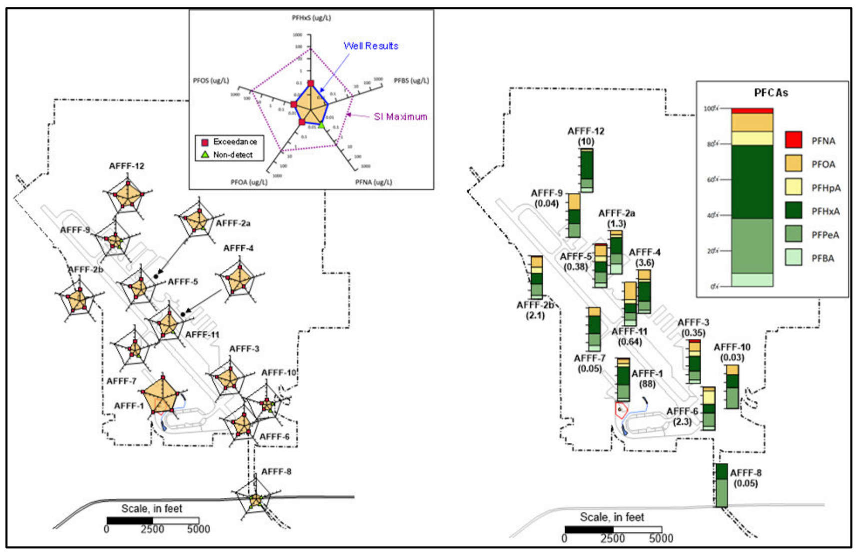
PFAS Visualization Case Studies for Improving Conceptual Models



By Grant Carey, Ph.D.

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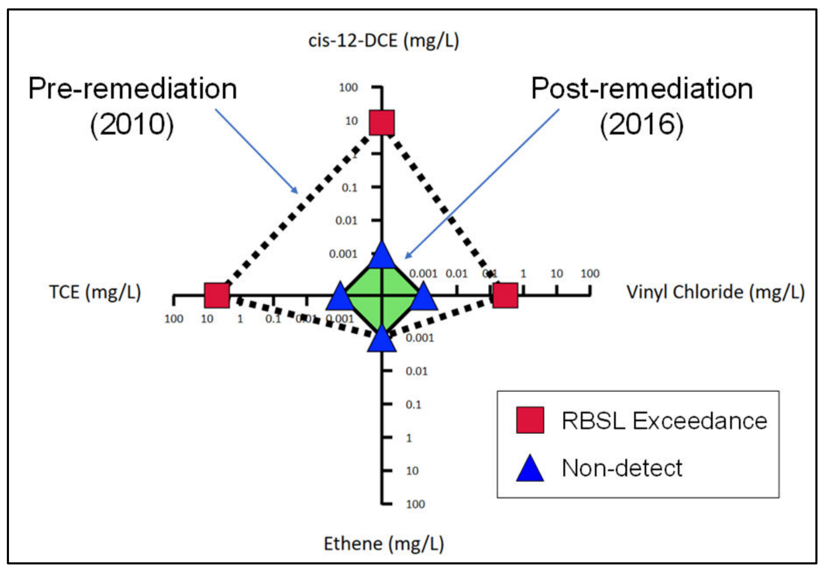

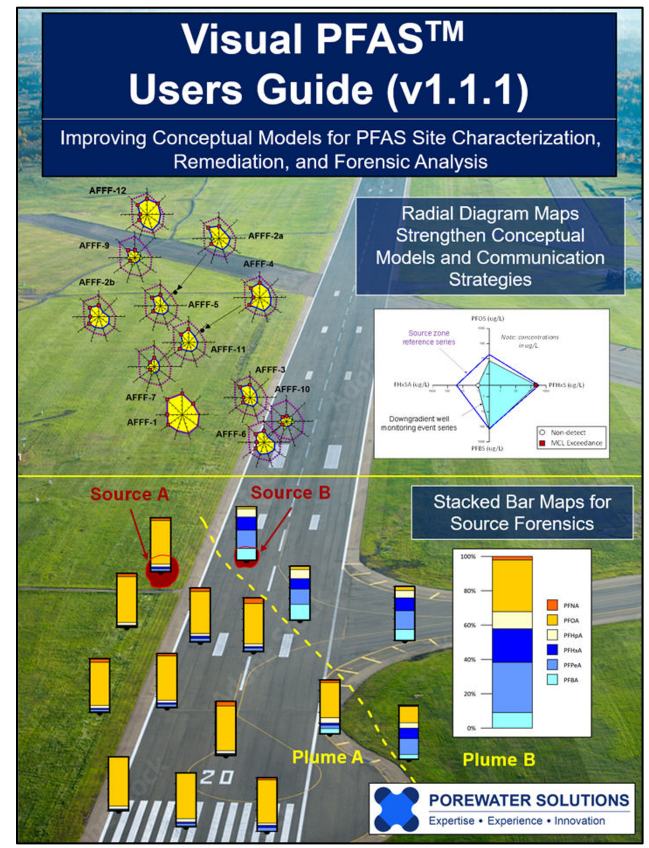

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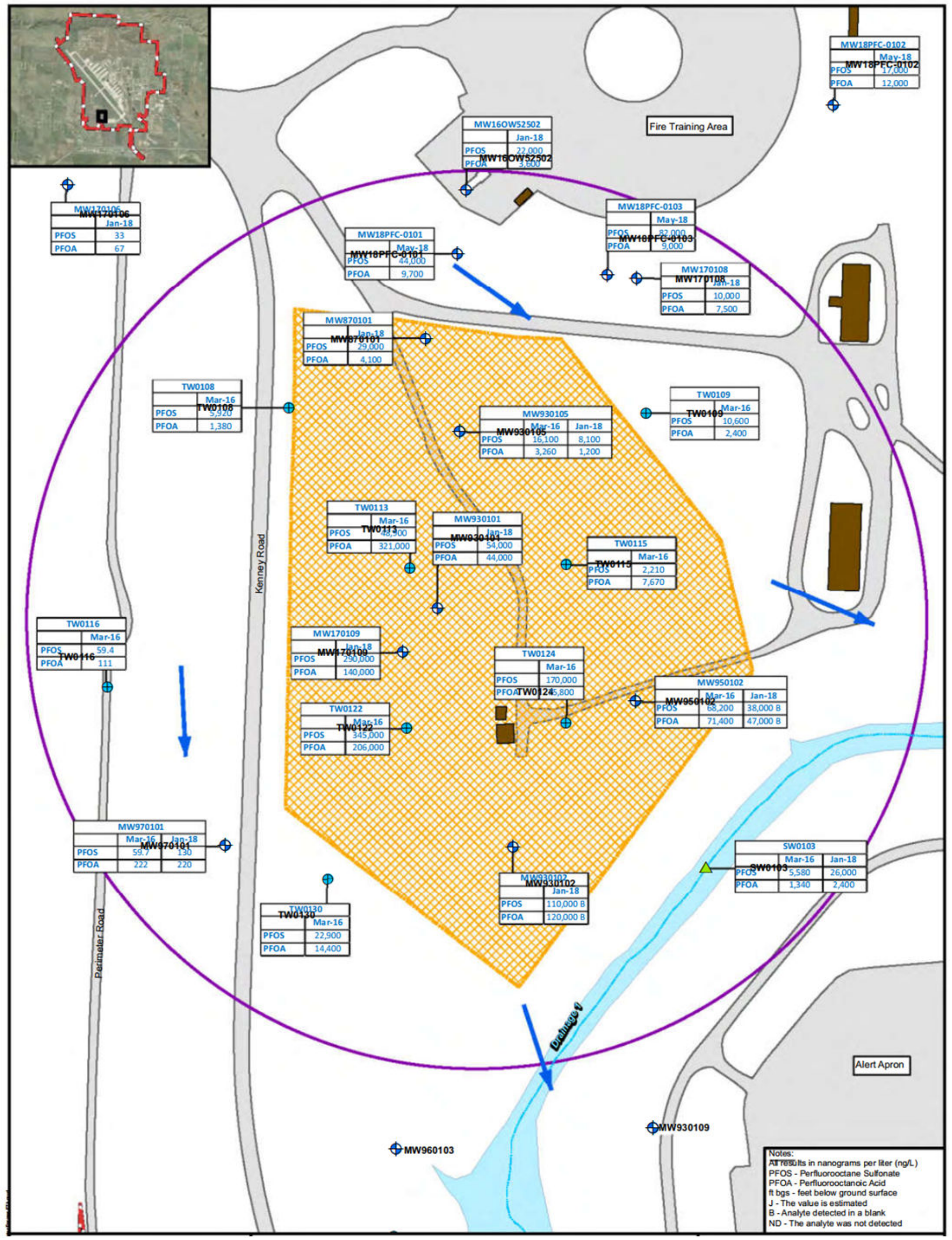
PFAS Site Characterization



