AFFF-Impacted Site Case Studies
   - Site characterization, remediation, forensics
4. PFAS in the Vadose Zone
   - Porewater sample validation, SPLP comparison
5. Wrap-up Case Studies, Q&A

Quick PFAS Primer

Section 1

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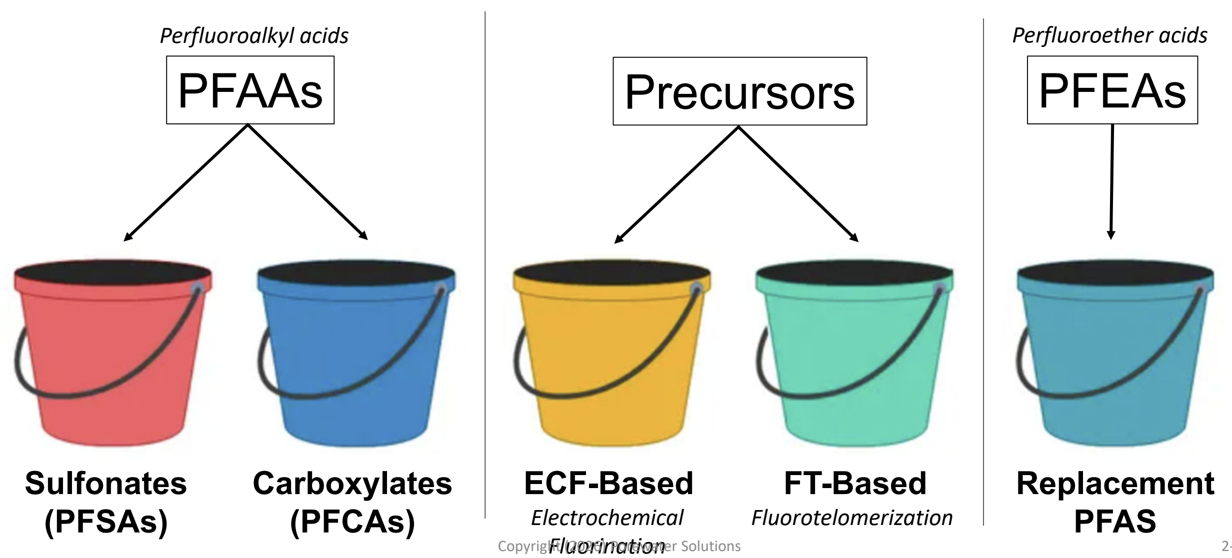
EPA Method 1633 (40 Analytes)



 2-8

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EPA Method 1633 (40 Analytes)

PFAAs		Precursors		PFEAs
PFBS (C4)	PFBA (C4)	NEtFOSA (C10)	3:3 FTCA (C6)	11Cl-PF3OUdS (C10)
PFPeS (C5)	PFPeA (C5)	NMeFOSA (C9)	5:3 FTCA (C8)	9Cl-PF3ONS (C8)
PFHxS (C6)	PFHxA (C6)	PFOSA (C8)	7:3 FTCA (C10)	ADONA (C7)
PFHpS (C7)	PFHpA (C7)	NEtFOSAA (C12)	4:2 FTS (C6)	HFPO-DA (C6)
PFOS (C8)	PFOA (C8)	NMeFOSAA (C11)	6:2 FTS (C8)	NFDHA (C5)
PFNS (C9)	PFNA (C9)	NEtFOSE (C12)	8:2 FTS (C10)	PFEESA (C4)
PFDS (C10)	PFDA (C10)	NMeFOSE (C11)		PFMBA (C5)
PFDoS (C12)	PFUnA (C11)			PFMPA (C4)
	PFDoA (C12)	**Biodegrade to:** PFOS	**Biodegrade to:** C4 to C8 Carboxylates	
	PFTrDA (C13)			
	PFTA (C14)			

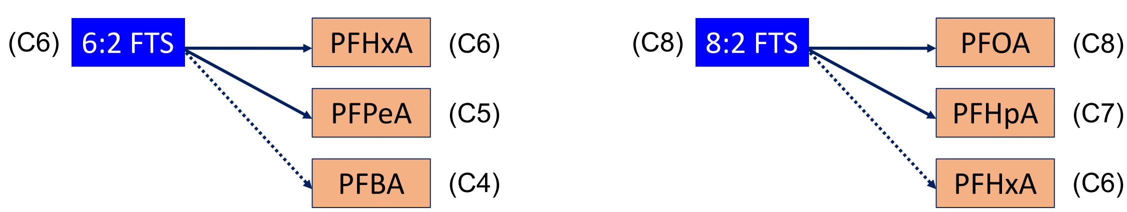
Sulfonates	**Carboxylates**	**ECF-Based**	**FT-Based**	**Replacements**

2-9

9

6:2 FTS and 8:2 FTS Transformation Pathways

Precursor Transformation Pathways



Modern AFFF **Legacy AFFF**

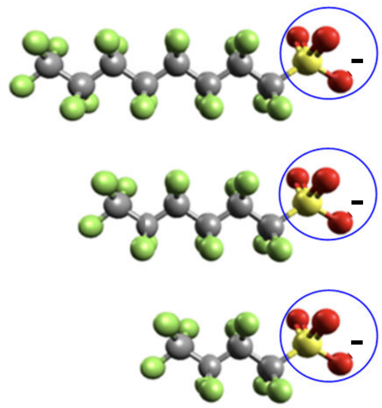
Exercise caution when incorporating enhanced bioremediation or chemical oxidation at AFFF-impacted sites.

These remedies may stimulate precursor biodegradation which can cause increased concentrations of regulated PFAAs.

3-10

10

PFAS Overview: Sulfonates (PFSAs)



PFOS (C8)

PFHxS (C6)

PFBS (C4)

Tail

Long-chain Sulfonates

Stronger adsorption to:

- Natural organic matter
- Air-water interfaces
- NAPL-water interfaces
- Sorbents (e.g. GAC/CAC)

NOM: Natural Organic Matter

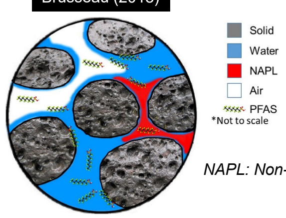
PFAS Adsorption Processes

(See Section 2.2)

Site Characterization

Natural Organic Matter (NOM), Air-Water Interface, and NAPL-water Interface

Brusseau (2018)



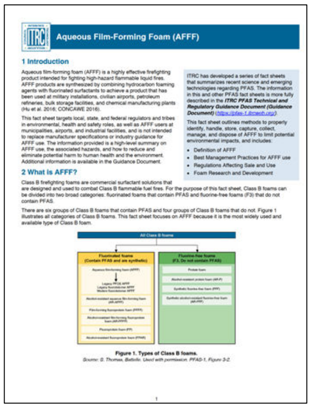
NAPL: Non-aqueous phase liquid

PFAS adsorption is important to characterize at sites because these processes govern:

- Retention in vadose zone or below the water table
- Travel time in expanding plumes
- Remediation viability
- Remediation timeframe

Impacts from AFFF Products

ITRC AFFF Fact Sheet (2024)


Aqueous Film-Forming Foam (AFFF)

1 Introduction

Aqueous film-forming foam (AFFF) is a highly effective firefighting product intended for fighting high-hazard flammable liquid fires. AFFF products are synthesized by combining hydrocarbon foaming agents with fluorinated surfactants to achieve a product that has been used at military installations, civilian airports, petroleum refineries, bulk storage facilities, and chemical manufacturing plants (Hu et al. 2016; CONCAWE 2016).

This fact sheet targets local, state, and federal regulators and tribes in environmental, health and safety roles, as well as AFFF users at municipalities, airports, and industrial facilities, and is not intended to replace manufacturer specifications or industry guidance for AFFF use. The information provided is a high-level summary on AFFF use, the associated hazards, and how to reduce and eliminate potential harm to human health and the environment. Additional information is available in the Guidance Document.

ITRC has developed a series of fact sheets that summarizes recent science and emerging technologies regarding PFAS. The information in this and other PFAS fact sheets is more fully described in the ***ITRC PFAS Technical and Regulatory Guidance Document (Guidance Document)*** (https://pfas-1.itrcweb.org/).

This fact sheet outlines methods to properly identify, handle, store, capture, collect, manage, and dispose of AFFF to limit potential environmental impacts, and includes:

- Definition of AFFF
- Best Management Practices for AFFF use
- Regulations Affecting Sale and Use
- Foam Research and Development

2 What is AFFF?

Class B firefighting foams are commercial surfactant solutions that are designed and used to combat Class B flammable fuel fires. For the purpose of this fact sheet, Class B foams can be divided into two broad categories: fluorinated foams that contain PFAS and fluorine-free foams (F3) that do not contain PFAS.

There are six groups of Class B foams that contain PFAS and four groups of Class B foams that do not. Figure 1 illustrates all categories of Class B foams. This fact sheet focuses on AFFF because it is the most widely used and available type of Class B foam.

Figure 1. Types of Class B foams.
Source: S. Thomas, Battelle. Used with permission. PFAS-1, Figure 3-2.

1

ECF: Electrochemical Fluorination
FT: Fluorotelomerization

Legacy ECF (Late 1960s-2002)	Legacy FT (Late 1970s-2016)	Modern FT
	Long-chain	Short-chain

Soil/GW Impacts: (Legacy ECF)
High PFOS, PFHxS
Lower PFCAs (e.g., PFOA)

Soil/GW Impacts: (Legacy FT and Modern FT)
High FtS
High PFCAs (PFBA → PFOA)
Lower PFSAs

Product differentiation clues:
- Sulfonates vs Carboxylates
- Long-chain vs short-chain Carboxylates

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PFAS Visualization Methods

Section 2

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PFAS Site Characterization

GW/Soil Samples

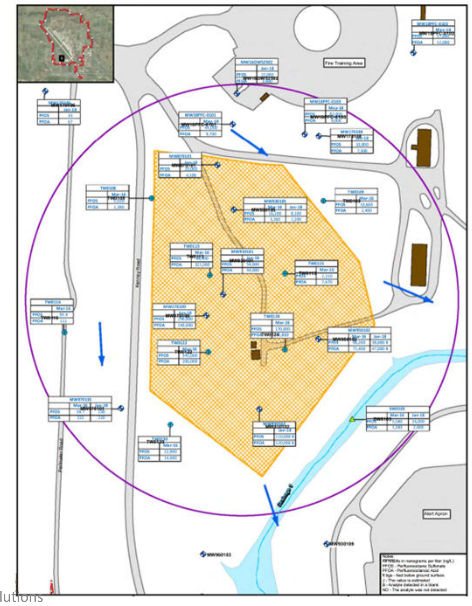
- Up to 40 PFAS analytes
  - Precursors, regulated PFAS
- Organic co-occurring chemicals
- Redox indicators

Table 3 PFAS Analytical Results

PFAS µg/L

Monitoring Well ID	Perfluorooctanoic acid (PFOA)	Perfluorooctanesulfonic acid (PFOS)	Sum of PFOA and PFOS	Perfluorobutanoic acid (PFBA)	Perfluoropentanoic acid (PFPeA)	Perfluorohexanoic acid (PFHxA)	Perfluoroheptanoic acid (PFHpA)	Perfluorononanoic acid (PFNA)	Perfluorodecanoic acid (PFDA)	Perfluoroundecanoic acid (PFUnA)	Perfluorododecanoic acid (PFDoA)	Perfluorotridecanoic acid (PFDoA)	Perfluorotetradecanoic acid (PFTeDA)
MW96BGO408	0.0035 J	0.0077	0.0112 J	0.0091 J	0.0034 J	0.0042 J	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U
MW96BGO422	**0.303**	**4.68**	**4.983**	0.127	0.408	0.535	0.136	0.0047 J	0.0040 U	0.0040 U	0.0040 U	0.0040 U	0.0040 U
MW96BGO425	0.0043 J	0.0222	0.0265 J	0.0056 J	0.0052 J	0.0064 J	0.0021 J	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U
MW972406	**0.32**	**2.97**	**3.29**	0.151	0.469	0.592	0.153	0.0043 J	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW972408	**0.187**	**1.4**	**1.587**	0.0828	0.255	0.301	0.0833	0.0027 J	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U
MW972410	**0.115**	**0.403**	**0.518**	0.0623	0.173	0.208	0.0562	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW982415	0.0617	0.0158	**0.0775**	0.0289	0.0633	0.0983	0.0229	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW982416	**0.103**	**0.31**	**0.413**	0.0561	0.151	0.185	0.049	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW982422	**0.282**	**1.73**	**2.012**	0.137	0.432	0.525	0.133	0.0023 J	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U
MW002422	**0.0748**	**0.121**	**0.1958**	0.0395	0.0935	0.131	0.0302	0.0040 U	0.0040 U	0.0040 U	0.0040 U	0.0040 U	0.0040 U
MW002423	0.0538	0.0135	0.0673	0.0487	0.0968	0.162	0.0336	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW09OB01	**0.0785**	**0.112**	**0.1905**	0.0438	0.115	0.151	0.0354	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW09OB02	0.0613	**0.0955**	**0.1568**	0.0331	0.0862	0.115	0.0259	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW09OB03	**0.075**	**0.183**	**0.258**	0.0398	0.112	0.132	0.0324	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U
MW09OB04	**0.108**	**0.306**	**0.414**	0.0543	0.162	0.19	0.046	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.0038 U
MW09OB05	**0.149**	**0.565**	**0.714**	0.0759	0.21	0.258	0.069	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW09OB06	**0.156**	**0.655**	**0.811**	0.0779	0.216	0.264	0.072	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U
MW09OB07	**0.171**	**0.622**	**0.793**	0.0841	0.237	0.293	0.0767	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 UJ
MW09OB08	**0.135**	**0.352**	**0.487**	0.076	0.232	0.296	0.0691	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U	0.0042 U

Monitoring Well ID	Perfluorobutanesulfonic acid (PFBS)	Perfluoropentanesulfonic acid (PFPeS)	Perfluorohexanesulfonic acid (PFHxS)	Perfluoroheptanesulfonic acid (PFHpS)	Perfluorononanesulfonic acid (PFNS)	Perfluorodecanesulfonic acid (PFDS)	Perfluorooctane sulfonamide (PFOSA)	2-(N-Methyl-perfluorooctane sulfonamido) acetic acid	2-(N-Ethyl-perfluorooctane sulfonamido acetic acid	4:2 Fluorotelomer sulfonate (4:2 FTS)	6:2 Fluorotelomer sulfonate (6:2 FTS)	8:2 Fluorotelomer sulfonate (8:2 FTS)
MW96BGO408	0.0091	0.0057 J	0.036	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.015 U	0.015 U	0.0077 U	0.0077 U	0.0077 U
MW96BGO422	0.176	0.212	1.7	0.132	0.0040 U	0.0040 U	0.0040 U	0.016 U	0.016 U	0.0080 U	0.104	0.0080 U
MW96BGO425	0.0061 J	0.0047 J	0.029	0.0038 U	0.0038 U	0.0038 U	0.0038 U	0.015 U	0.015 U	0.0077 U	0.0077 U	0.0077 U
MW972406	0.209	0.223	1.58	0.112	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.129	0.0083 U
MW972408	0.117	0.124	0.937	0.0564	0.0038 U	0.0038 U	0.0038 U	0.015 U	0.015 U	0.0077 U	0.0698	0.0077 U
MW972410	0.0992	0.0992	0.665	0.0267	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0111 J	0.0083 U
MW982415	0.0892	0.0643	0.288	0.0066 J	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0083 U	0.0083 U
MW982416	0.0949	0.104	0.668	0.0231	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0083 U	0.0083 U
MW982422	0.201	0.213	1.49	0.0927	0.0038 U	0.0038 U	0.0038 U	0.015 U	0.015 U	0.0077 U	0.0881	0.0077 U
MW002422	0.0899	0.0856	0.438	0.0138	0.0021 J	0.0040 U	0.0040 U	0.016 U	0.016 U	0.0080 U	0.0080 U	0.0080 U
MW002423	0.16	0.122	0.59	0.0075 J	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0083 U	0.0083 U
MW09OB01	0.106	0.098	0.473	0.0153	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0083 U	0.0083 U
MW09OB02	0.075	0.0712	0.38	0.0122	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0057 J	0.0083 U
MW09OB03	0.0763	0.0916	0.501	0.0167	0.0038 U	0.0038 U	0.0038 U	0.015 U	0.015 U	0.0077 U	0.0077 U	0.0077 U
MW09OB04	0.0898	0.11	0.716	0.0261	0.0038 U	0.0038 U	0.0038 U	0.015 U	0.015 U	0.0077 U	0.0049 J	0.0077 U
MW09OB05	0.121	0.125	0.916	0.0363	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0130 J	0.0083 U
MW09OB06	0.125	0.128	0.953	0.0407	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0163 J	0.0083 U
MW09OB07	0.134	0.135	0.981	0.0484	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0204	0.0083 U
MW09OB08	0.123	0.148	0.95	0.0325	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0066 J	0.0083 U



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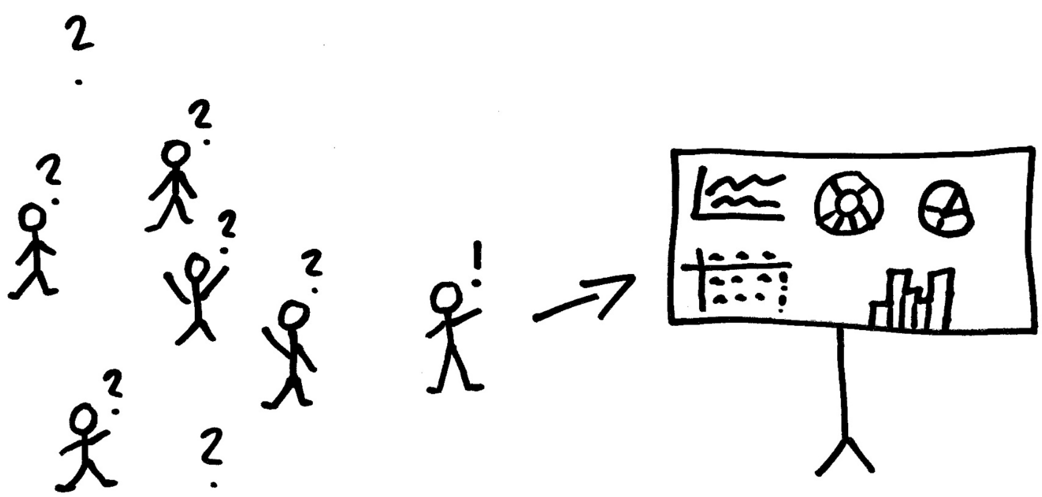
How Can We Effectively Communicate PFAS Results?