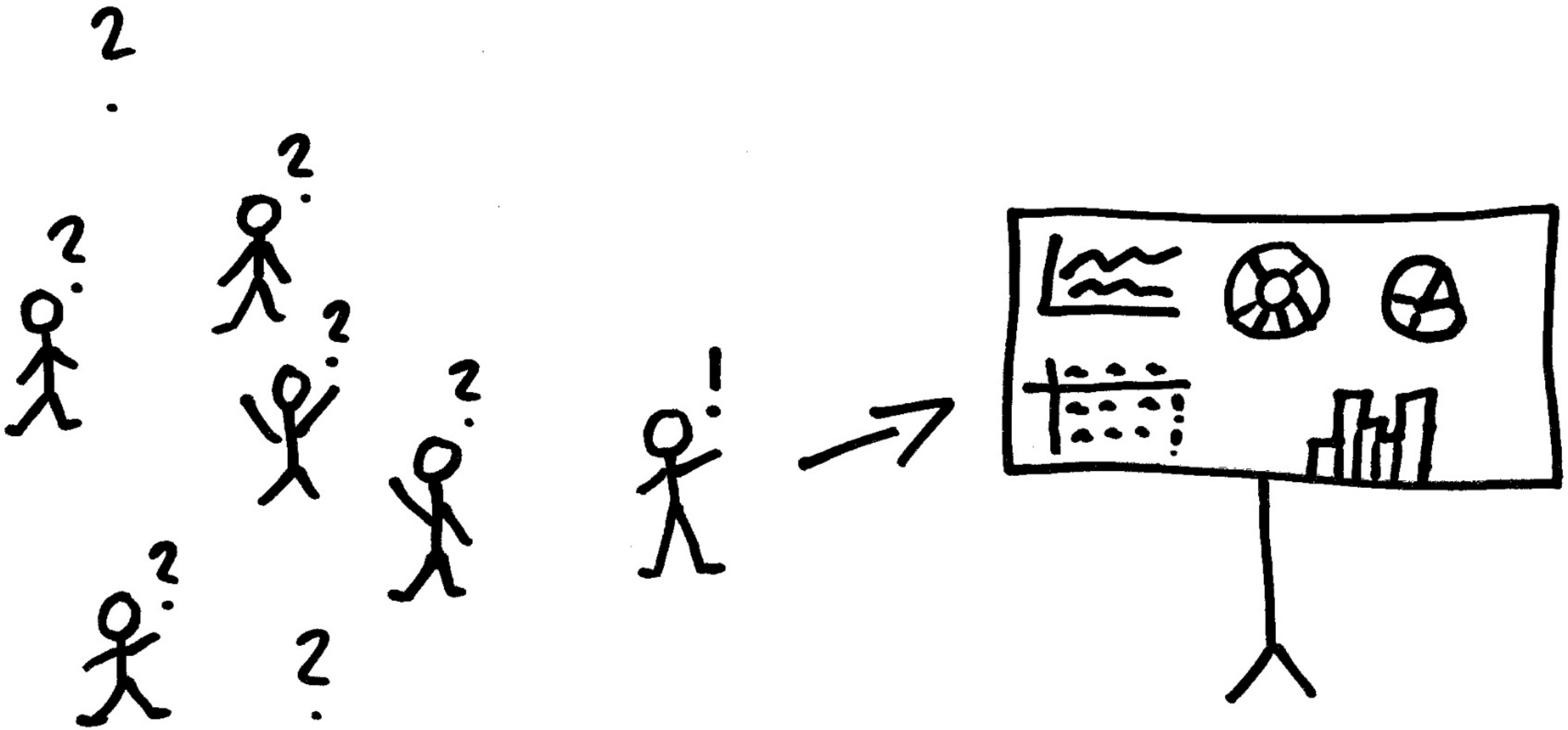
GW/Soil Samples

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

Table 3 PFAS Analytical Results

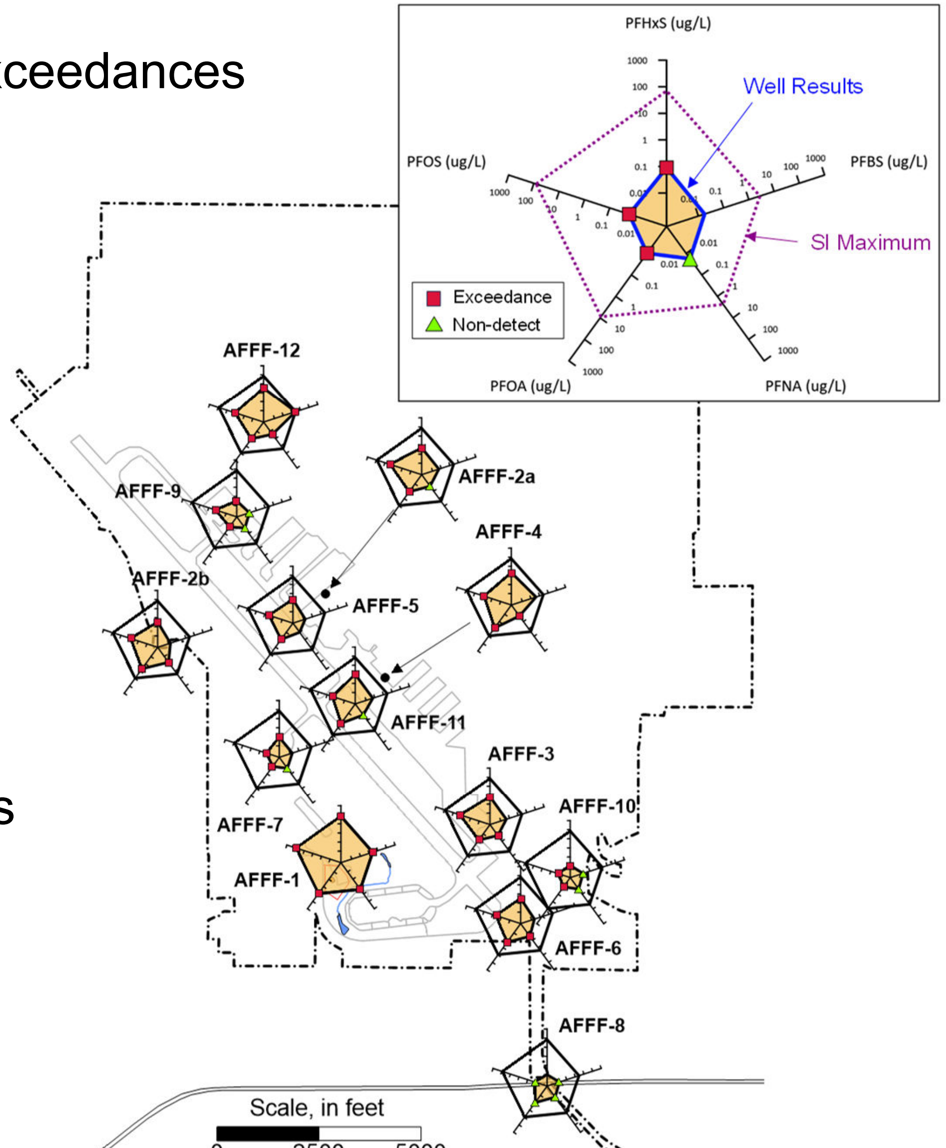
Monitoring Well ID	PFAS µg/L																								
	Perfluorooctanoic acid (PFOA)	Perfluorooctanesulfonic acid (PFOS)	Sum of PFOA and PFOS	Perfluorobutanoic acid (PFBA)	Perfluoropentanoic acid (PFPeA)	Perfluorohexanoic acid (PFHxA)	Perfluoroheptanoic acid (PFHpA)	Perfluorononanoic acid (PFNA)	Perfluorodecanoic acid (PFDA)	Perfluoroundecanoic acid (PFUnA)	Perfluorododecanoic acid (PFDoA)	Perfluorotridecanoic acid (PFDoA)	Perfluorotetradecanoic acid (PFTeDA)	Perfluorobutanesulfonic acid (PFBS)	Perfluoropentanesulfonic acid (PFPeS)	Perfluorohexanesulfonic acid (PFHxS)	Perfluoroheptanesulfonic acid (PFHpS)	Perfluorononanesulfonic acid (PFNS)	Perfluorodecanesulfonic acid (PFDS(	Perfluorooctane sulfonaminde (PFOSA)	2-(N-Methyl-perfluorooctane sulfonamido) acetic acid (MeFOSAA)	2-(N-Ethyl-perfluorooctane sulfonamido acetic acid (EtFOSAA)	4:2 Fluorotelomer sulfonate (4:2 FTS)	6:2 Fluorotelomer sulfonate (6:2 FTS)	8:2 Fluorotelomer sulfonate (8:2 FTS)
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	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	**0.303**	**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	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	0.0043 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	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	**0.32**	**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	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	**0.187**	**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	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	**0.115**	**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	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	0.0617	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	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	**0.103**	**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	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	**0.282**	**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	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	**0.0748**	**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	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	0.0538	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	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	**0.0785**	**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	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	0.0613	**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	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	**0.075**	**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	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	**0.108**	**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	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	**0.149**	**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	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	**0.156**	**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	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	**0.171**	**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	0.134	0.135	0.981	0.0434	0.0042 U	0.0042 U	0.0042 U	0.017 U	0.017 U	0.0083 U	0.0204	0.0083 U
MW09OB08	**0.135**	**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	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

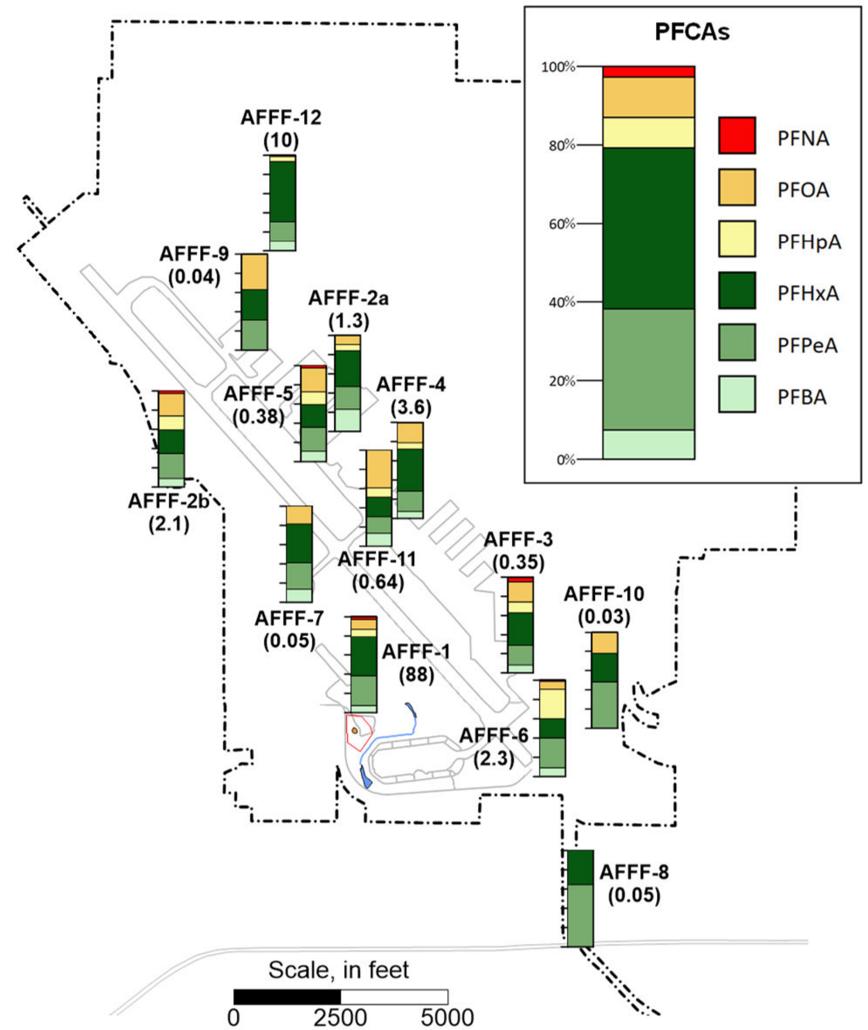
How Can We Effectively Communicate PFAS Results?



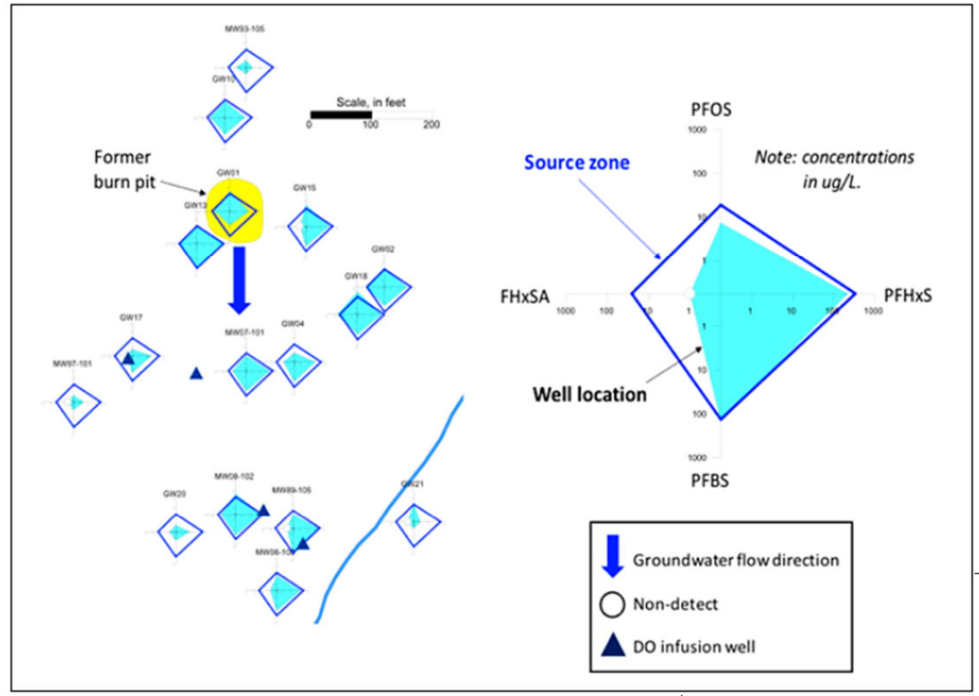
Radial Diagram and Stacked Bar Maps

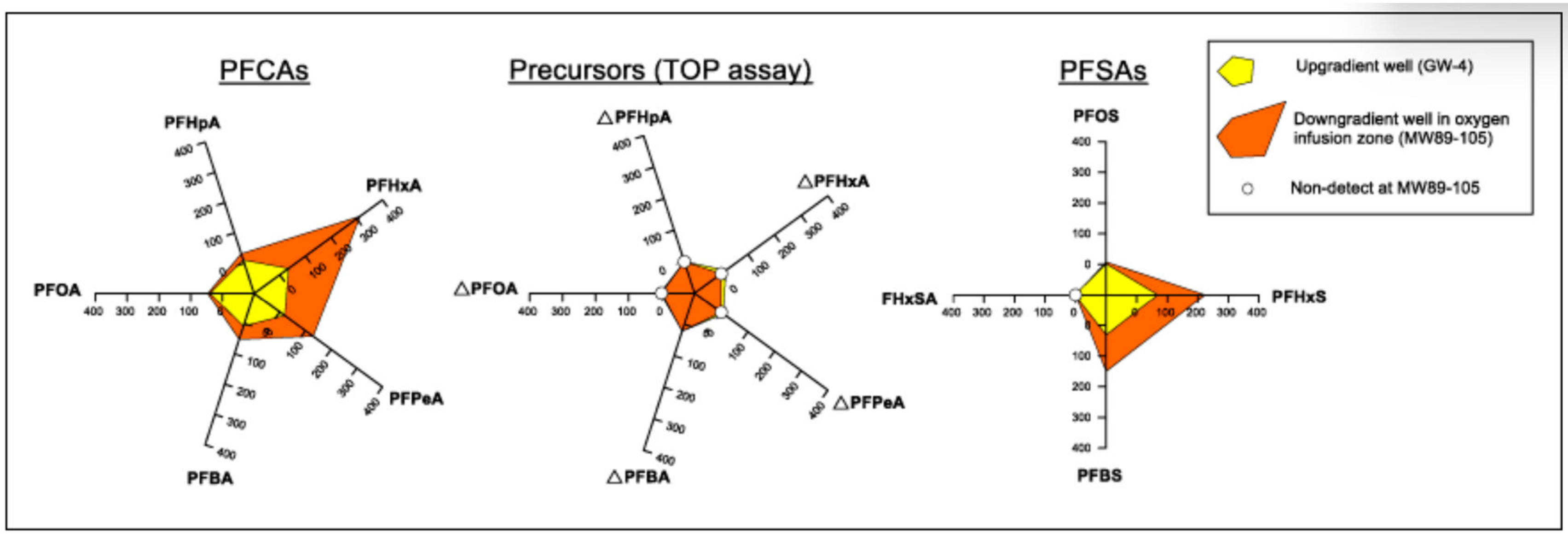
1. Identify chemical & location exceedances
2. Plume delineation
3. Short vs long-chain
4. Precursor transformations
5. Flow path attenuation
6. Site vs background
7. TOP assay results
8. Remediation monitoring
9. Source differentiation forensics

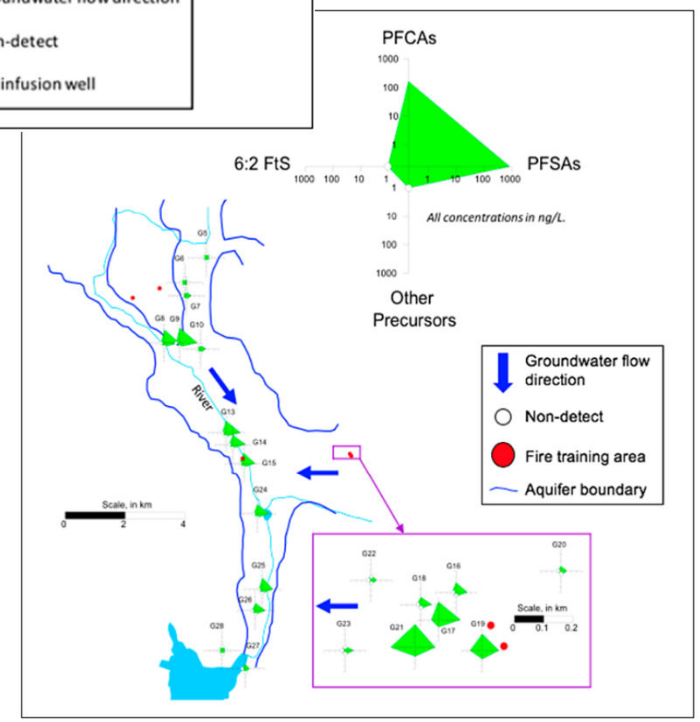




ITRC PFAS Guidance: Radial Diagram Examples







Case Study Outline

1. **PFAS site characterization (SD AFB)**
2. **PFAS remediation (Navy site)**
   - PlumeStop® barrier
3. **Chlorinated solvent remediation: (Regenesis site, MI)**
   - 3-D Microemulsion® (3Dme)
   - PlumeStop®, Hydrogen Releasing Compound™ (HRC), Bio-Dechlor Inoculum® Plus (BDI+)
4. **Redox zone delineation (MI AFB, MI Landfill)**
5. **Visual PFAS™ Overview**

PFAS Site Characterization
South Dakota AFB

Section 1

In Submittal to Remediation Journal

DRAFT – In Submittal to the Remediation Journal

Visualizing PFAS Trends at a South Dakota AFFF-Impacted Site

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

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ABSTRACT: Various visualization alternatives are demonstrated for evaluating PFAS trends at an 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 PFOS+PFOA concentrations in AFFF source areas. Then a more detailed analysis of trends, including the potential for precursor transformations to 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 sulfonates and carboxylates in groundwater, which may help to identify relative contributions of AFFF products derived from ECF 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.

Data Availability Statement: Data sharing not applicable – no new data generated. Data were derived from existing public domain resources, including: McGuire et al., 2014 (https://pubmed.ncbi.nlm.nih.gov/24866261/), and Aerostar, 2019 (https://ar.cce.af.mil/ViewPdf?id=604149&token=I2208V8VBb6zxQzqUdjuogg5xV418wJyfFi5FbJJiMI%3D).