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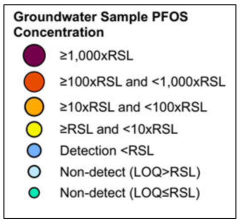
16

Single Species Options

- PFAS concentrations – symbol colors (and size) based on conc.
- Exceedance magnitudes

$$EM = \frac{\text{Well concentration}}{\text{Cleanup criterion}}$$



Exceedance Magnitude maps show:

1. Exceedance locations
2. Magnitude of reduction needed to attain remedial goals

- Concentration contours

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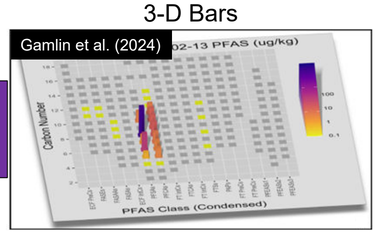
Evaluating PFAS Inter-Relationships

Trend Evaluation:

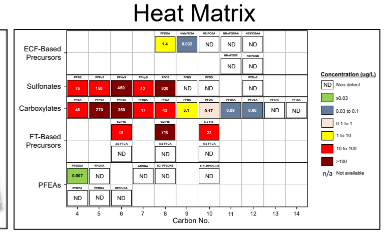
1. All exceedances
2. Short vs long-chain
3. Sulfonates vs carboxylates
4. Precursor degradation
5. Flow path attenuation
6. Site vs background
7. Remediation monitoring
8. Source fingerprints

Single Sample or Source Area

3-D Bars



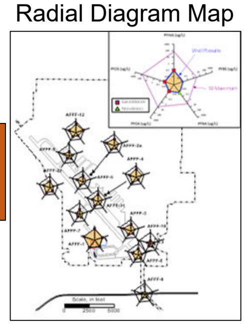
Heat Matrix



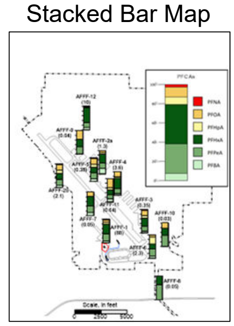
Maps: Spatial Trend Analysis

Carey et al. (2025)

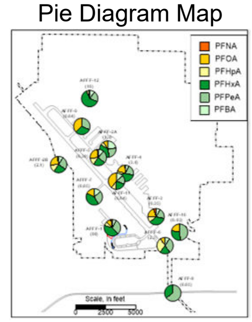
Radial Diagram Map



Stacked Bar Map



Pie Diagram Map



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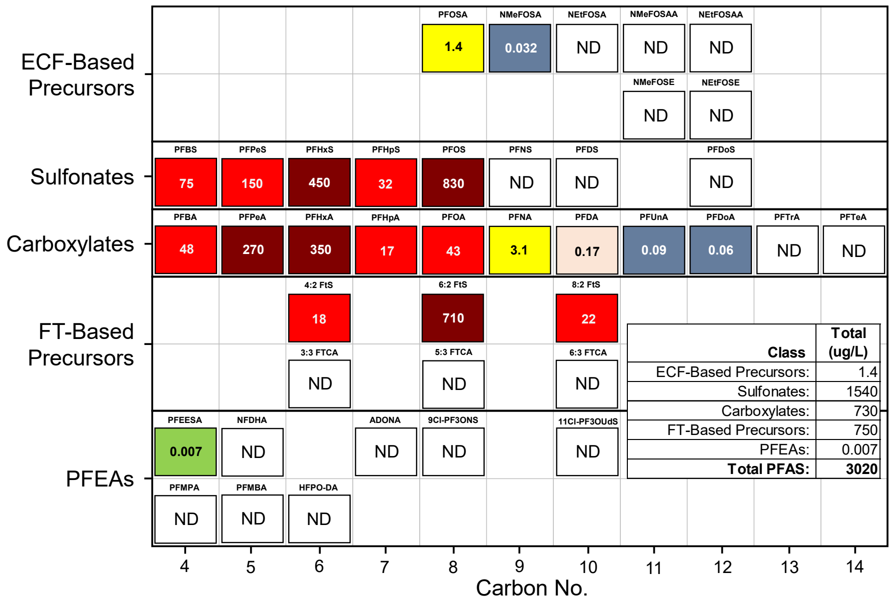
Heat Matrix for EPA Method 1633 Analytes



Concentration (ug/L)

- ND Non-detect
- ≤0.03
- 0.03 to 0.1
- 0.1 to 1
- 1 to 10
- 10 to 100
- >100
- n/a Not available

Method 1633 Heat Matrix Template.pptx

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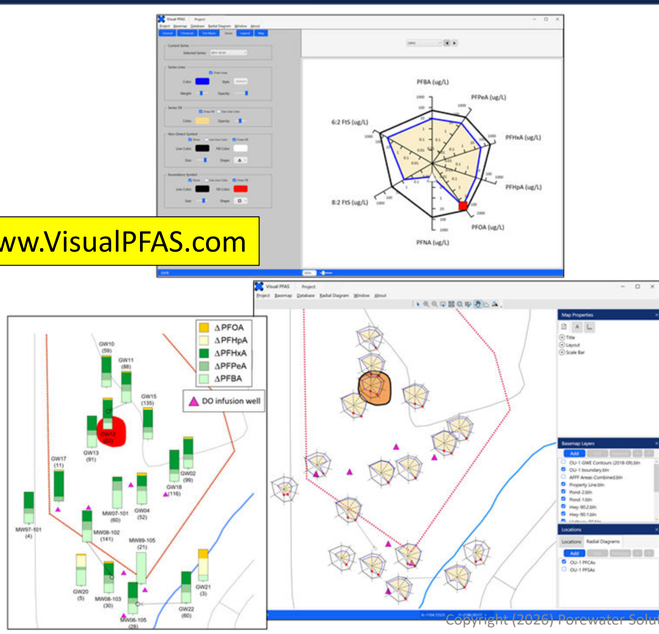
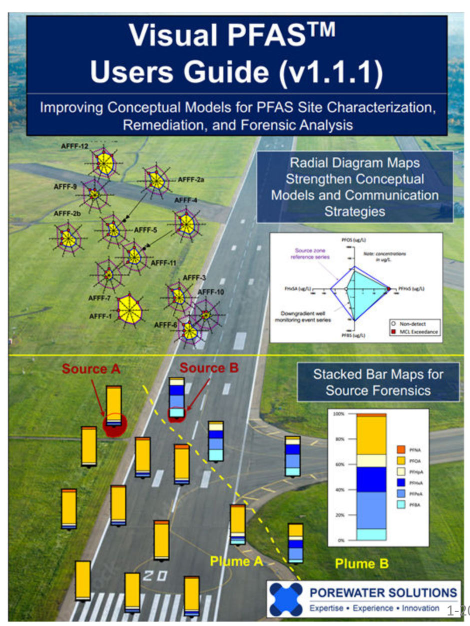
Visual PFAS™ for Mapping PFAS Inter-Relationships

www.VisualPFAS.com





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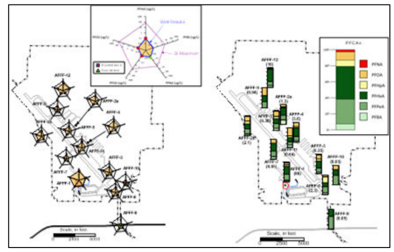
NGWA PFAS Forensic Methods White Paper

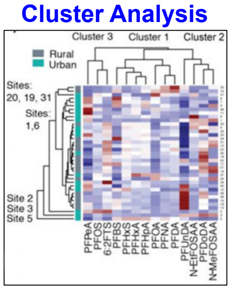
National Ground Water Association
PFAS Forensic Methods White Paper (Draft)

Radial Diagram & Stacked Bar Maps

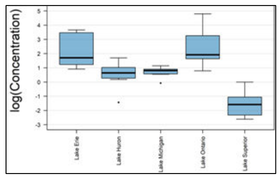


Heat Maps

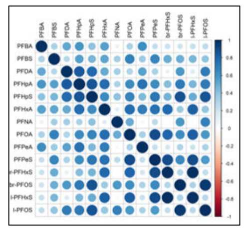
Cluster Analysis



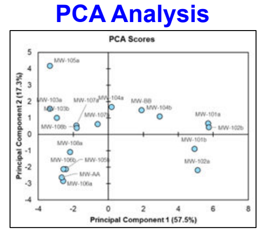
Box and Whisker Plots



Correlation Matrices



PCA Analysis



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PFAS Site Characterization South Dakota AFB

Remediation Journal WILEY

RESEARCH ARTICLE OPEN ACCESS

Visualizing PFAS Trends at a South Dakota AFFF-Impacted Site

Grant R. Carey[1,2] | Rita K. Krebs[3] | Gabriel T. Carey[1] | Mia Rebeiro-Tunstall[1] | Jeremiah Duncan[4] | Gillian N. Carey[1] | Kiera Rooney[1]

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Received: 26 December 2024 | **Revised:** 10 May 2025 | **Accepted:** 28 May 2025

Keywords: AFFF | forensic | PFAS | radial diagram | stacked bar | visualization

ABSTRACT
Various visualization alternatives are demonstrated for evaluating per-and polyfluoroalkyl substances (PFAS) trends at an aqueous film forming foam- (AFFF-) impacted site in South Dakota, including the use of radial diagrams, stacked bar maps, and pie charts. The purpose of this study was to compare and contrast visualization methods which may be used for PFAS site characterization or forensic assessments. PFAS groundwater concentration trends are first visualized based on site-wide wells with maximum perfluorosulfonic acid (PFOS) plus perfluorooctanoic acid (PFOA) concentrations in AFFF source areas. Then a more detailed analysis of trends, including the potential for precursor transformations to perfluoroalkyl acids (PFAAs), is presented for a smaller portion of the site where former fire training activities were conducted. The advantages of using radial diagram reference series, such as maximum source or background concentrations, to better illustrate changes along a flow path are discussed. The benefits of including symbols on radial diagram maps to illustrate where PFAS are non-detect or are in exceedance of site cleanup criteria, particularly in support of a PFAS plume delineation, are demonstrated. Radial diagrams and stacked bar maps are used to illustrate the relative proportion of perfluoroalkyl sulfonates and carboxylates in groundwater, which may help to identify relative contributions of AFFF products derived from electrochemical fluorination versus telomerization manufacturing processes. The benefit of using select PFAS ratios on radial diagram axes to support a combined assessment of precursor transformation and PFAA production along a flow path is demonstrated. Stacked bar maps are shown to have significant advantages over pie charts for PFAS forensic analyses.

1 | Introduction

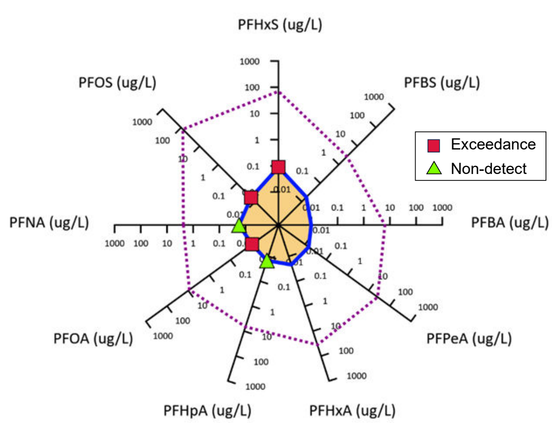
Per- and polyfluoroalkyl substances (PFAS) are widespread in the environment, and some PFAS are both resistant to degradation and are toxic at very low concentrations. PFAS that are regulated due to toxicity in groundwater and drinking water are typically a subset of constituents within the perfluoroalkyl acids (PFAAs) class. PFAAs may be further subdivided into two groups: perfluoroalkyl carboxylates (*carboxylates*) and perfluoroalkyl sulfonates (*sulfonates*). Precursors are parent PFAS species which may biodegrade, predominantly under aerobic conditions in groundwater, to PFAAs, which are recalcitrant due to the strength of the carbon-fluorine bond.

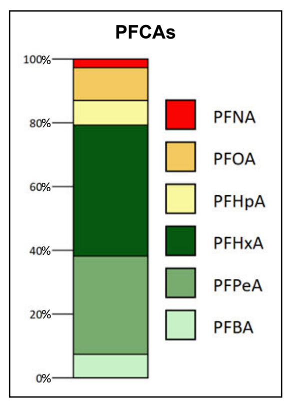
The US Environmental Protection Agency (USEPA; 2024) recently introduced new maximum contaminant levels (MCLs) including for the following PFAAs, which are typically present at AFFF-impacted sites: perfluorooctane sulfonate (PFOS) at 0.004 µg/L, perfluorohexane sulfonate (PFHxS) at 0.010 µg/L, perfluorooctanoate (PFOA) at 0.004 µg/L, and perfluorononanoate (PFNA) at 0.010 µg/L. These low MCLs pose a challenge to site remediation because PFAS concentrations in

Email: gcarey@porewater.com

Remediation Journal, 2025; 35:e70023
https://doi.org/10.1002/rem.70023 1 of 18

Section 3.1





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Acknowledgements

AIR FORCE CIVIL ENGINEER CENTER

Rita Krebs

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Gillian Carey
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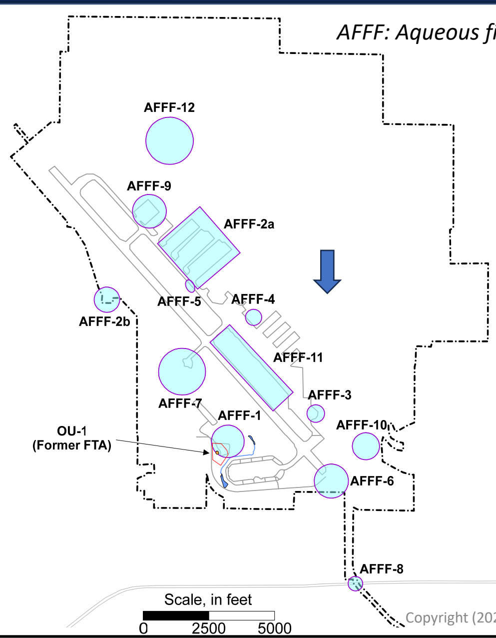
AFFF Source Areas

AFFF: Aqueous film-forming foam



AFFF Area	Location
AFFF-1	Current FTA
AFFF-2a AFFF-2b	70, 80, 90 Rows; and Outfall #3
AFFF-3	Building 618
AFFF-4	Former Fire Station (Building 7506)
AFFF-5	B-52 Crash (1972)
AFFF-6	B-1 Crash (1988)
AFFF-7	Delta Taxiway West Crash (2000)
AFFF-8	Marten Crash (2006)
AFFF-9	Crash 4 (2001)
AFFF-10	Wastewater Treatment Plant
AFFF-11	Spray Nozzle Test Area
AFFF-12	Building 88240
OU-1	Former Fire Training Area