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

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

1

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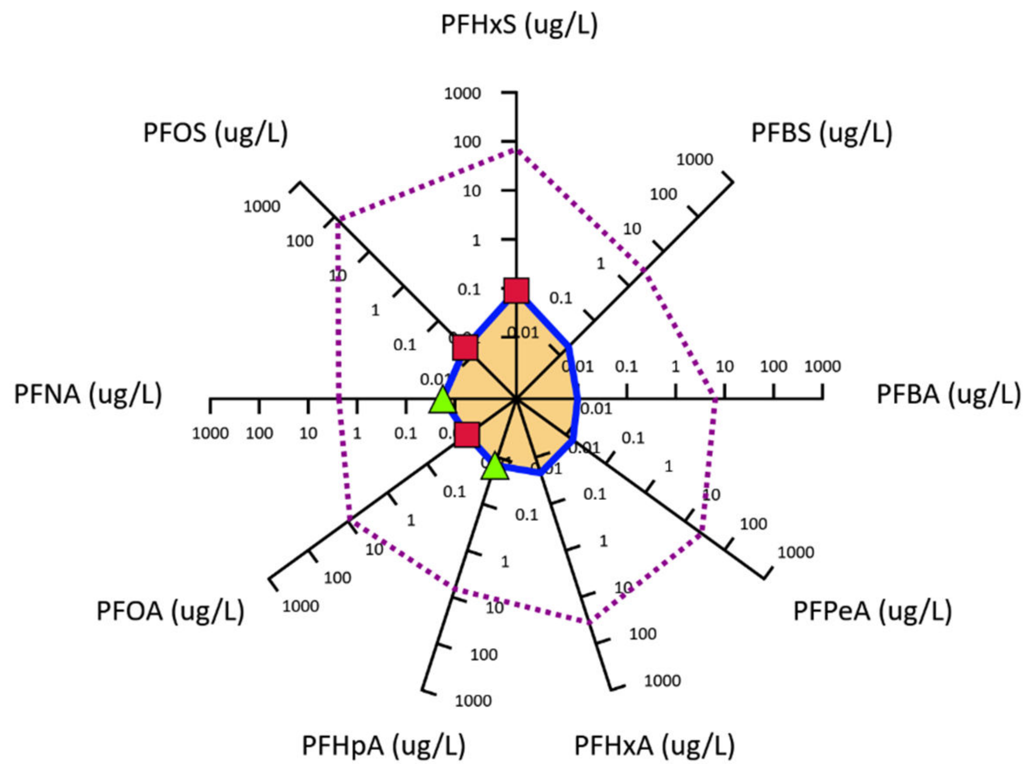

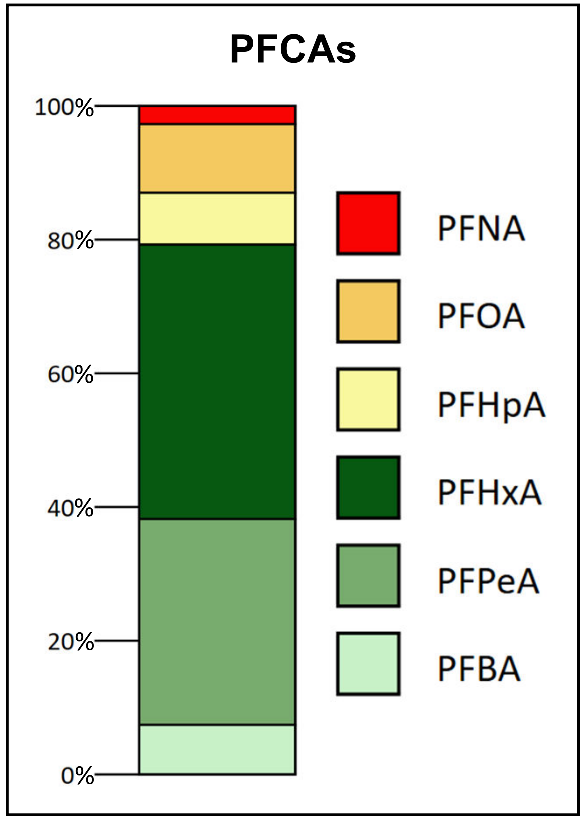

Acknowledgements

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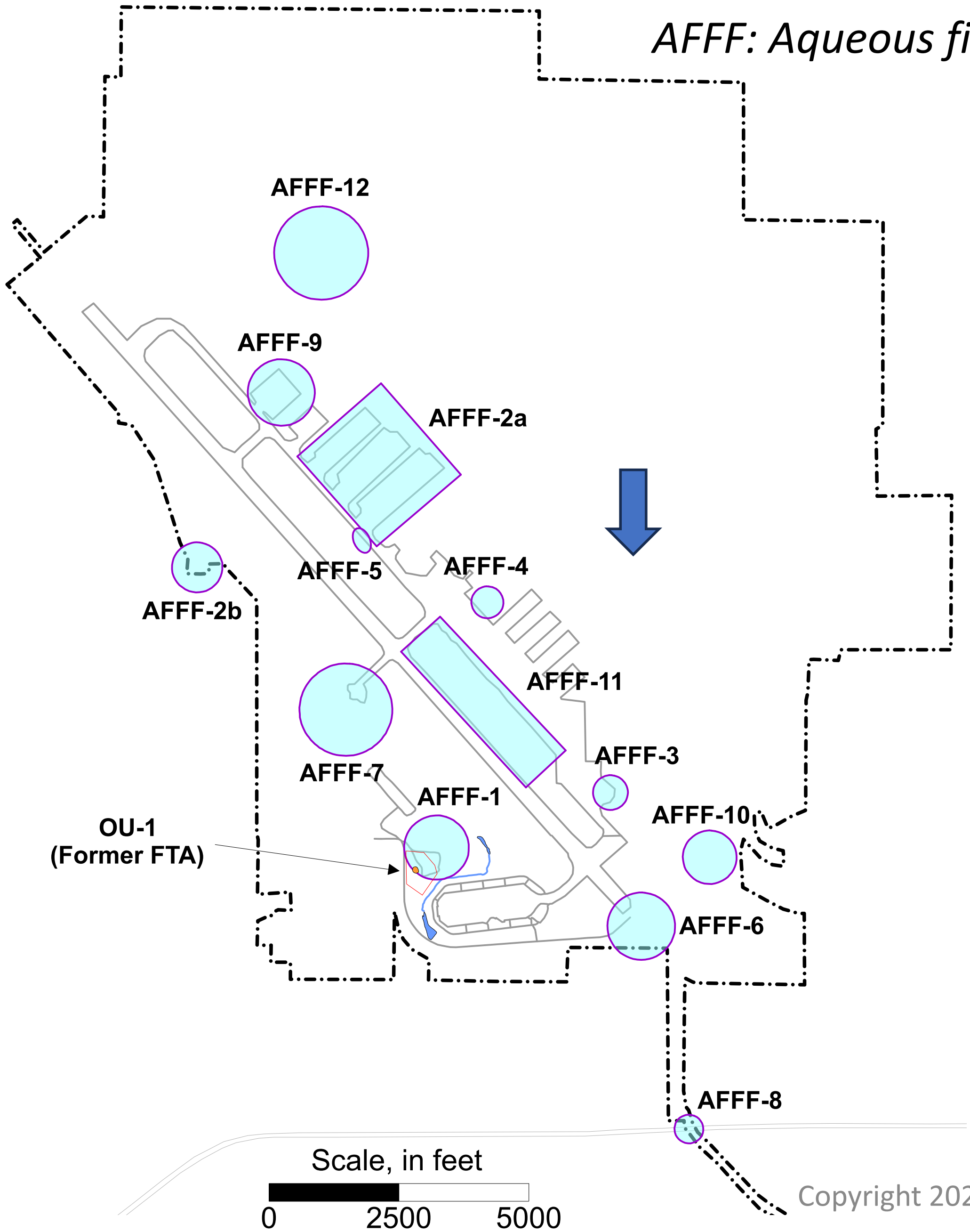
AFFF Source Areas

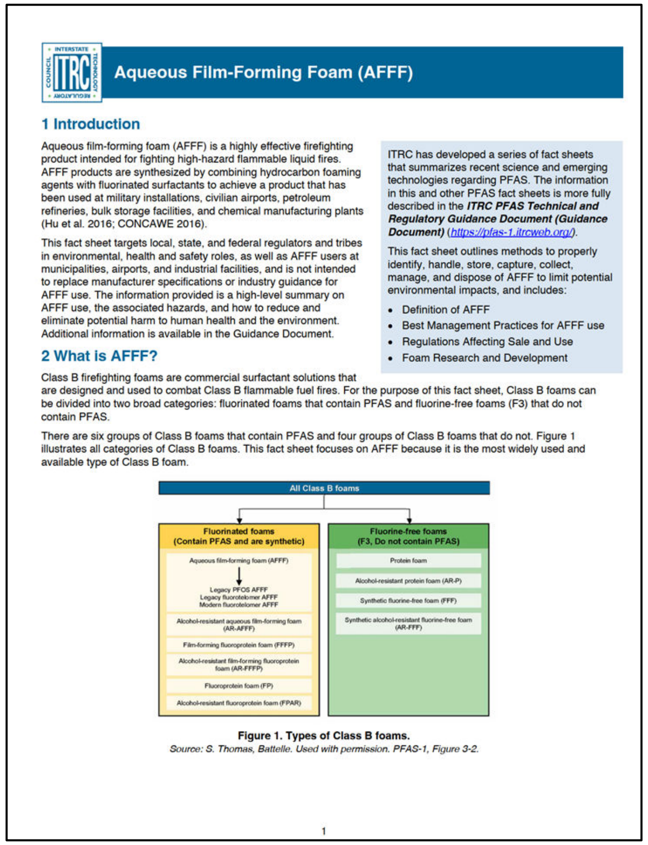
AFFF: Aqueous film-forming foam



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

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

Legacy ECF
(Late 1960s-2002)

Legacy FT
(Late 1970s-2016)
Long-chain

Modern FT
Short-chain

High PFOS, PFHxS
Lower PFCAs (e.g., PFOA)

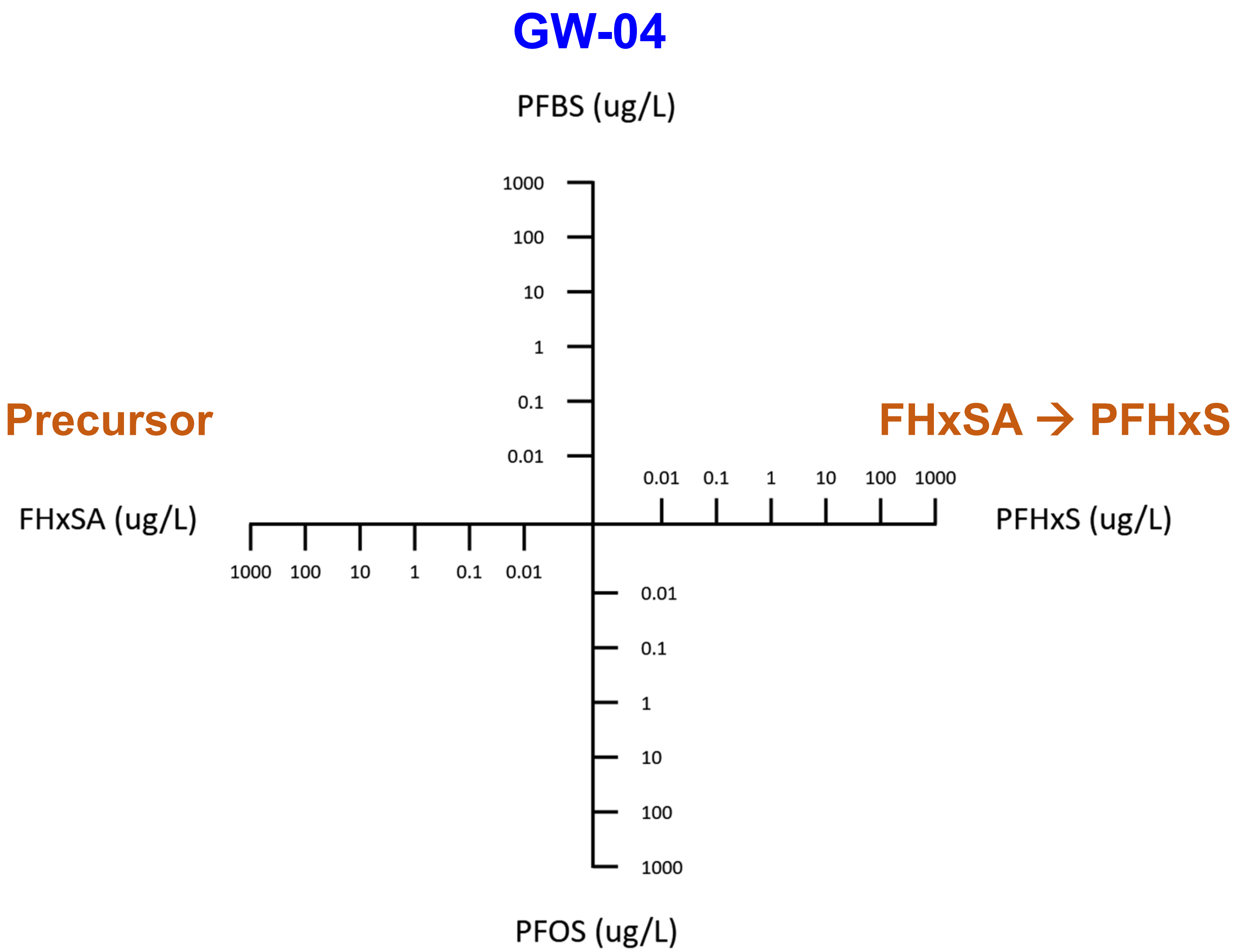
High FtS
High PFCAs (PFBA → PFOA)
Lower PFSAs