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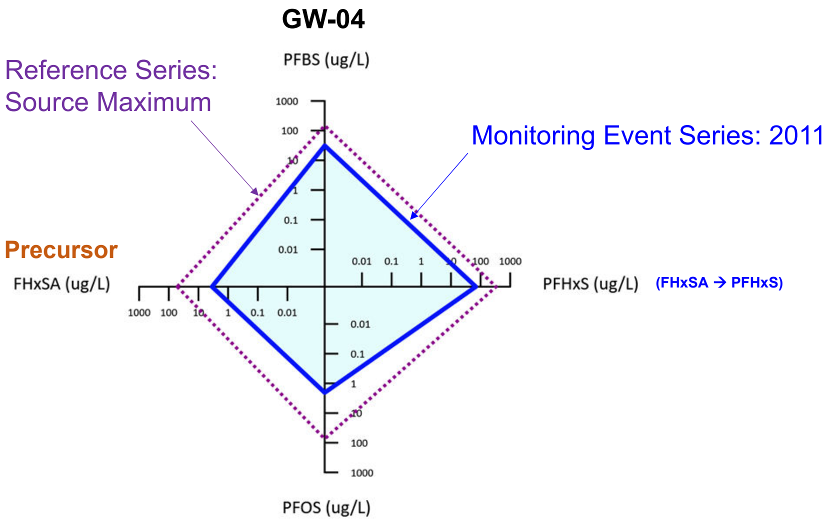
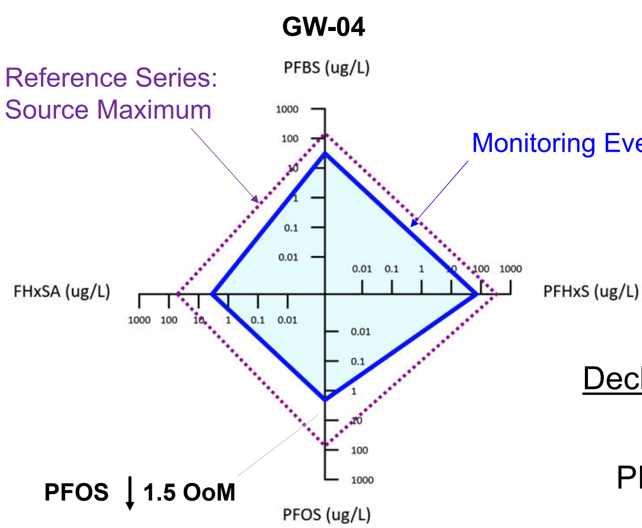
PFSAs Radial Diagram: Near-Source Well



PFSAs Radial Diagram: Near-Source Well



<u>Declining concentrations from source area</u>

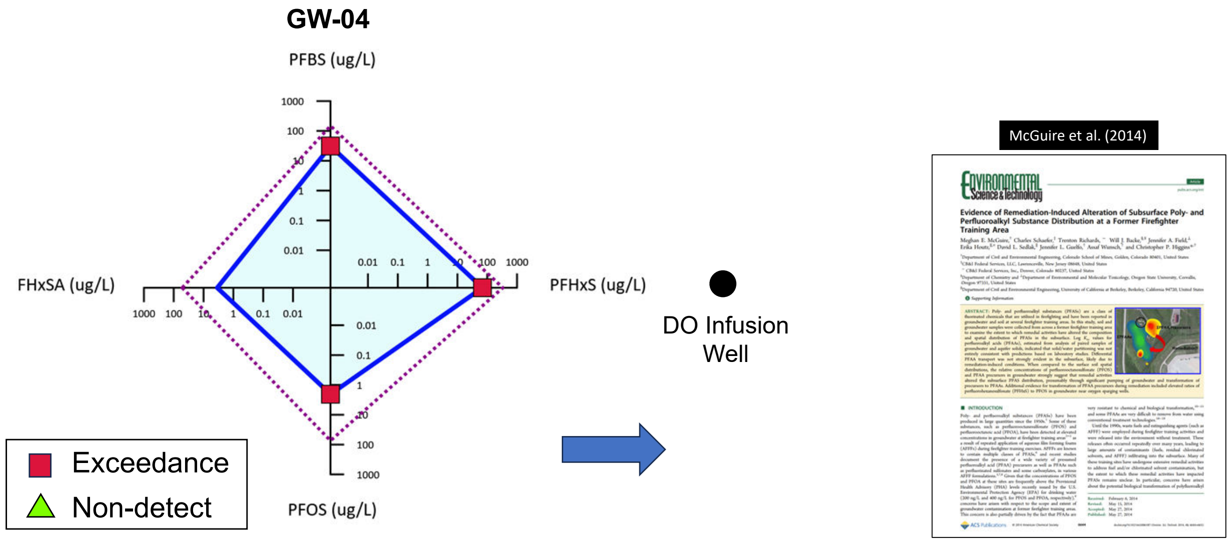
FHxSA: 1 OoM

PFBS, PFHxS: 0.5 OoM

PFOS: 1.5 OoM

OoM: Orders of Magnitude

PFSAs Radial Diagram: Trends Along Flow Path



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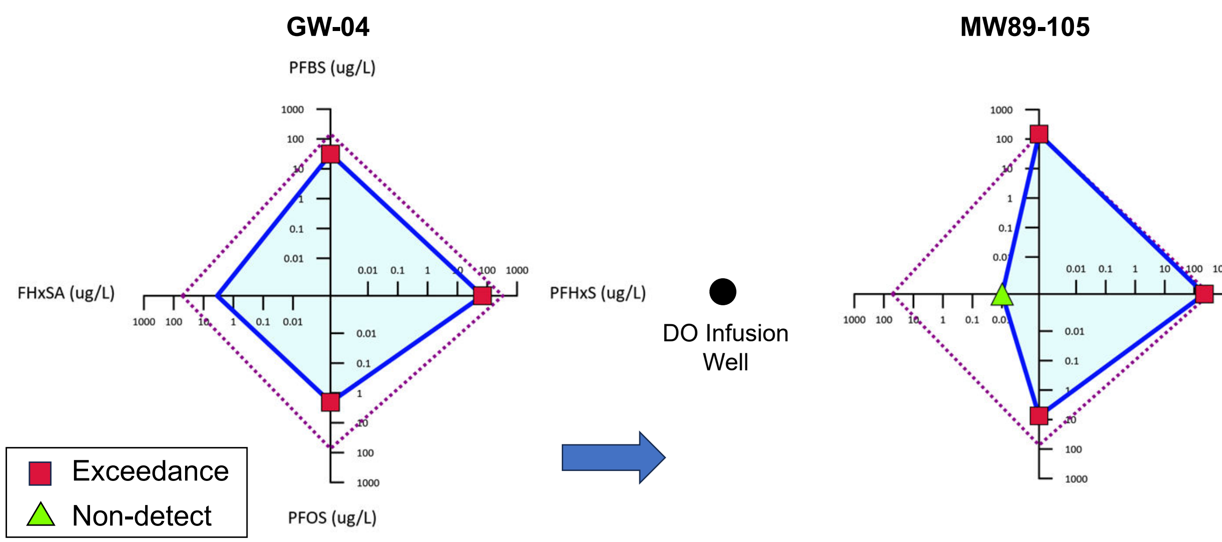
PFSAs Radial Diagram: Trends Along Flow Path



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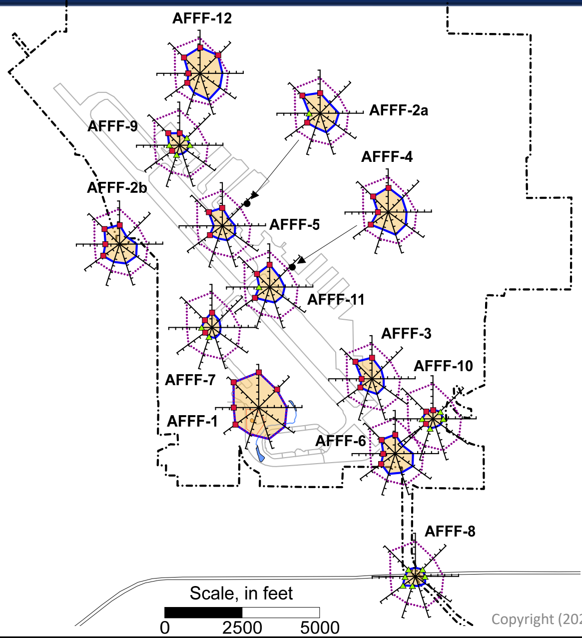
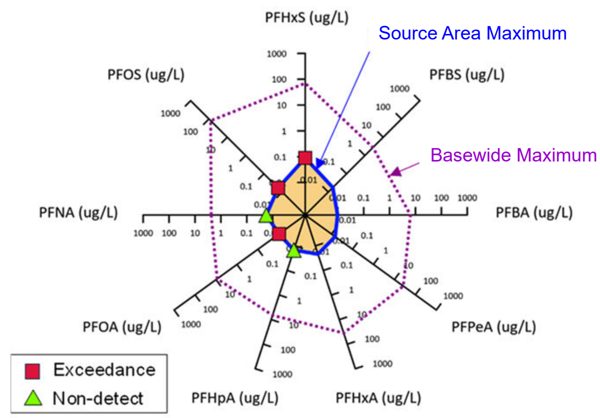
AFFF Source Areas: PFAAs (Site Inspection)





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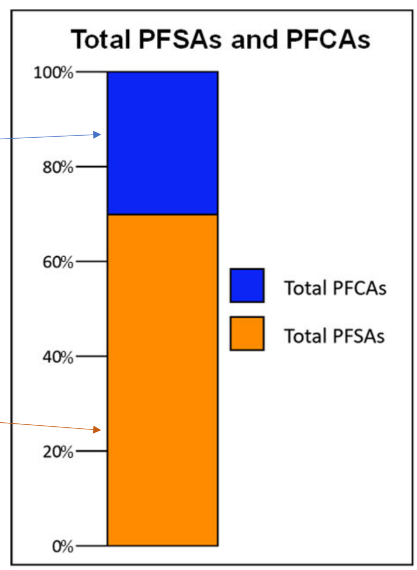
Stacked Bar Chart Example

AFFF Product:
Fluorotelomerization
(FT) Process

AFFF Product:
Electrochemical Fluorination
(ECF) Process



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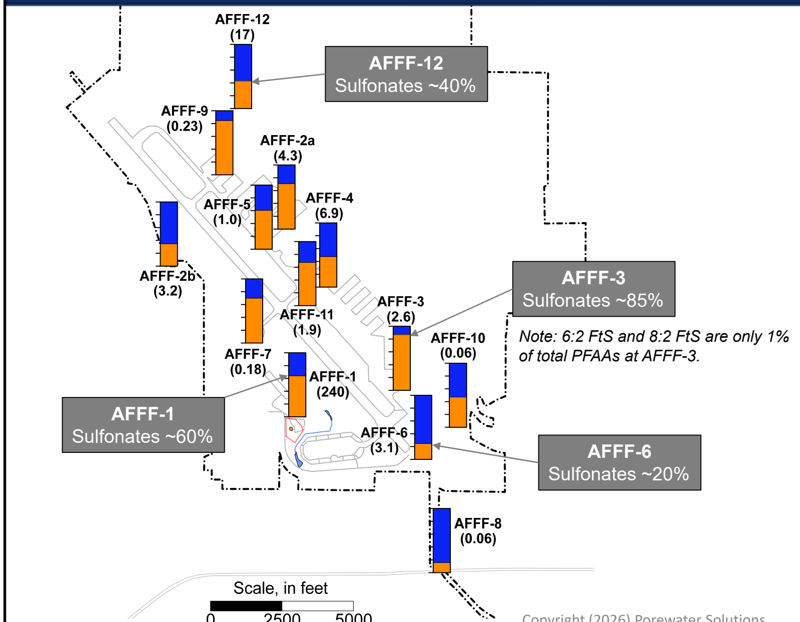
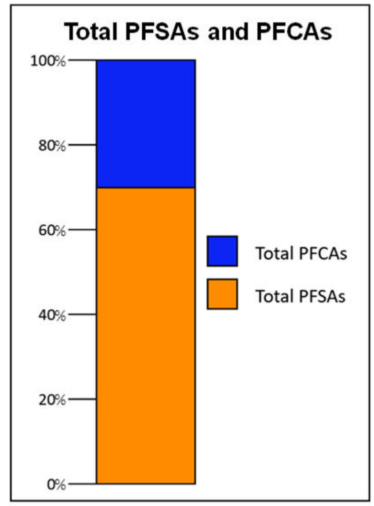
Stacked Bar Chart Example





Note: Values in brackets below the stacked bar labels represent Total PFAA concentrations.

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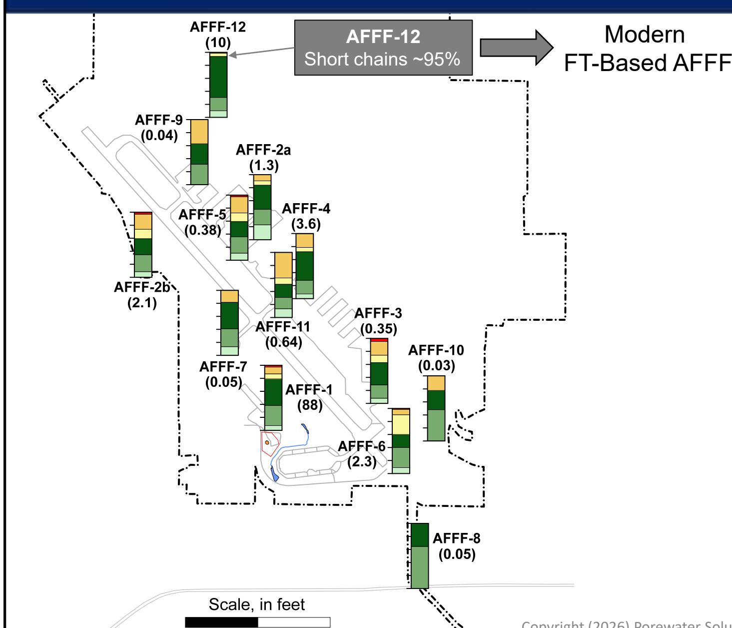
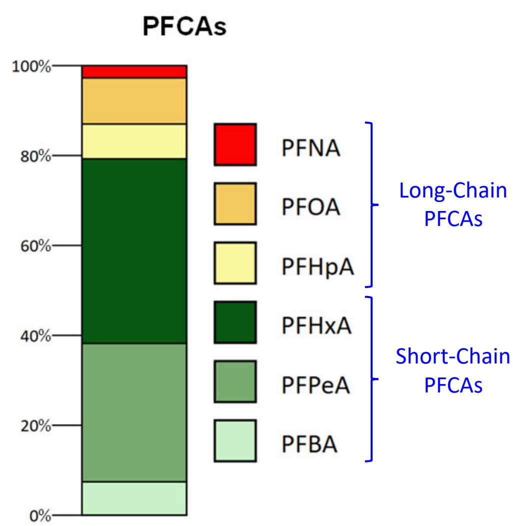
Source Area Short vs Long-Chain PFCAs





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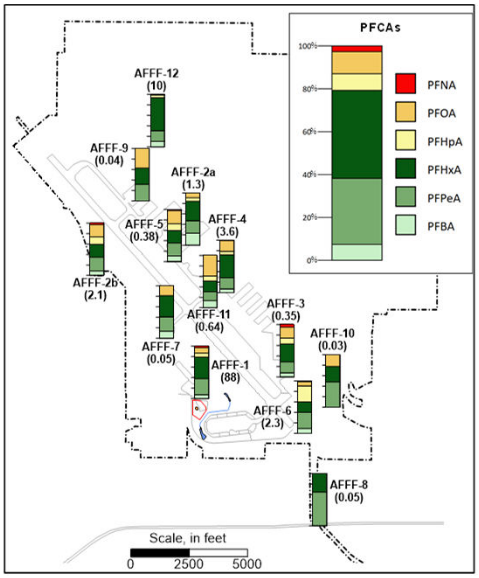
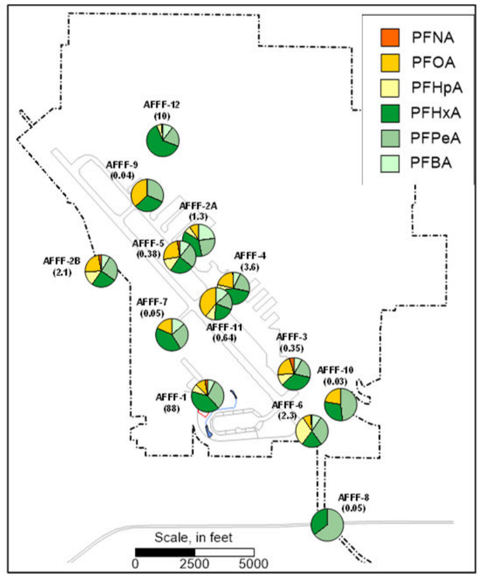
Stacked Bar vs Pie Chart Maps





Advantages of Stacked Bar Maps:

- Estimating proportions
- More intuitive (linear short- to long-chain)
- Comparing between wells