<u>Product differentiation clues:</u>

- PFSAs vs PFCAs
- Long-chain vs short-chain PFCAs

ECF: Electrochemical Fluorination
FT: Fluorotelomerization

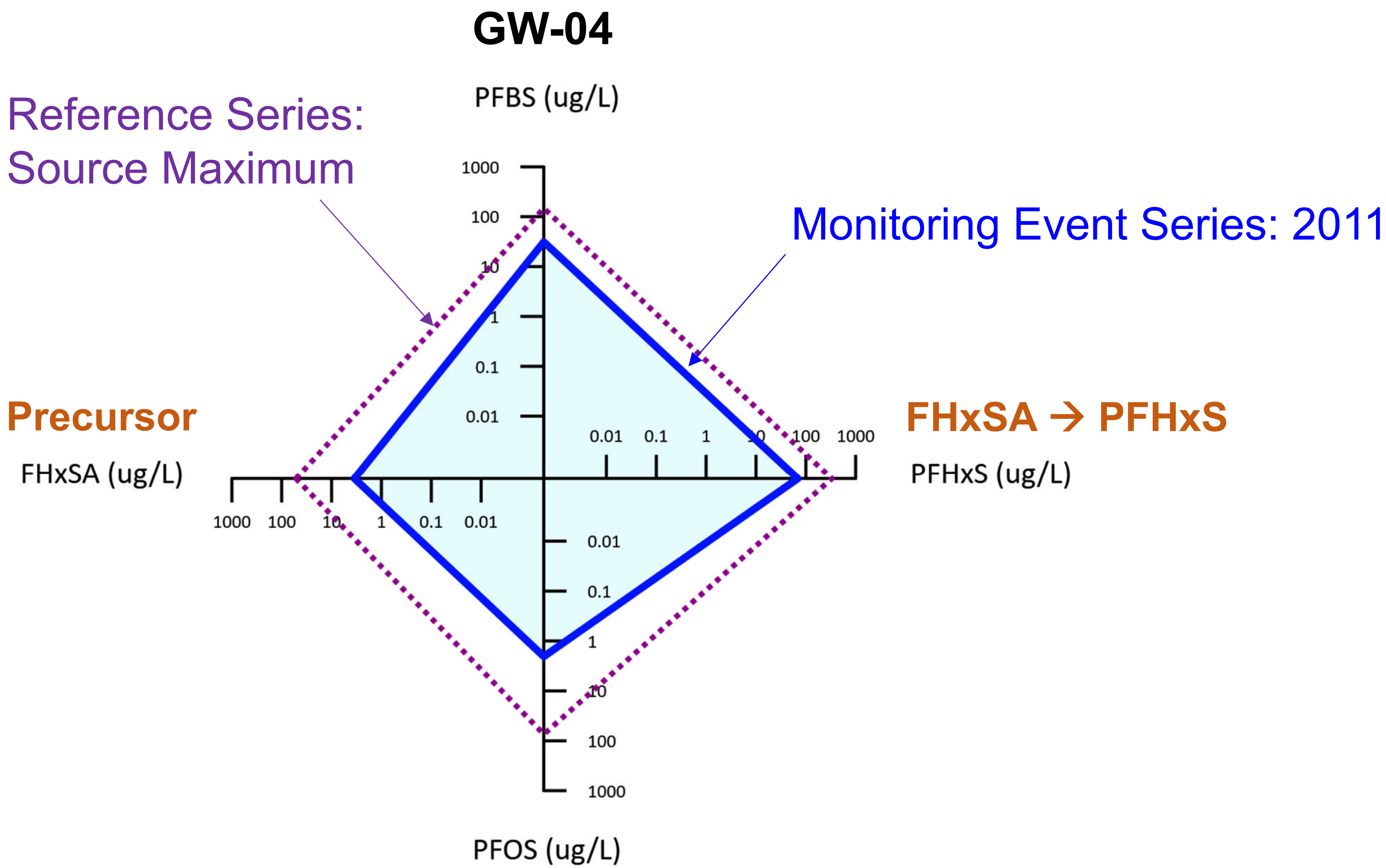
PFSAs Radial Diagram: Near-Source Well



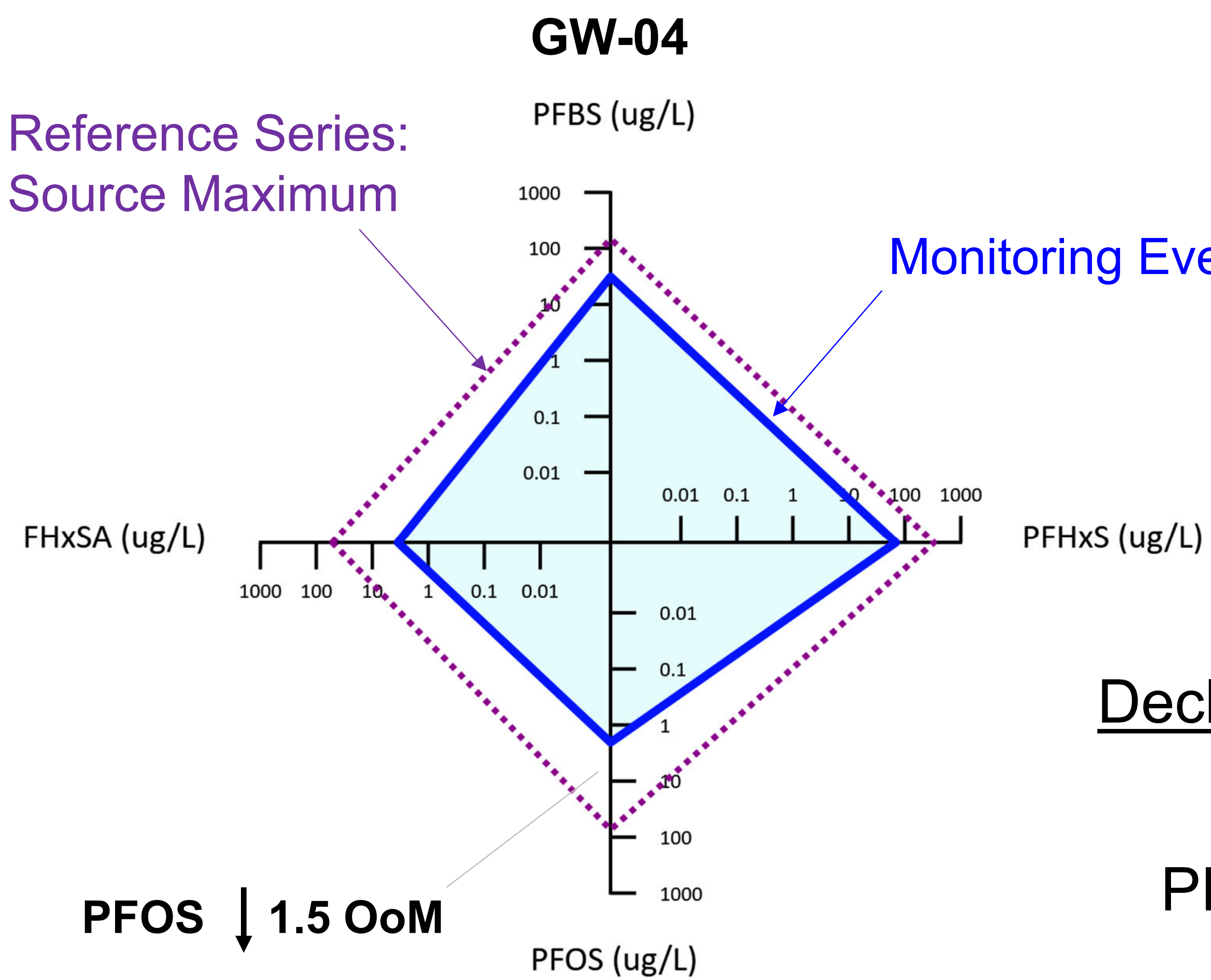
Radial Diagram Construction

1. Precursor and PFSAs
   - Transformation evidence
   - PFHxS is a daughter product
2. Uniform axis ranges
   - Identify chemicals with high/low C
3. Log scale
   - Each tick mark interval = 10x change
     i.e., 1 OoM
   - Most PFAS sites vary by Orders of Magnitude
4. Minimize tick mark intervals
   - Min range = 0.01 ug/L

PFSAs Radial Diagram: Near-Source Well



PFSAs Radial Diagram: Near-Source Well



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

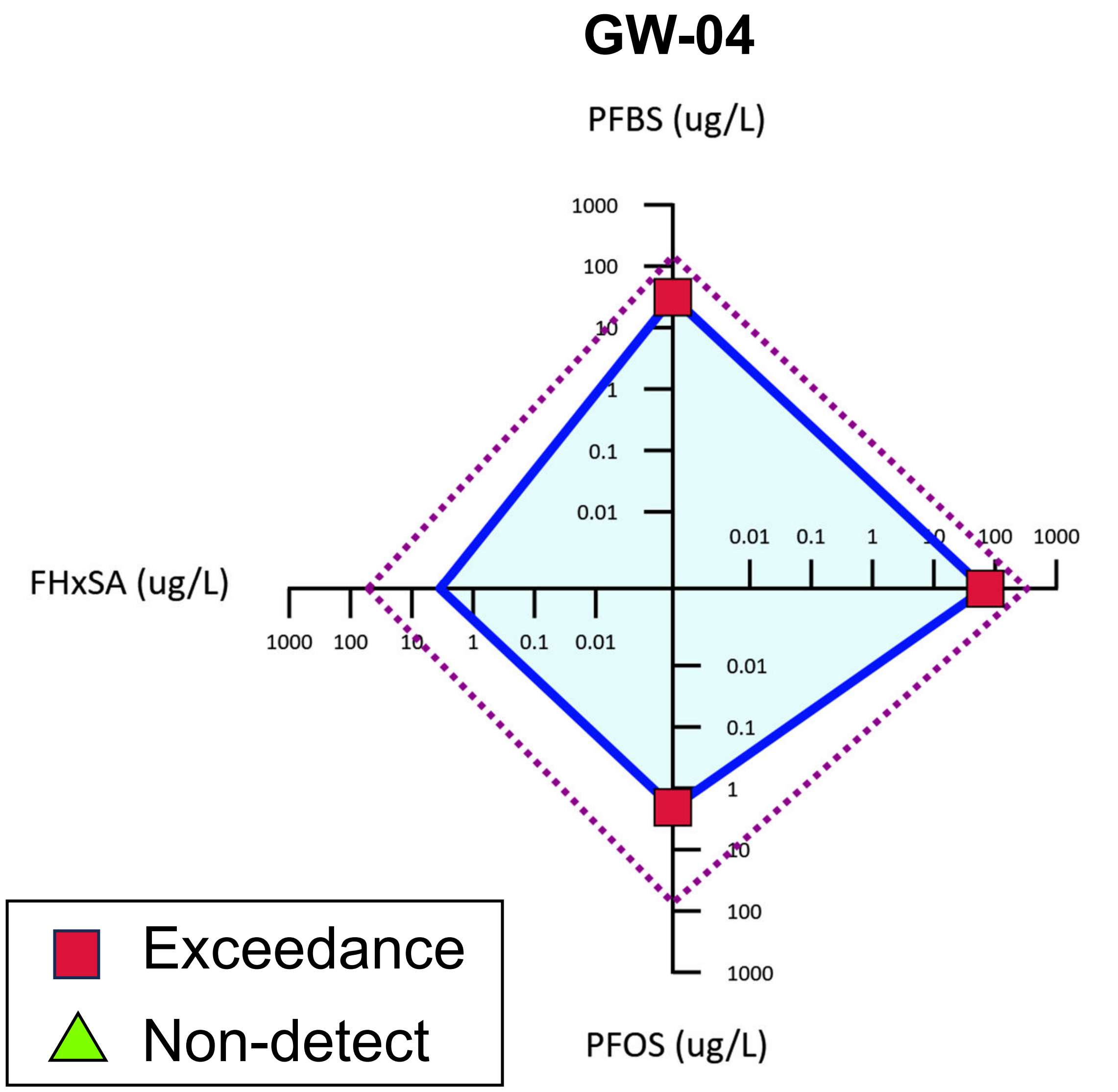
FHxSA: 1 OoM

PFBS, PFHxS: 0.5 OoM

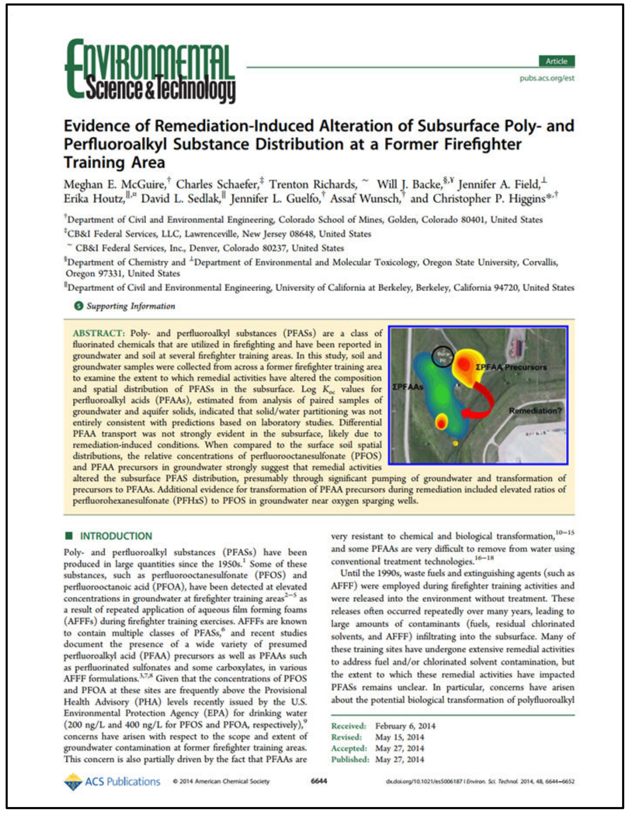
PFOS: 1.5 OoM

OoM: Orders of Magnitude

PFSAs Radial Diagram: Trends Along Flow Path



DO Infusion Well



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Article

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Evidence of Remediation-Induced Alteration of Subsurface Poly- and Perfluoroalkyl Substance Distribution at a Former Firefighter Training Area

Meghan E. McGuire,[†] Charles Schaefer,[‡] Trenton Richards,[~] Will J. Backe,[§,¥] Jennifer A. Field,[⊥] Erika Houtz,[∥,¤] David L. Sedlak,[∥] Jennifer L. Guelfo,[†] Assaf Wunsch,[†] and Christopher P. Higgins*[,†]

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Supporting Information

ABSTRACT: Poly- and perfluoroalkyl substances (PFASs) are a class of fluorinated chemicals that are utilized in firefighting and have been reported in groundwater and soil at several firefighter training areas. In this study, soil and groundwater samples were collected from across a former firefighter training area to examine the extent to which remedial activities have altered the composition and spatial distribution of PFASs in the subsurface. Log K_{oc} values for perfluoroalkyl acids (PFAAs), estimated from analysis of paired samples of groundwater and aquifer solids, indicated that solid/water partitioning was not entirely consistent with predictions based on laboratory studies. Differential PFAA transport was not strongly evident in the subsurface, likely due to remediation-induced conditions. When compared to the surface soil spatial distributions, the relative concentrations of perfluorooctanesulfonate (PFOS) and PFAA precursors in groundwater strongly suggest that remedial activities altered the subsurface PFAS distribution, presumably through significant pumping of groundwater and transformation of precursors to PFAAs. Additional evidence for transformation of PFAA precursors during remediation included elevated ratios of perfluorohexanesulfonate (PFHxS) to PFOS in groundwater near oxygen sparging wells.

ΣPFAA Precursors
ΣPFAAs
Remediation?

INTRODUCTION

Poly- and perfluoroalkyl substances (PFASs) have been produced in large quantities since the 1950s.[1] Some of these substances, such as perfluorooctanesulfonate (PFOS) and perfluorooctanoic acid (PFOA), have been detected at elevated concentrations in groundwater at firefighter training areas[2−5] as a result of repeated application of aqueous film forming foams (AFFFs) during firefighter training exercises. AFFFs are known to contain multiple classes of PFASs,[6] and recent studies document the presence of a wide variety of presumed perfluoroalkyl acid (PFAA) precursors as well as PFAAs such as perfluorinated sulfonates and some carboxylates, in various AFFF formulations.[3,7,8] Given that the concentrations of PFOS and PFOA at these sites are frequently above the Provisional Health Advisory (PHA) levels recently issued by the U.S. Environmental Protection Agency (EPA) for drinking water (200 ng/L and 400 ng/L for PFOS and PFOA, respectively),[9] concerns have arisen with respect to the scope and extent of groundwater contamination at former firefighter training areas. This concern is also partially driven by the fact that PFAAs are very resistant to chemical and biological transformation,[10−15] and some PFAAs are very difficult to remove from water using conventional treatment technologies.[16−18]

Until the 1990s, waste fuels and extinguishing agents (such as AFFF) were employed during firefighter training activities and were released into the environment without treatment. These releases often occurred repeatedly over many years, leading to large amounts of contaminants (fuels, residual chlorinated solvents, and AFFF) infiltrating into the subsurface. Many of these training sites have undergone extensive remedial activities to address fuel and/or chlorinated solvent contamination, but the extent to which these remedial activities have impacted PFASs remains unclear. In particular, concerns have arisen about the potential biological transformation of polyfluoroalkyl

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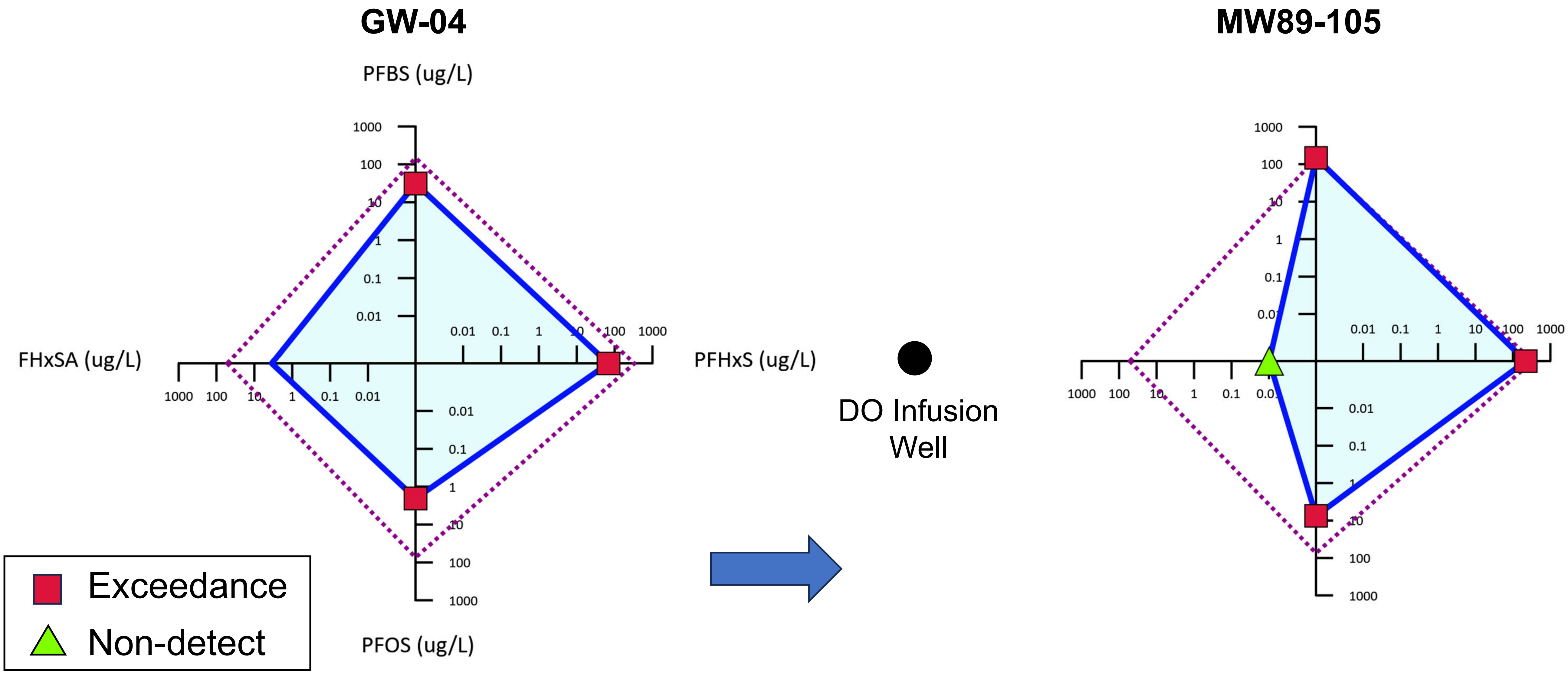
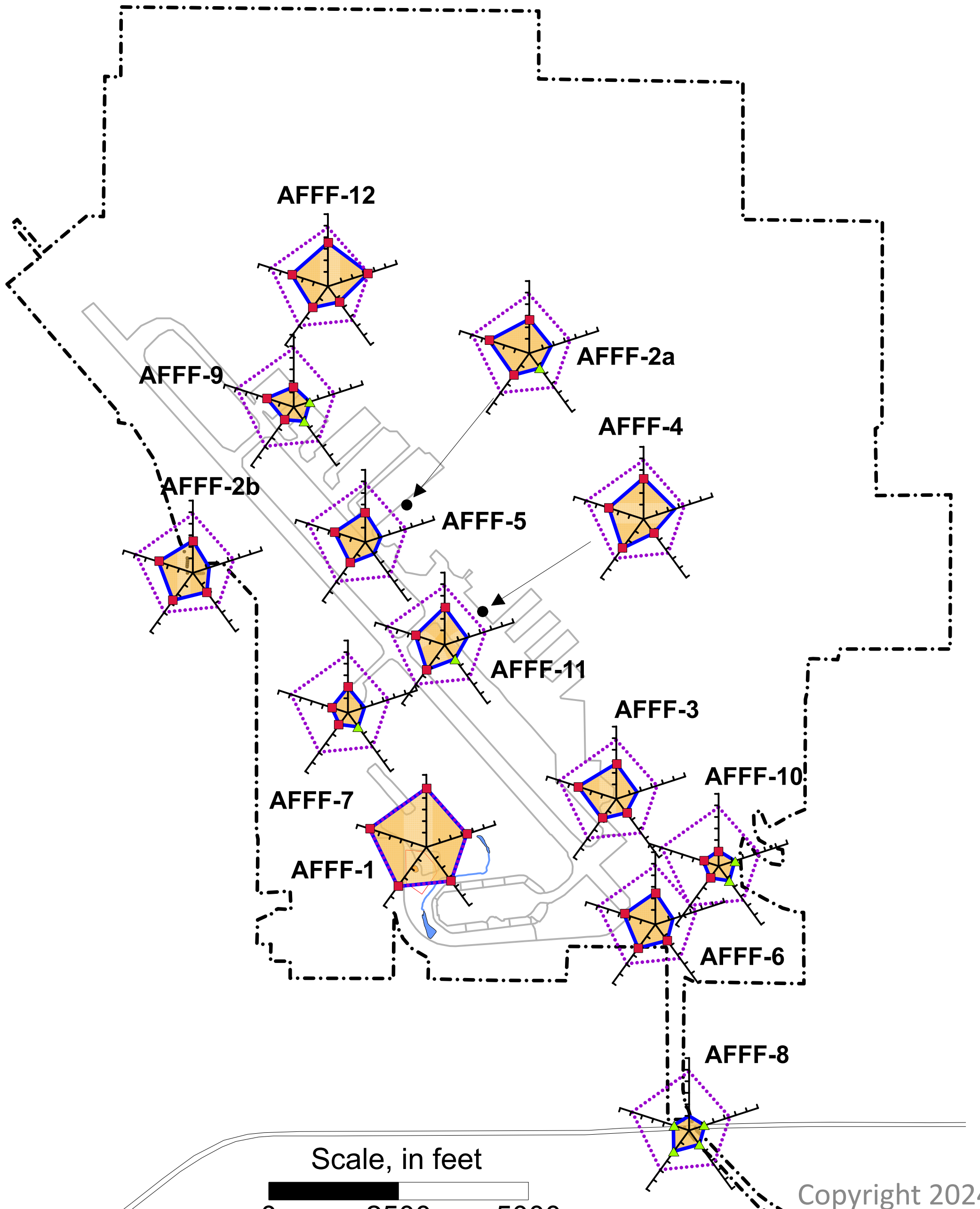
Reference: McGuire et al. (2014)