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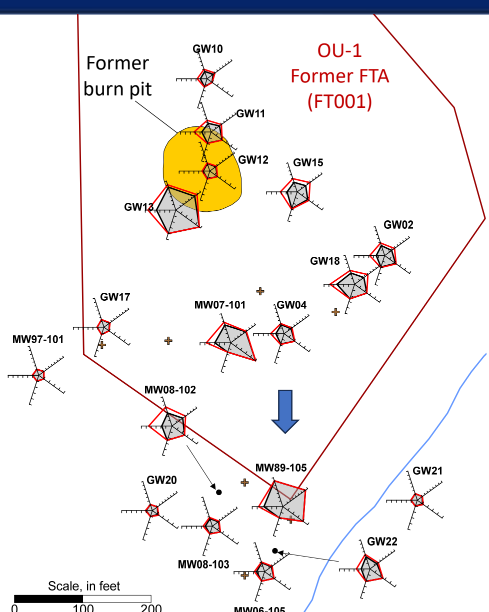
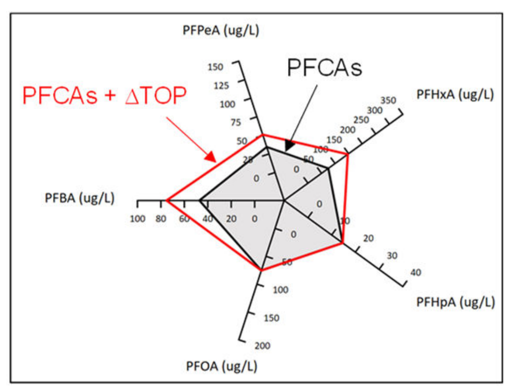
OU-1 (Former FTA): TOP Assay Results





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Ratios as Evidence of Precursor Transformations

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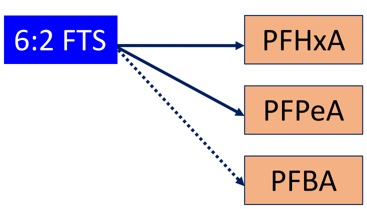
South Dakota Installation: 6:2 FTS Ratios at MW89-105



Biodegradation Process

Precursor concentration: ↓

Daughter product (PFAA) concentration: ↑

Ratio: ↓

$$\text{Ratio} = \frac{\text{Parent}}{\text{Daughter Product}}$$

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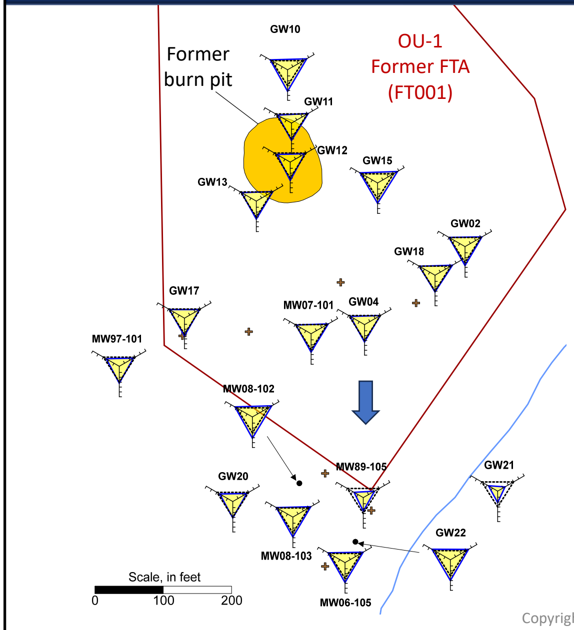
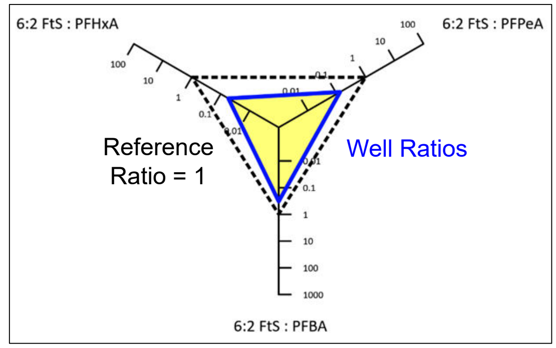
OU-1 (Former FTA): 6:2 FtS Ratios



Carey et al. (2025)



+ DO Infusion Well

Ellsworth AFB
Vadose Zone Case Study

Carey et al. (2026a,b)

PFAS Vadose Zone Mass Discharge at an AFFF-Impacted Site: 1. Validation Based on a Multiple Lines-of-Evidence Approach

By Grant R. Carey[1,2,*], David T. Adamson[3], Rita K. Krebs[4], Mia Rebeiro-Tunstall[1], Kevin G. Mumford[5], Bo Guo[6], Gabriel T. Carey[1], Kiera Rooney[1], and Sabrina Moga[1]

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[2] Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario

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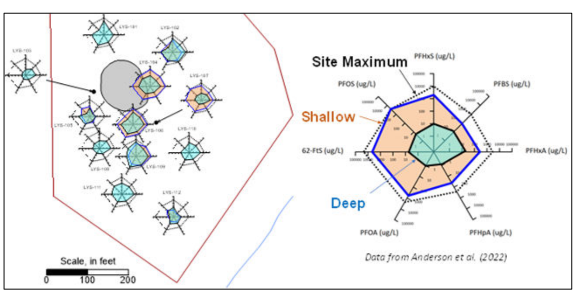
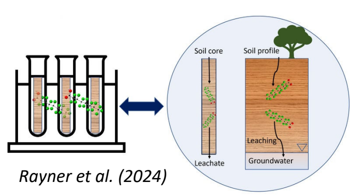
Correspondence: Grant Carey (gcarey@porewater.com)

Keywords: PFAS, AFFF, vadose zone, air-water interface, mass discharge

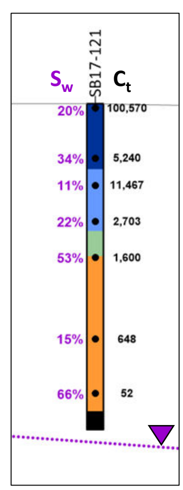
Abstract: Questions have recently been raised about the suitability of using porewater samples collected with suction lysimeters to estimate PFAS mass discharge in the vadose zone. Multiple lines of evidence were evaluated to determine if porewater samples collected during a data gaps investigation (DGI) in the former fire training area (FFTA) at Ellsworth Air Force Base were reproducible and representative. Lines of evidence used include supplemental geologic and hydrogeologic data which show the presence of a semi-continuous silt/clay layer directly above the water table throughout much of the FFTA, and gravimetric moisture content results that demonstrate vertical water flow at a depth of 15 ft is substantially limited due to semi-arid climatic conditions. Radial diagrams were used to visually demonstrate that there was negligible variability in porewater concentrations caused by varying sample yields in the deep zone. Additional lysimeters installed in the FFTA during the remedial investigation (RI) did not result in a significant difference in the estimated vertical mass discharge, which demonstrates that the number of lysimeter sampling points in this area is sufficient. Strong attenuation in PFAS soil concentrations with depth validates the order(s) of magnitude reduction between shallow and deep porewater concentrations observed near the former burn pit. Vadose zone PFAS mass discharge is shown to be 4% to 19%

Email: **gcarey@porewater.com**





Rayner et al. (2024)



Ellsworth AFB Case Study Acknowledgements

AIR FORCE CIVIL ENGINEER CENTER — **Rita Krebs**

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Queen's UNIVERSITY — **Kevin Mumford**

THE UNIVERSITY OF ARIZONA — **Bo Guo**

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Mia Rebeiro-Tunstall
Gabriel Carey

Kiera Rooney
Sabrina Moga
Maya Worthing

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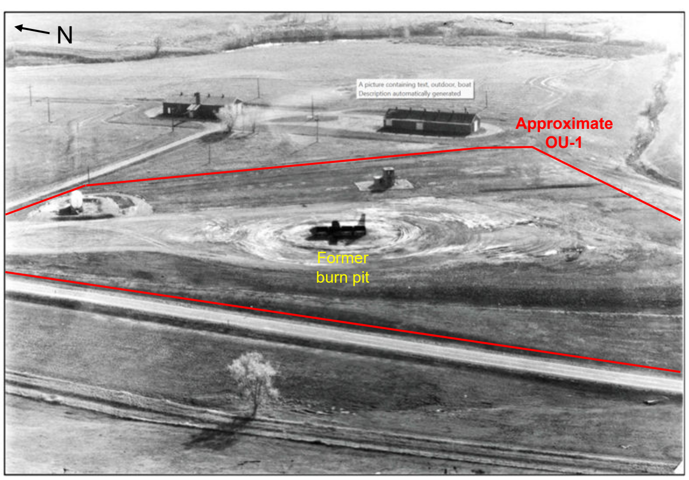
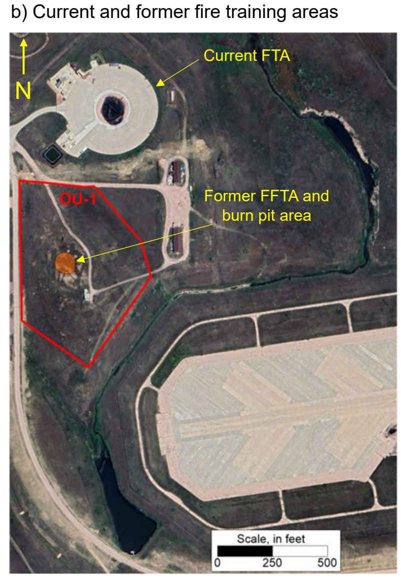
Current and Former Fire Training Areas

a) Former fire training area in 1985 (Rita Krebs, 2025)



b) Current and former fire training areas



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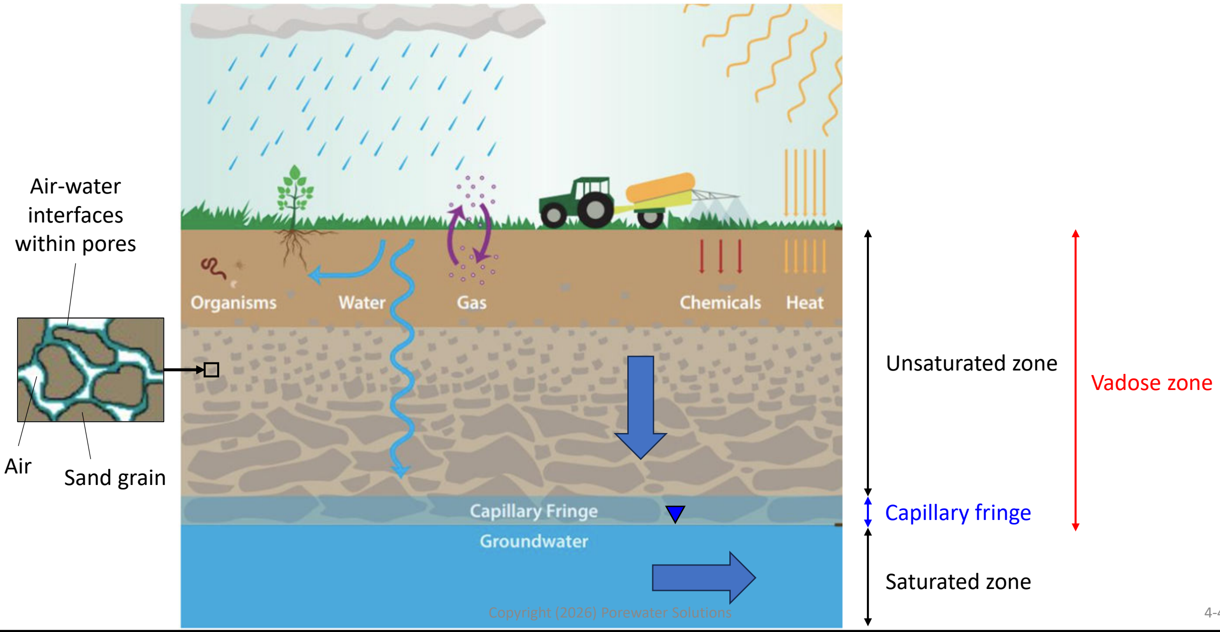
Vadose Zone Cross-Section



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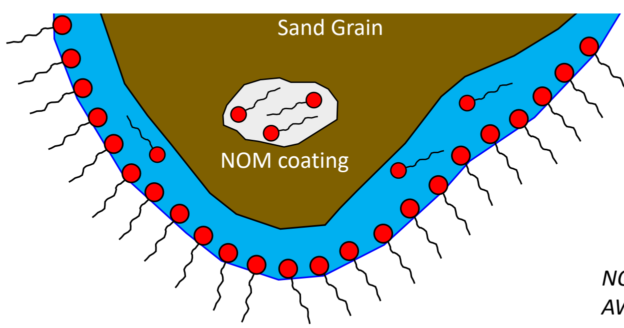
PFAS Mass Components in Soil



NOM: Natural organic matter
AWI: Air-water interface

<u>Three Mass Components in total soil concentration:</u>

1. Aqueous phase
2. Adsorbed to NOM
3. Adsorbed to AWI

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Long-Chain PFAS Adsorb to Air-Water Interfaces

Brusseau et al. (2018)

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Assessing the potential contributions of additional retention processes to PFAS retardation in the subsurface

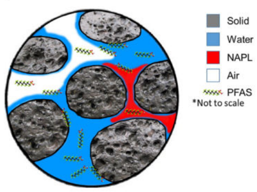
CrossMark

Mark L. Brusseau
429 Shantz Bldg, Soil, Water and Environmental Science Department, Hydrology and Atmospheric Sciences Department, School of Earth and Environmental Sciences, University of Arizona, United States

HIGHLIGHTS

- A comprehensive model for PFAS retention in porous media is proposed.
- Adsorption at the air-water interface contributes greatly to PFOA/PFOS retention.
- Adsorption at the NAPL-water interface and NAPL partitioning are also significant.

GRAPHICAL ABSTRACT



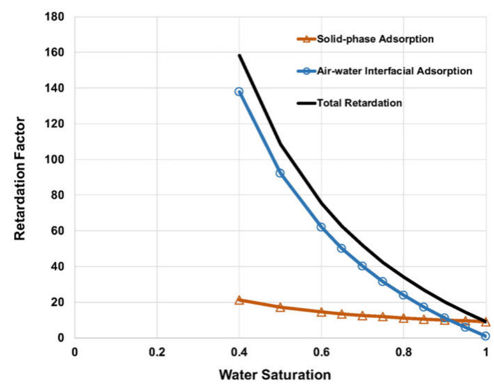


Fig. 2. Impact of water saturation on PFOS retardation factors for solid-phase adsorption, air-water interface adsorption, and the sum of the two (total).

Retardation Coefficient (R)

R = Retardation coefficient (dimensionless)
K_{oc} = organic carbon partitioning coefficient (L/kg)
f_{oc} = fraction of organic carbon content (g/g)
ρ_b = dry bulk density (kg/L)
θ_w = water-filled porosity (m^3/m^3)
K_{aw} = air-water interfacial adsorption coefficient (cm^3/cm^2)
A_{aw} = air-water interfacial area (cm^2/cm^3)

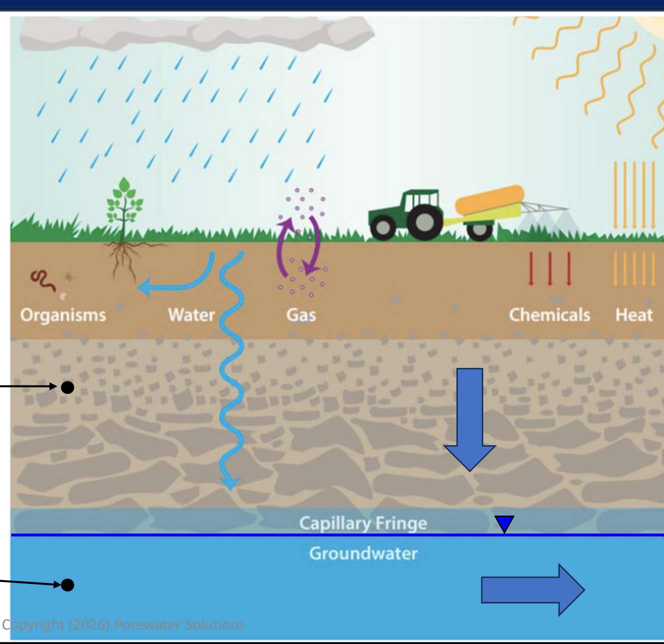
Brusseau and Guo (2022)

Unsaturated Zone

$$R = 1 + \frac{\rho_b}{\theta_w} K_{oc} f_{oc} + \frac{K_{aw} A_{aw}}{\theta_w}$$

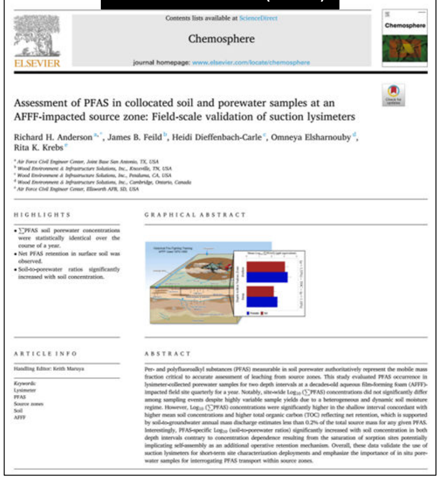
Saturated Zone

$$R = 1 + \frac{\rho_b}{\theta_w} \underbrace{K_{oc} f_{oc}}_{K_d}$$



Lysimeter Locations: DGI and RI

Anderson et al. (2022)



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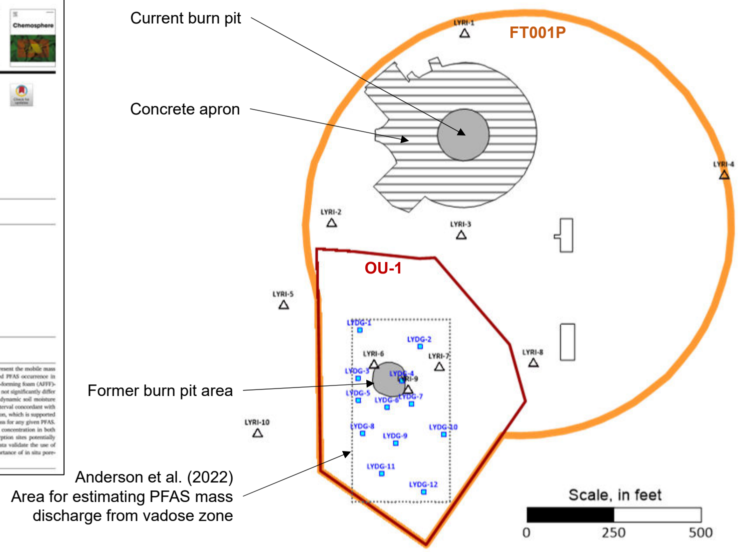
Assessment of PFAS in collocated soil and porewater samples at an AFFF-impacted source zone: Field-scale validation of suction lysimeters

Richard H. Anderson, James B. Feild, Heidi Dieffenbach-Carle, Omneya Elsharnouby, Rita K. Krebs



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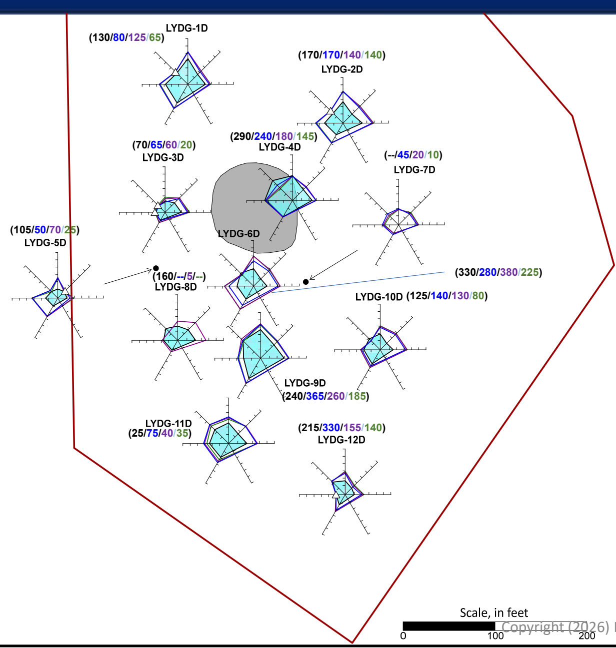
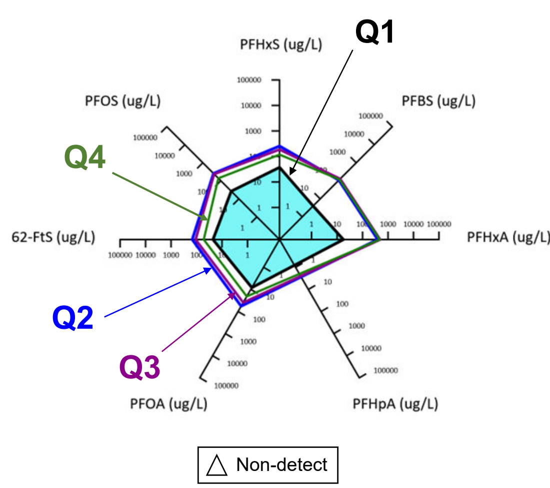
Checking Porewater Sample Reproducibility



Sample yields (mL) by event:
(25/75/40/35)

-- Insufficient sample volumetric yield



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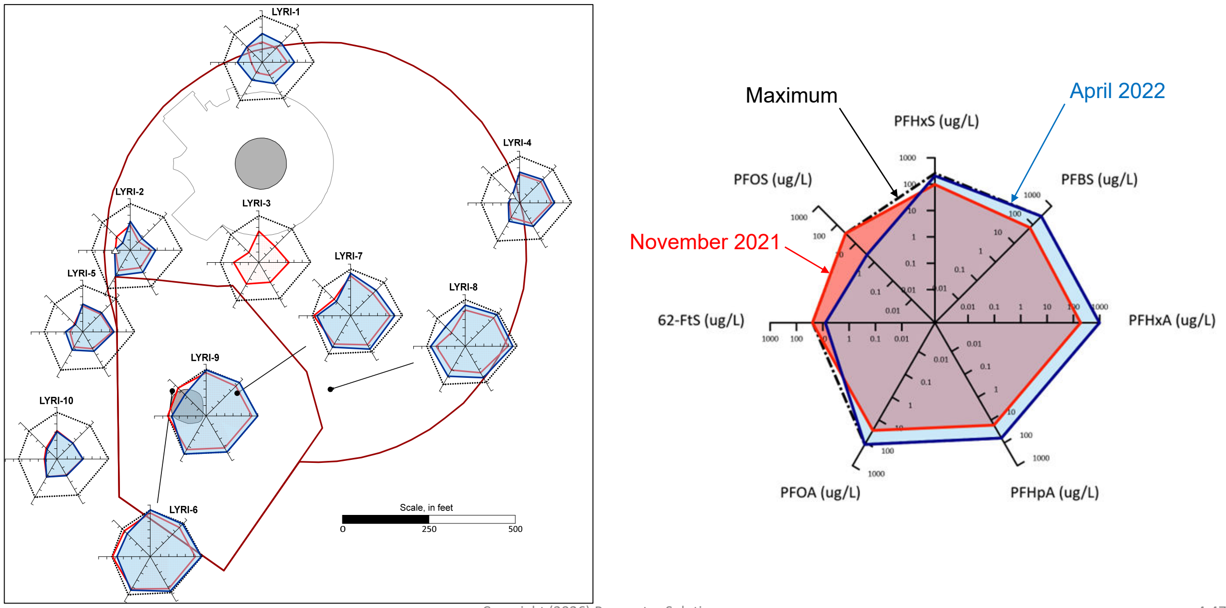
RI Lysimeters



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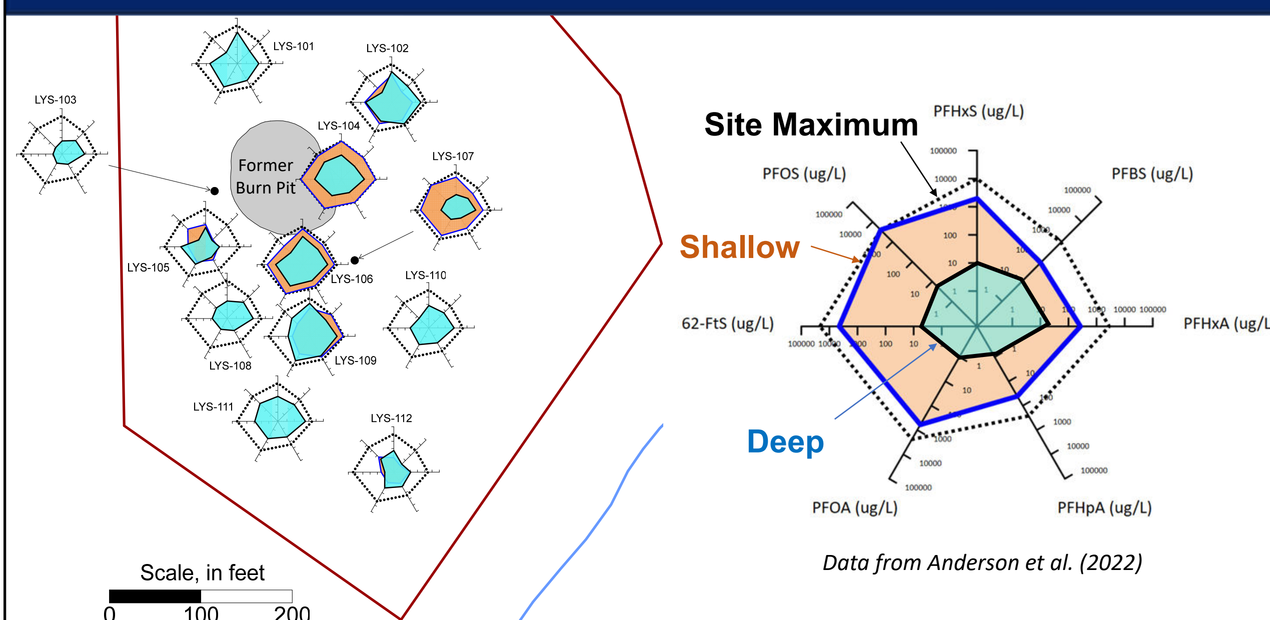
Shallow versus Deep Porewater Concentrations



Data from Anderson et al. (2022)

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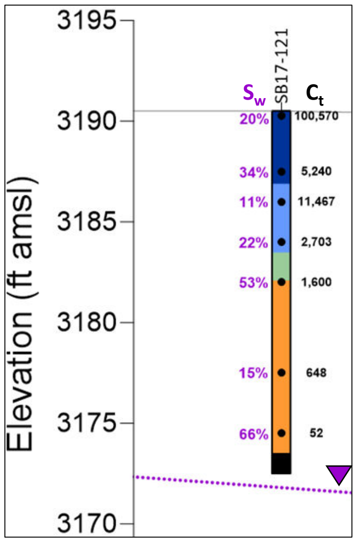
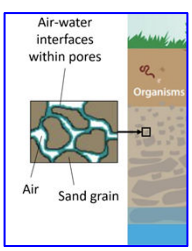
Case Studies of PFAS Attenuation in Vadose Zone



Semi-Arid Climate (P = 16 inch/year)
AF_{vz} 2000x

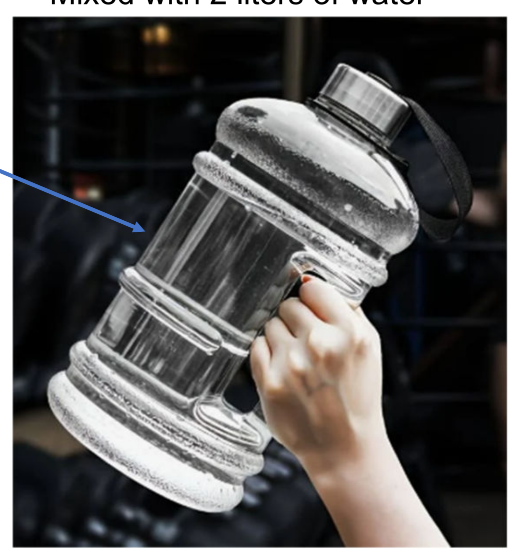
- No recovery
- SC: Silt or clay
- SS or CG: Silty sand or clayey gravel
- FS: Very fine sand to fine sand
- MS or CS: Medium to coarse sand
- SG or G: Gravel
- B: Bedrock
- Top of silt/clay layer in other soil borings
- Water table (January 2018)
- 275 Sum of PFAS of Interest in porewater or groundwater (ug/L)
- 502 Sum of PFAS of Interest in soil (ug/kg)
- 20% Water saturation estimated based on moisture content

SPLP Tests: 20x Mass Ratio (Liquid-Solid)



4 Tablespoons of soil
(0.1 kg ~ 0.06 L)

Mixed with 2 liters of water



S_w	V_{PW} (Liters)	Dilution Factor, *LLDF*
15%	0.004	530
50%	0.012	160

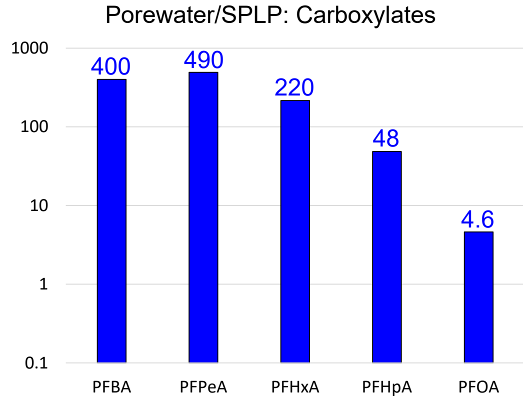
ρ_b = 1.6 kg/L
θ_t = 0.40 L/L

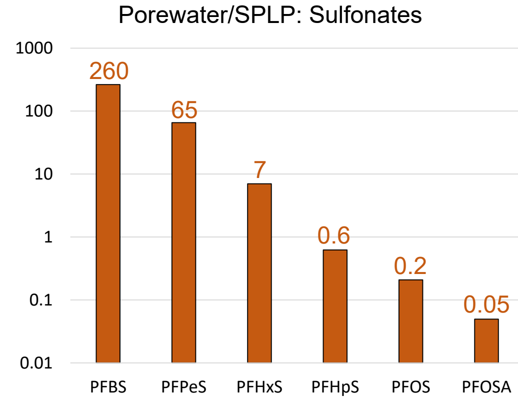
$$LLDF = \frac{(20\ L/kg)\ \rho_b}{S_w\ \theta_t}$$

where *LLDF* = liquid-to-liquid dilution factor (dimensionless);
ρ_b = soil dry bulk density (kg/L);
S_w = water saturation (%); and
θ_t = total porosity (L/L).

Ratio of Porewater to SPLP Leachate

LYRI-9: S_w = 13%



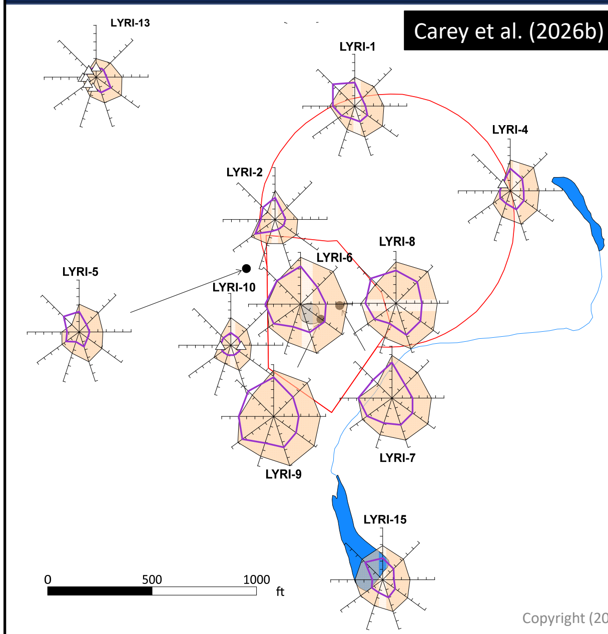


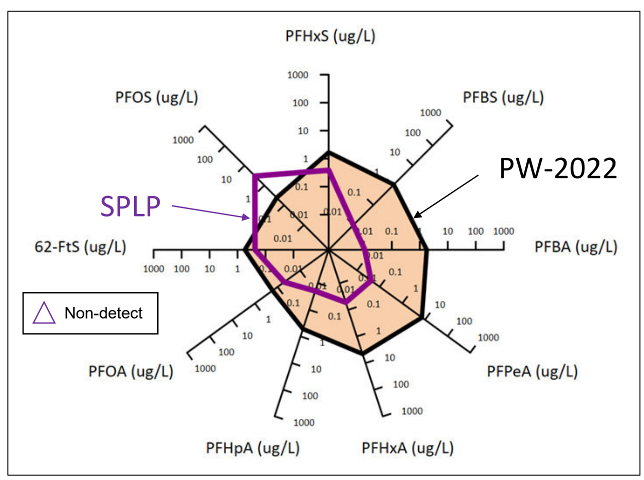
Carey et al. (2026b)

$$C_{SPLP} = C_p \left(\frac{\frac{\theta_w}{\rho_b}\left(1+K_d\frac{\rho_b}{\theta_w}+\frac{K_{aw}a_{aw}}{\theta_w}\right)}{(K_d+20\ L/kg)} \right)$$

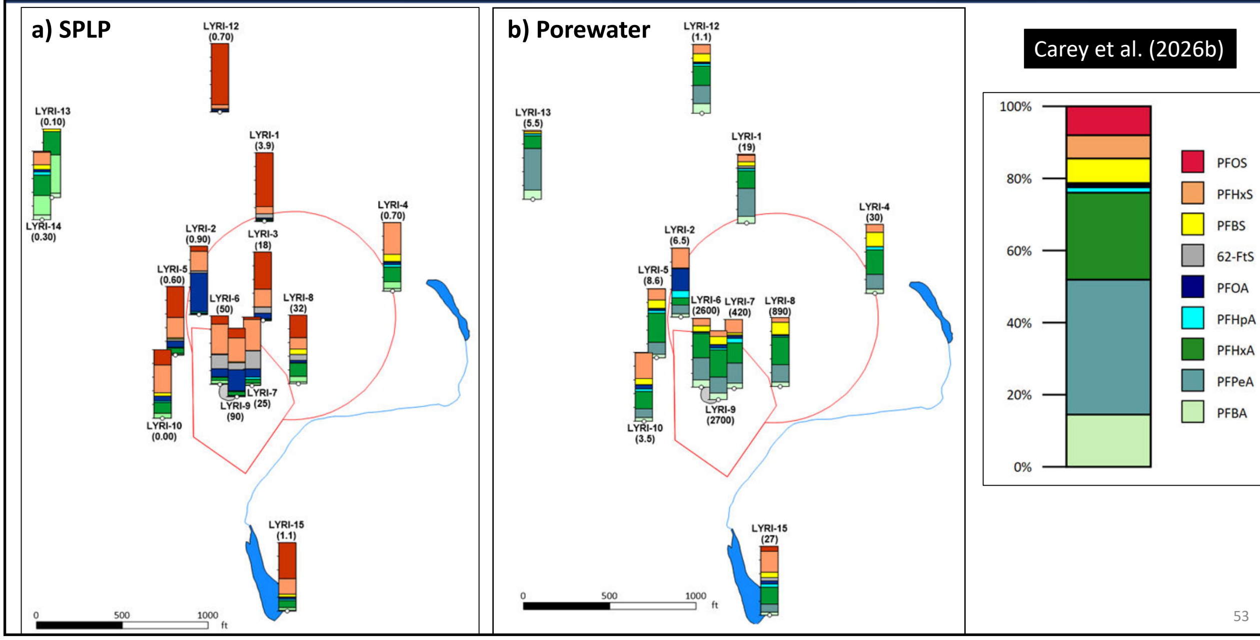
SPLP versus Porewater Concentrations

Carey et al. (2026b)

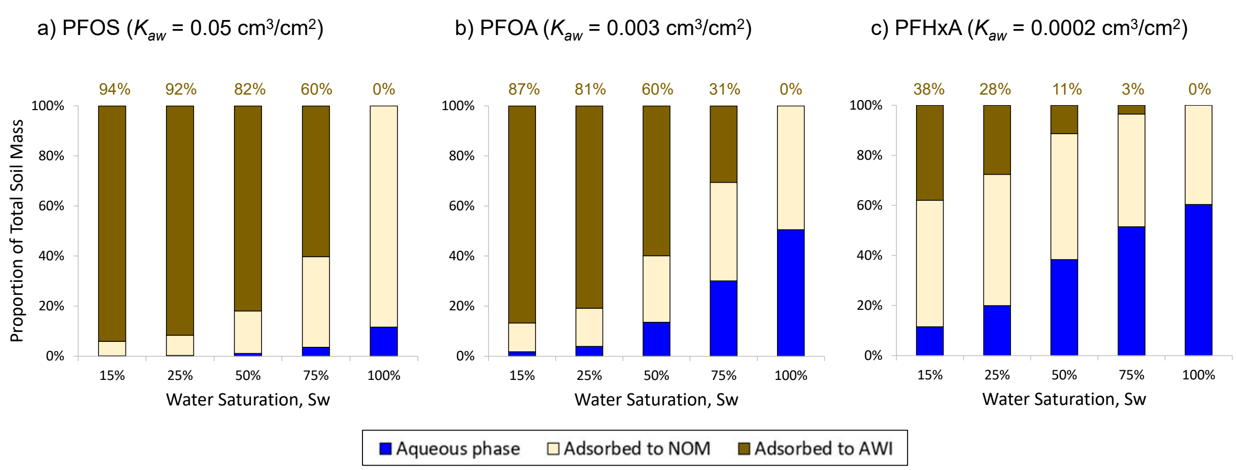




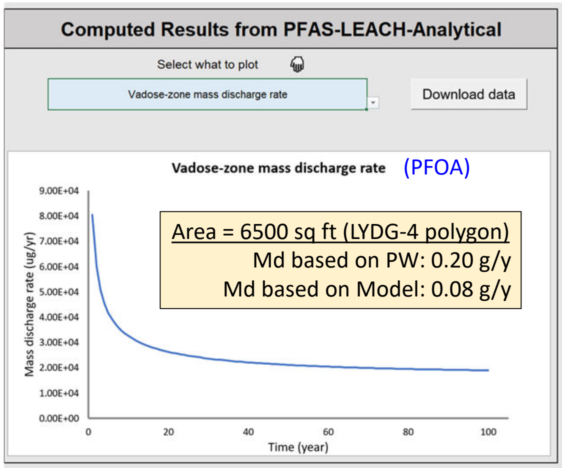
PFAS Composition: SPLP versus Porewater



PFAS Mass Distribution in the Vadose Zone



PFAS Leach: Mass Discharge at Former Burn Pit

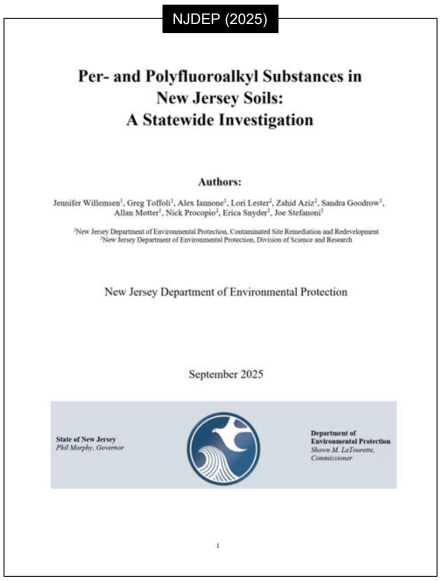


https://github.com/GuoSFPLab/PFAS-LEACH-Tier-3-4

New Jersey State-wide Background Soil Survey

Section 3.3

New Jersey Statewide PFAS Soil Survey


NJDEP (2025)

Per- and Polyfluoroalkyl Substances in
New Jersey Soils:
A Statewide Investigation

Authors:

Jennifer Willemsen[1], Greg Toffoli[1], Alex Iannone[1], Lori Lester[2], Zahid Aziz[2], Sandra Goodrow[1], Allan Motter[1], Nick Procopio[2], Erica Snyder[1], Joe Stefanoni[1]

[1]New Jersey Department of Environmental Protection, Contaminated Site Remediation and Redevelopment
[2]New Jersey Department of Environmental Protection, Division of Science and Research

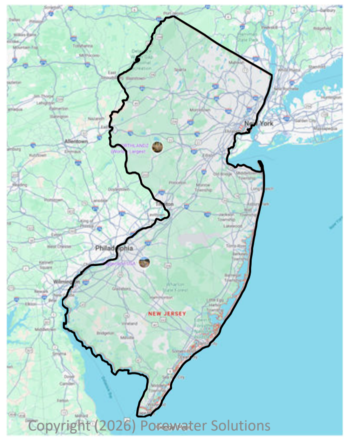
New Jersey Department of Environmental Protection

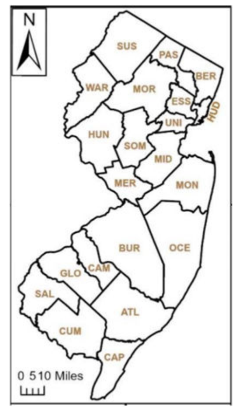
September 2025

State of New Jersey
Phil Murphy, Governor

Department of Environmental Protection
Shawn M. LaTourette, Commissioner

- **Goal:** To assess atmospheric deposition influence on PFAS in shallow soil
- 157 State-wide surficial soil samples





State-wide Maximum Surficial Soil Concentrations (ug/kg)

Class	4	5	6	7	8	9	10	11	12	13	14
ECF-Based Precursors					PFOSA ND	NMeFOSA ND	NEtFOSA ND	NMeFOSAA ND	NEtFOSAA ND		
								NMeFOSE ND	NEtFOSE ND		
Sulfonates	PFBS 0.22	PFPeS 0.087	PFHxS 0.83	PFHpS 0.049	PFOS 5.2	PFNS ND	PFDS 0.379		PFDoS 1.0		
Carboxylates	PFBA 2.7	PFPeA 3.6	PFHxA 2.6	PFHpA 3.2	PFOA 9.4	PFNA 8.1	PFDA 4.8	PFUnA 15	PFDoA 3.8	PFTrA 2.4	PFTeA 1.4
FT-Based Precursors			4:2 FtS ND		6:2 FtS 0.37		8:2 FtS ND				
			3:3 FTCA ND		5:3 FTCA ND		6:3 FTCA ND				
PFEAs	PFEESA ND	NFDHA ND		ADONA ND	9Cl-PF3ONS ND		11Cl-PF3OUdS ND				
	PFMPA ND	PFMBA ND	HFPO-DA 0.95								

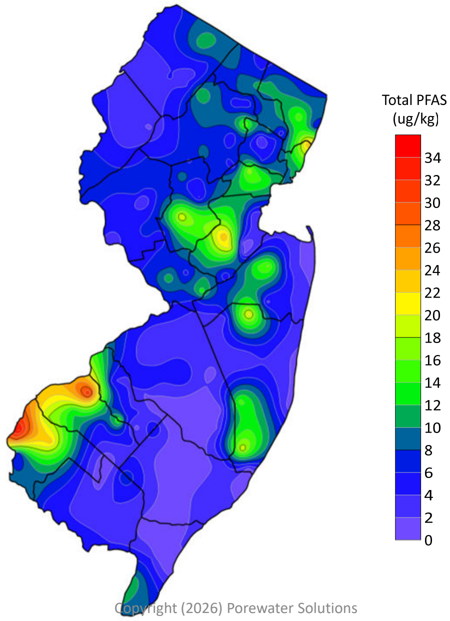
Carbon No.

Concentration (ug/kg)

- Non-detect
- 0 to 3
- 3 to 6
- 6 to 9
- 9 to 12
- 12 to 15
- n/a Not available

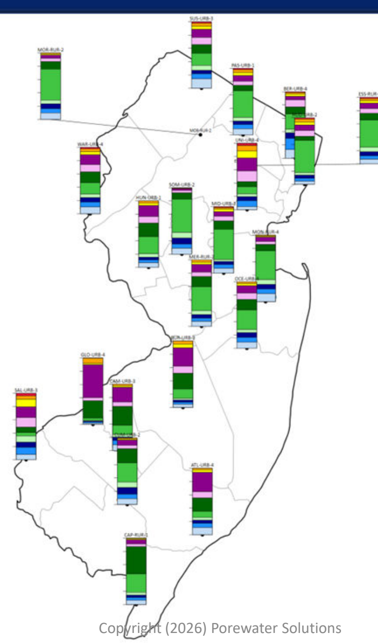
Method 1633 Heat Matrix Template.pptx

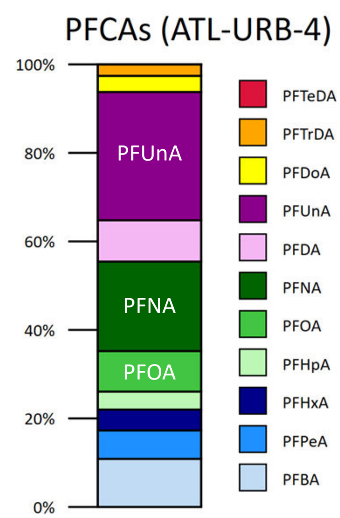
Heat Map Example: Total PFAS Contours



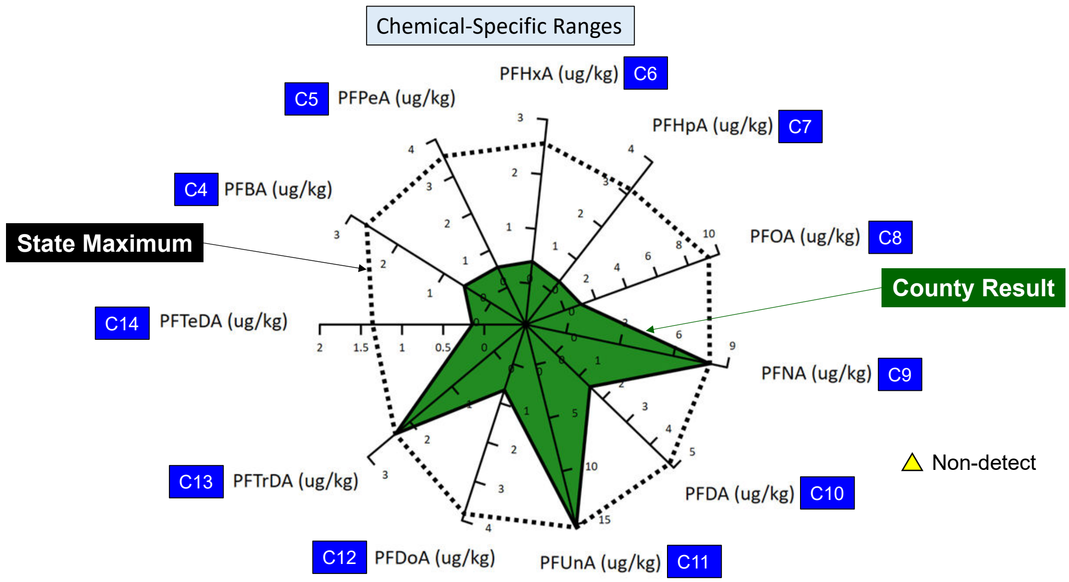
Stacked Bar Map: PFCAs

Note: County stacked bars plotted at Locations with maximum Total PFAS

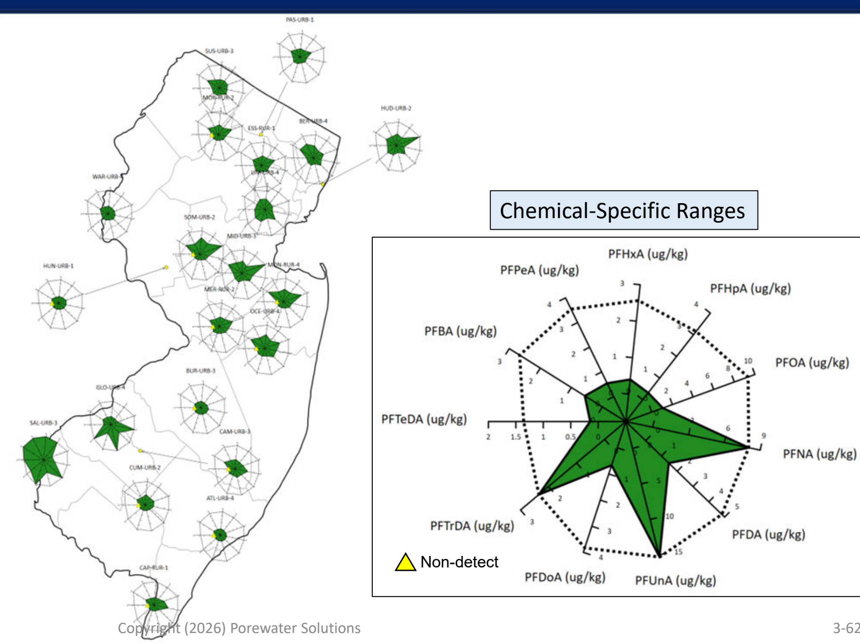




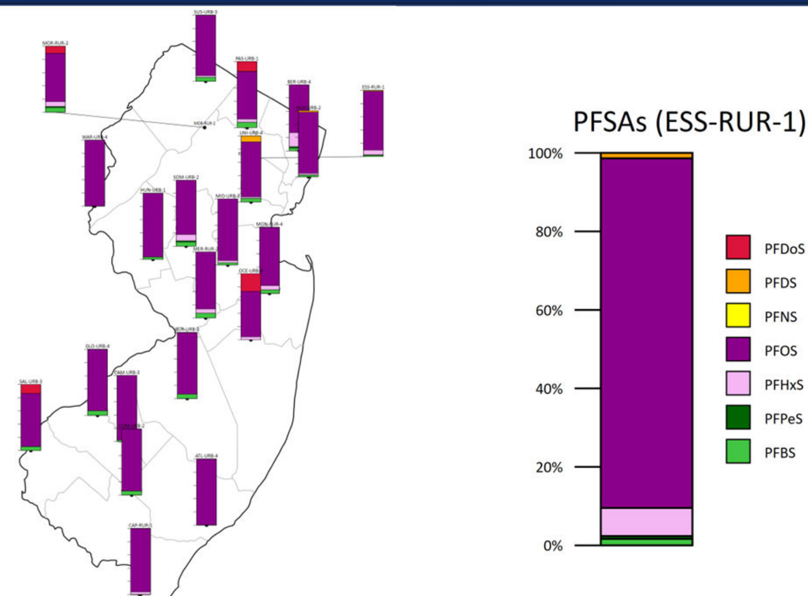
Radial Diagram Map: PFCAs (Arithmetic Scale)



Radial Diagram Map: PFCAs (Arithmetic Scale)



Stacked Bar Map: PFSAs

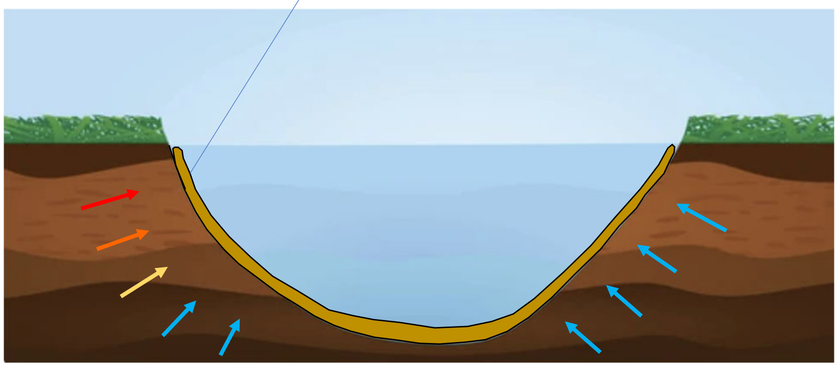


Michigan Case Study

Section 3.2

Groundwater Discharge Conceptual Model

- Discharge filtered in organic-rich sediments
- PFOS adsorption in sediments >> shorter-chains



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PFAS Sample Results Table

Sample Location	SW CM P23D	SW CM P23D	SW CM P12D	SW CM P3D	SW CM P3D	PW CM 01	PW CM 02	PW CM 03	PW CM 04	PW CM 05	PW CM 06	MW013 (2-7)	MW013 (13.5-14.5	MW-0013 (24-25)	MW013 (34-35)
Sample	FD1808301515GC	SW1808301515GC	SW1808301600GC	FD1808310950GC	SW1808310950GC	PW1808311100GC	PW1809041355GC	PW1809041415GC	PW1809041445GC	PW1809041545GC	PW1809041630GC				
Sample Type	Surface Water	Surface Water	Surface Water	Surface Water	Surface Water	Pore Water	Pore Water	Pore Water	Pore Water	Pore Water	Pore Water	GW	GW	GW	GW
Date Sampled	8-30-2018	8-30-2018	8-30-2018	8-31-2018	8-31-2018	8-31-2018	9-4-2018	9-4-2018	9-4-2018	9-4-2018	9-4-2018	01-Oct-18	01-Oct-18	01-Oct-18	01-Oct-18
Lab Report	1802887	1802887	1802887	1802887	1802887	1802887	1802900	1802900	1802900	1802900	1802900				
PFAS Compound	Duplicate			Duplicate											
Perfluorobutanoic acid (PFBA)	17.2	16.6	33.3	25.2	25.1	196.0	43.1	44.7	56.6	53.9	116.0	48.6	8.2	8.7	12.4
Perfluoropentanoic acid (PFPeA)	48.7	48.7	110.0	59.1	59.4	310.0	98.6	123.0	135.0	140.0	159.0	178.0	20.7	19.5	42.9
Perfluorohexanoic acid (PFHxA)	37.1	38.1	131.0	51.5	50.2	260.0	93.4	97.3	109.0	76.5	446.0	249.0	18.5	13.2	52.8
Perfluoroheptanoic acid (PFHpA)	10.8	11.4	48.8	20.3	19.3	77.1	24.2	27.5	37.4	8.8	121.0	77.2	1.4	1.9	13.5
Perfluorooctanoic acid (PFOA)	33.2	33.0	145.0	30.8	31.9	162.0	186.0	50.6	113.0	73.9	612.0	294.0	1.8	<1	41.0
Perfluorononanoic acid (PFNA)	1.6	1.9	8.9	ND	ND	5.5	2.3	4.4	16.5	3.9	3.8	7.9	<1	<1	<1
Perfluorodecanoic acid (PFDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluoroundecanoic acid (PFUnA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorododecanoic acid (PFDoA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorotridecanoic acid (PFTrDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorotetradecanoic acid (PFTeDA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorodecane sulfonic acid (PFDS)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Perfluorobutane sulfonic acid (PFBS)	ND	ND	8.4	2.3	2.4	21.3	2.3	2.2	10.1	ND	41.2	44.1	1.4	2.2	4.5
Perfluoropentane sulfonic acid (PFPeS)	2.3	2.2	12.6	3.0	3.4	15.3	2.9	2.6	15.4	1.8	34.6	33.9	<1	<1	6.1
Perfluorohexane sulfonic acid (PFHxS)	151.0	153.0	478.0	116.0	106.0	358.0	328.0	122.0	463.0	115.0	1100.0	932.0	4.1	1.7	102.0
Perfluoroheptane sulfonic acid (PFHpS)	12.6	10.8	19.2	4.0	3.9	7.5	155.0	8.8	33.4	16.0	ND	23.0	<1	<1	<1
Perfluorooctane sulfonic acid (PFOS)	271.0	281.0	1410.0	88.0	83.0	146.0	6240.0	994.0	3810.0	2120.0	42.2	425.0	1.7	<1	2.9
Perfluorononane sulfonic acid (PFNS)	ND	ND	ND	ND	ND	ND	ND	1.7	3.3	1.8	ND	ND	ND	ND	ND
Perfluorooctanesulfonamide (PFOSA)	ND	ND	5.3	ND	ND	ND	ND	11.9	3.5	122.0	ND	ND	ND	ND	ND
4:2 Fluorotelomer sulfonic acid (4:2 FTS)	1.9	1.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
6:2 Fluorotelomer sulfonic acid (6:2 FTS)	47.7	44.6	75.1	8.3	9.2	27.7	231.0	61.3	81.0	67.7	7.5	101.0			15.7
8:2 Fluorotelomer sulfonic acid (8:2FTS)	ND	ND	3.9	ND	ND	ND	ND	75.4	32.8	45.4	ND	ND	ND	ND	ND
N-Ethyl Perfluorooctane sulfonamindo acetic acid (EtFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
N-Methyl Perfluorooctane sulfonamide (MeFOSAA)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PFOA+PFOS	304.2	314.0	1555.0	118.8	114.9	308.0	6426.0	1044.6	3923.0	2193.9	654.2	719.0	3.5	ND	43.9
Total PFAS	635.1	643.1	2489.5	408.4	393.7	1586.4	7406.7	1627.4	4920.0	2846.6	2683.3	2413.7	57.8	47.2	293.8

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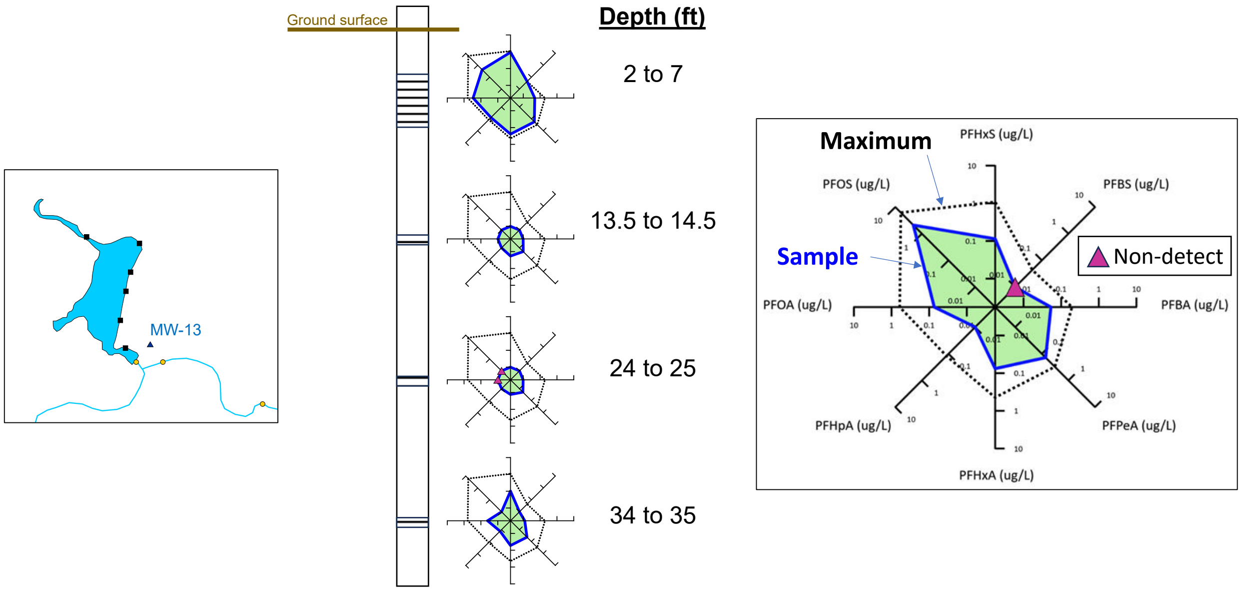
Nested Groundwater Samples (MW-13)



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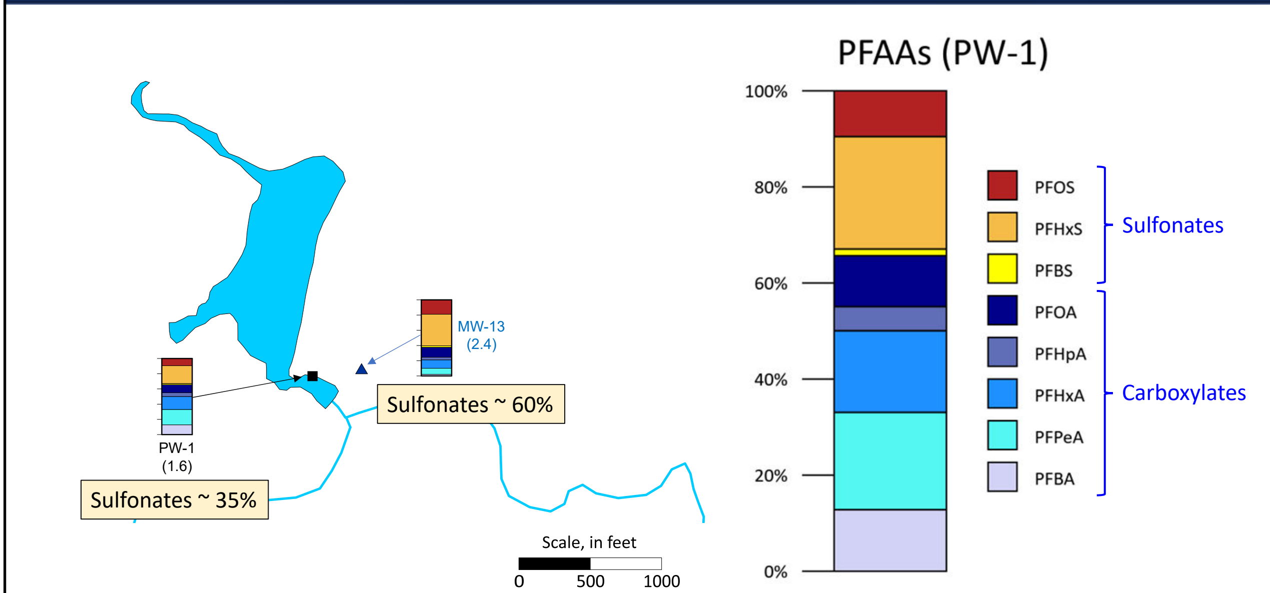
Adjacent GW and PW Samples – Stacked Bars



Note: Values in brackets are total PFAAs in ug/L.

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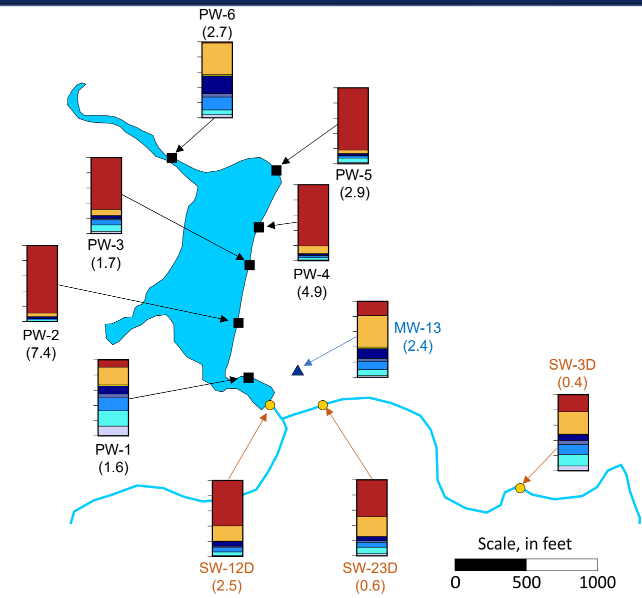
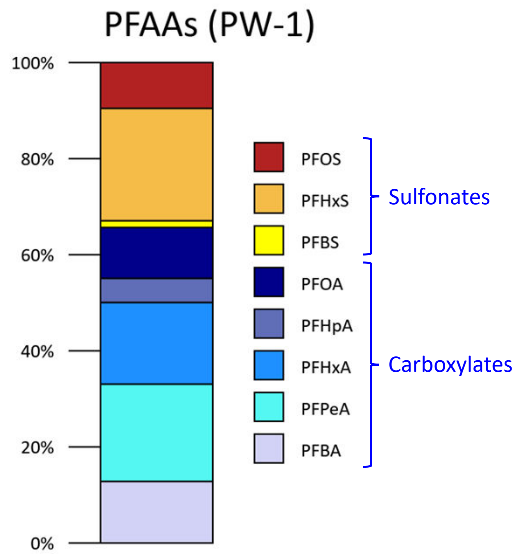
Wurtsmith AFB: GW, PW, SW





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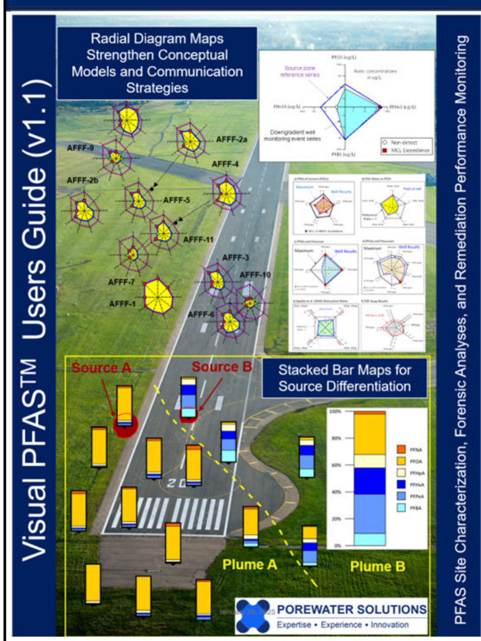
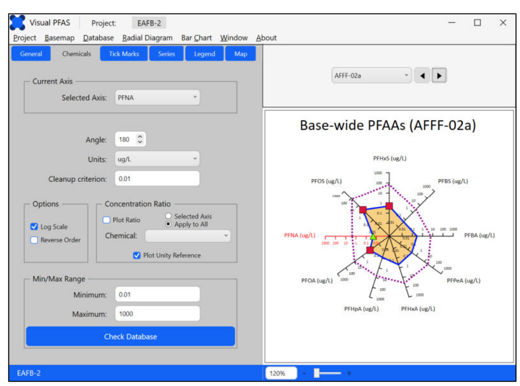
Visual PFAS™ Hands-On Demonstration





To learn more about Visual PFAS™:

www.VisualPFAS.com

Email gcarey@porewater.com for a hands-on demonstration, or to receive demo videos.

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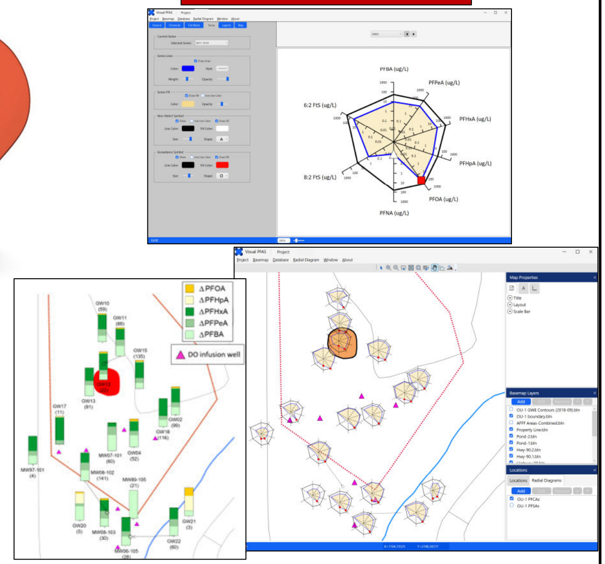
Questions?

Visual PFAS™

Grant R. Carey, Ph.D.
Porewater Solutions
gcarey@porewater.com
Phone: 613-890-2286



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Extra Slides

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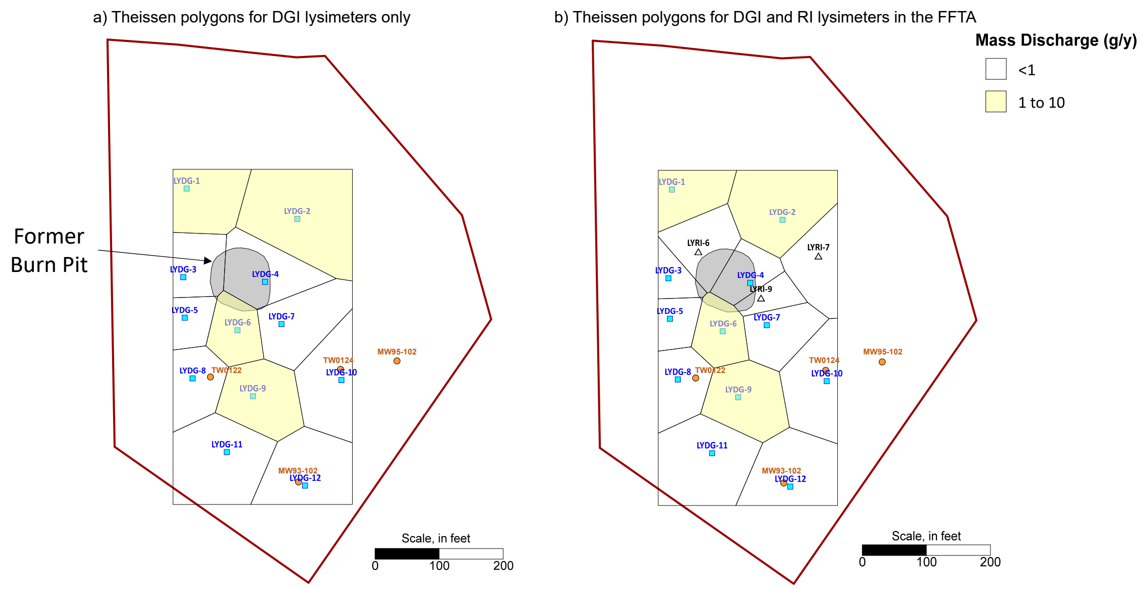
Theissen Polygons



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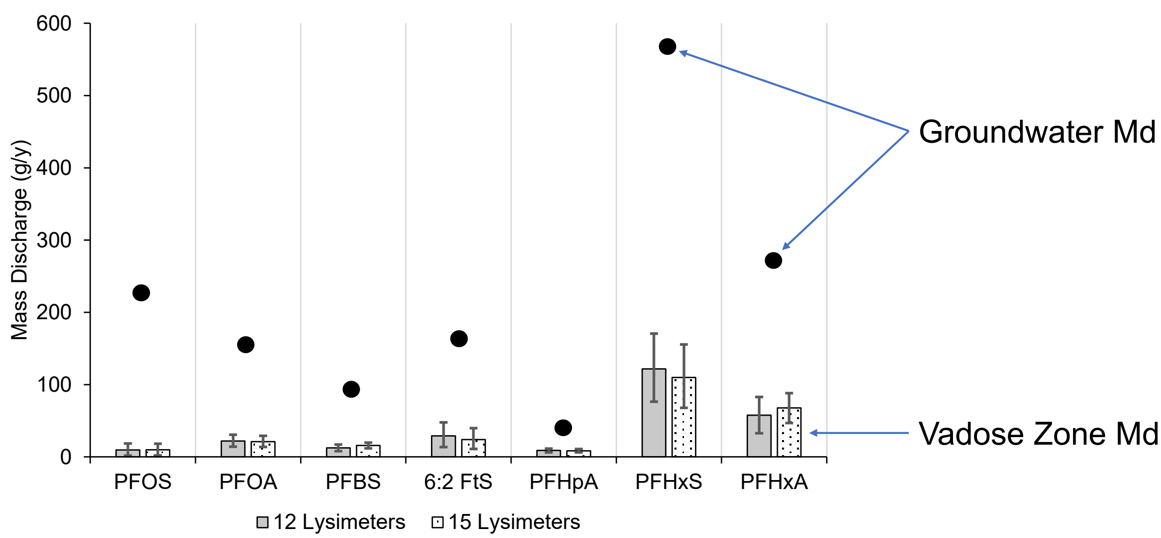
Mass Discharge (Md) Estimates

Carey et al. (2026a)



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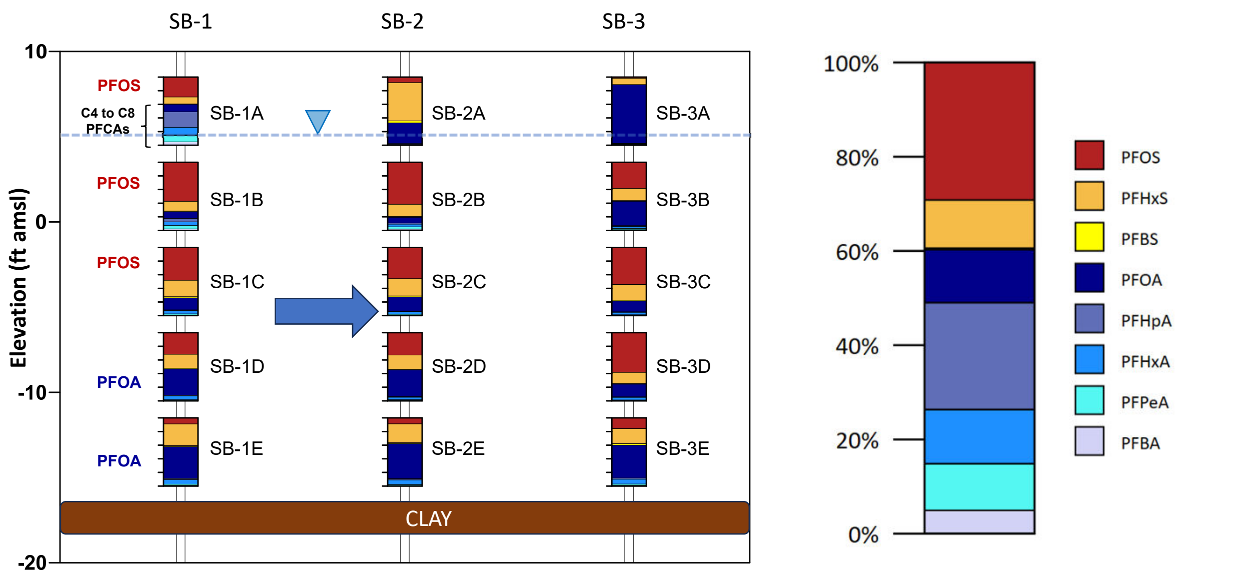
Navy Pre-Pilot Test: PFAAs Stacked Bar Map



 3-75

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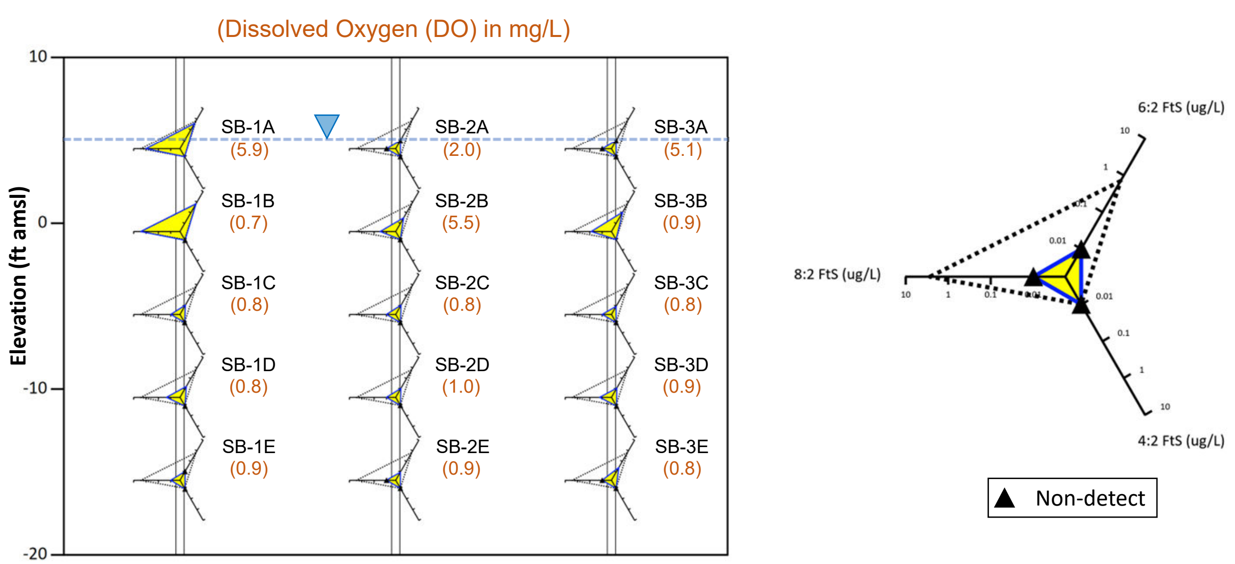
Navy Pre-Pilot Test: Precursor Radial Diagrams



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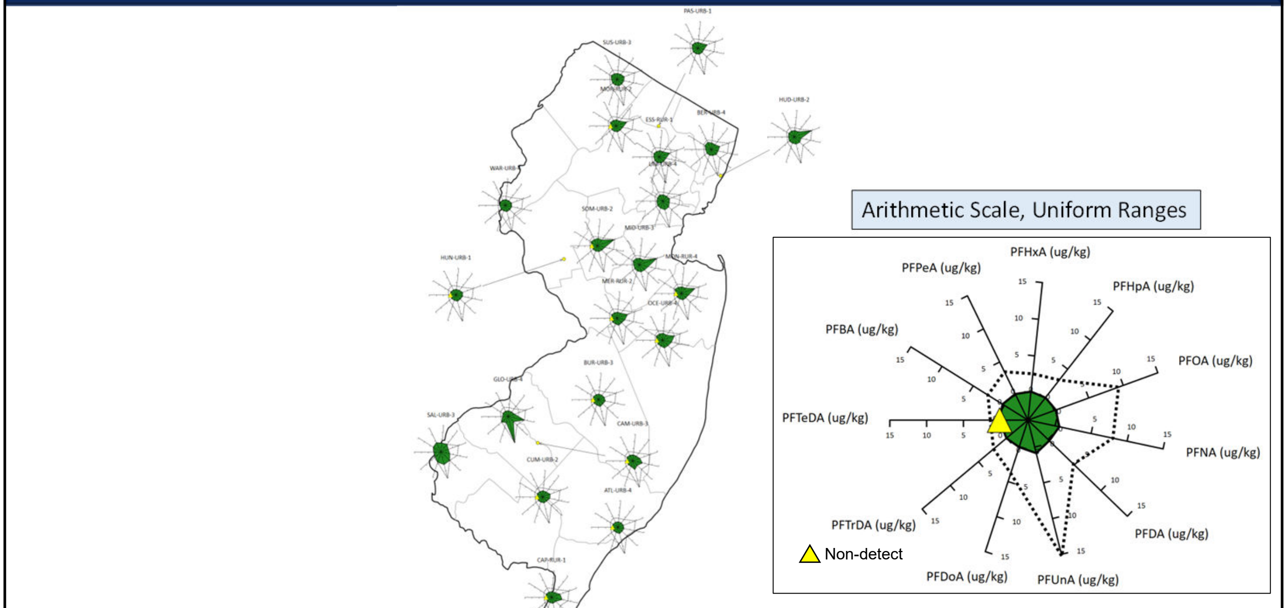
Radial Diagram Map: PFCAs (Uniform Ranges)



 3-77

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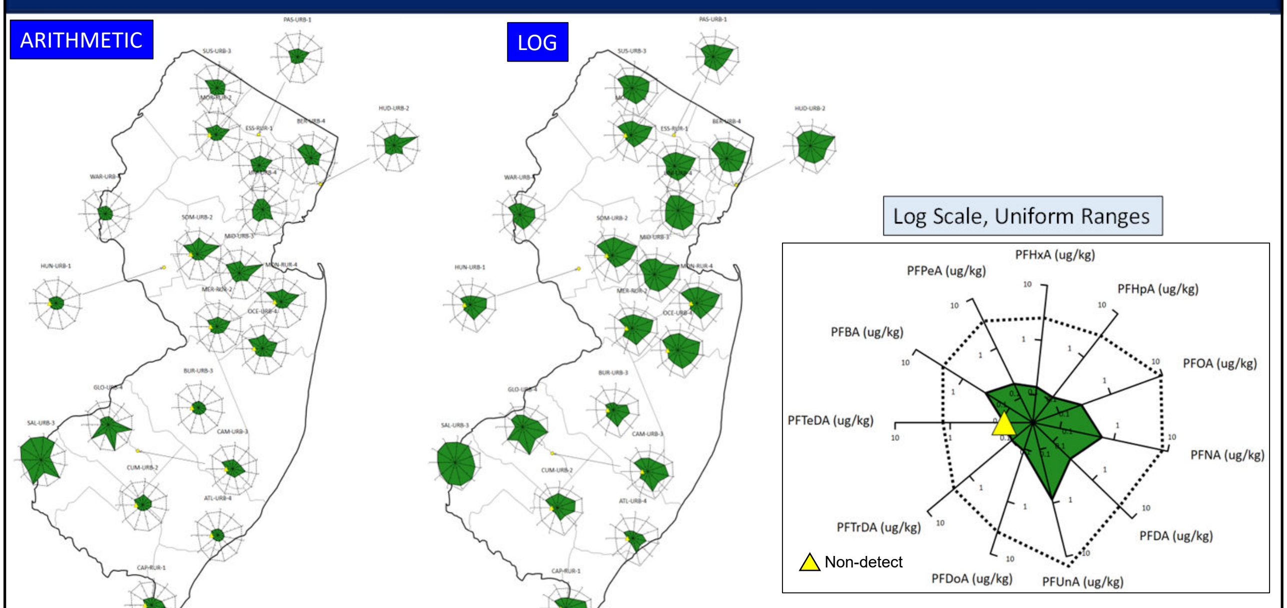
Radial Diagram Map: PFCAs (Log Scale)



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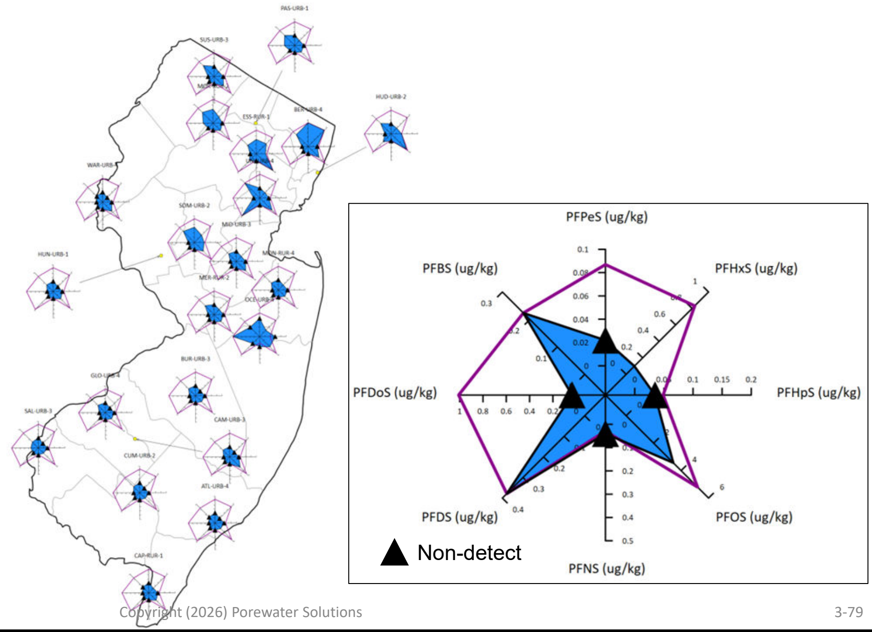
Radial Diagram Map: PFSAs (Arithmetic Scale)



Ratio of 6:2 FtS versus PFHxA in Groundwater

Note:

1. Multiple lines-of-evidence approach will strengthen a forensic analysis
2. Potential for differential adsorption needs to be assessed with ratio analyses

Check 6:2 FtS plume stability to confirm if differential adsorption is causing ratio decrease