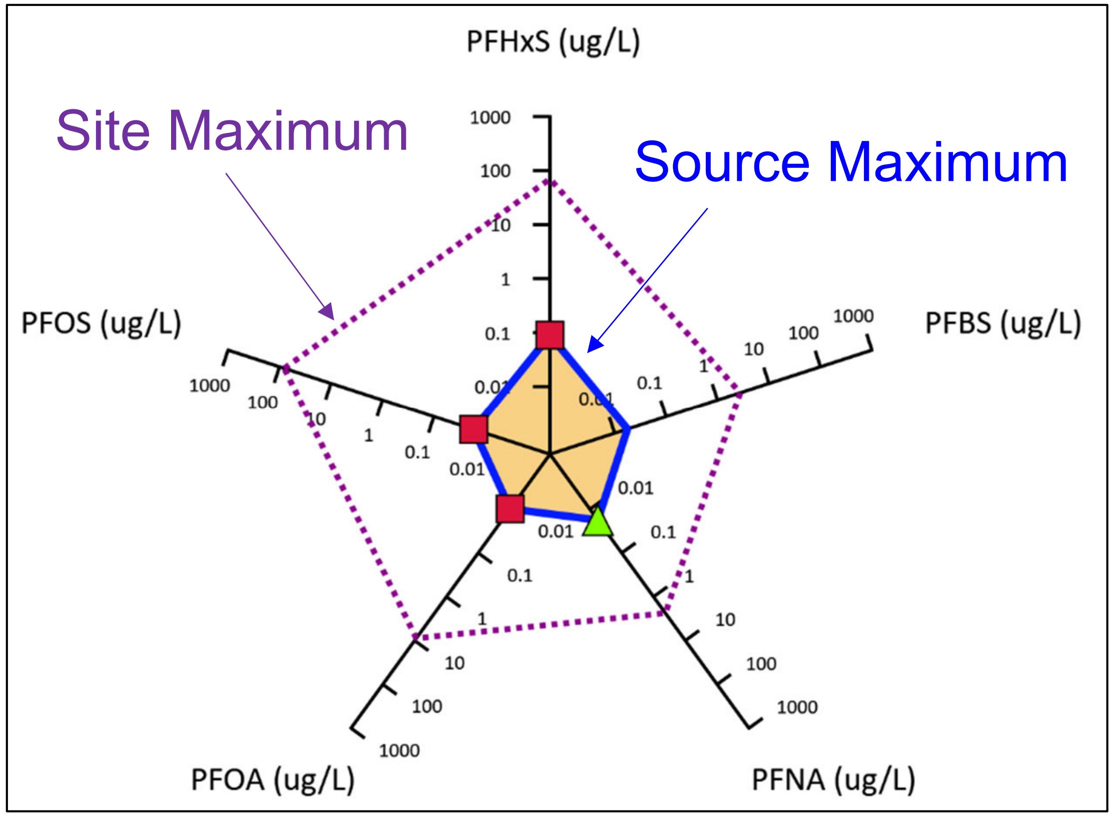
PFSAs Radial Diagram: Trends Along Flow Path



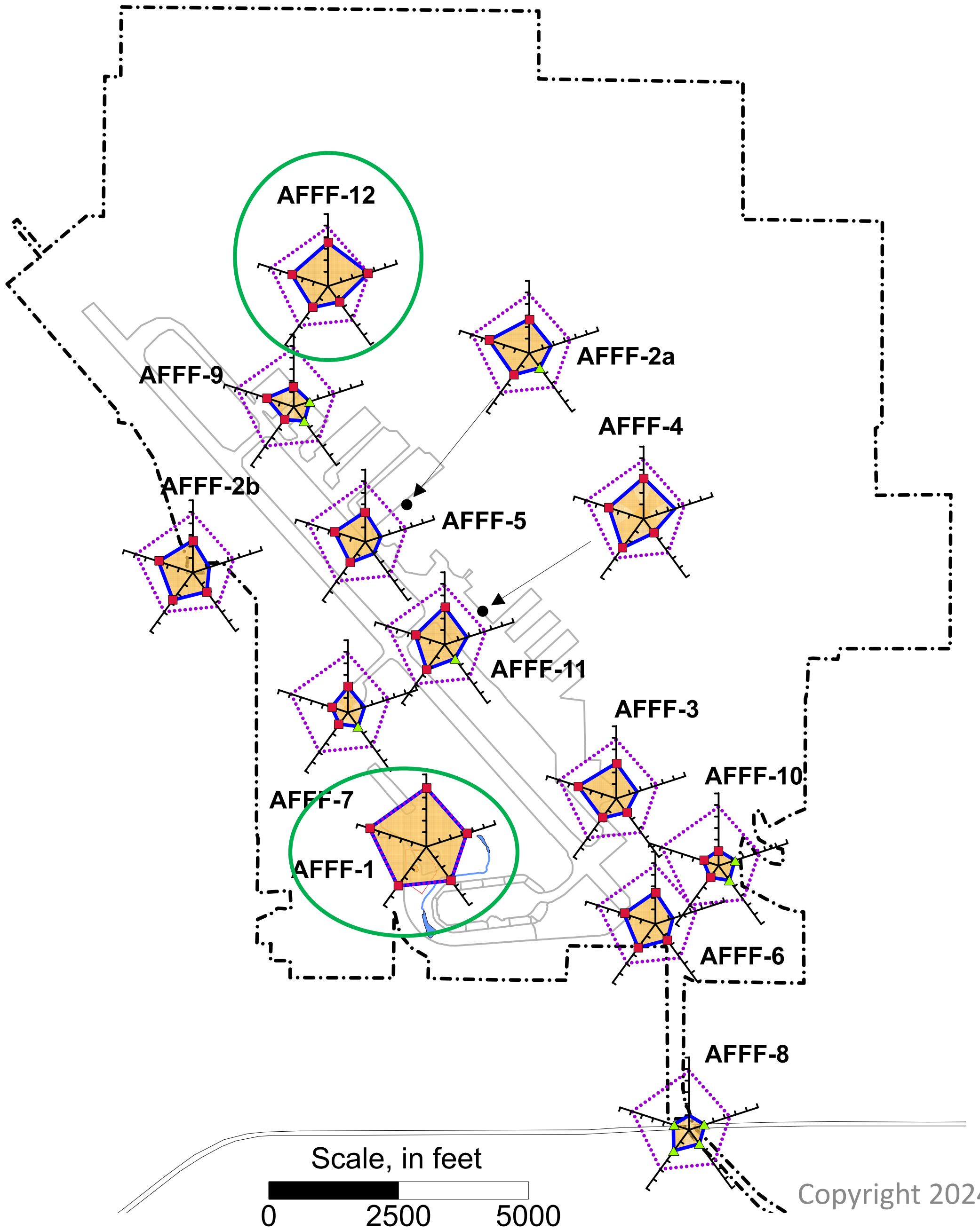
AFFF Source Areas: PFAS of Concern



Site Inspection (SI) Results



AFFF Source Areas: PFAS of Concern



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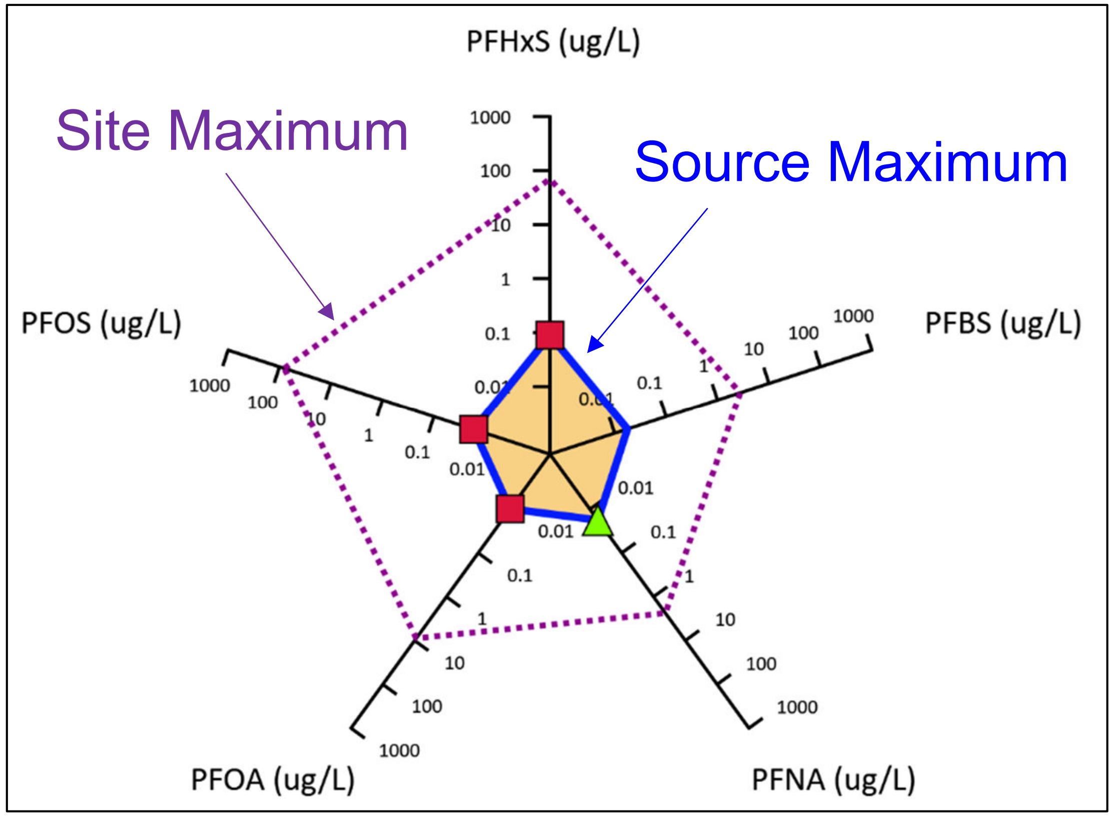
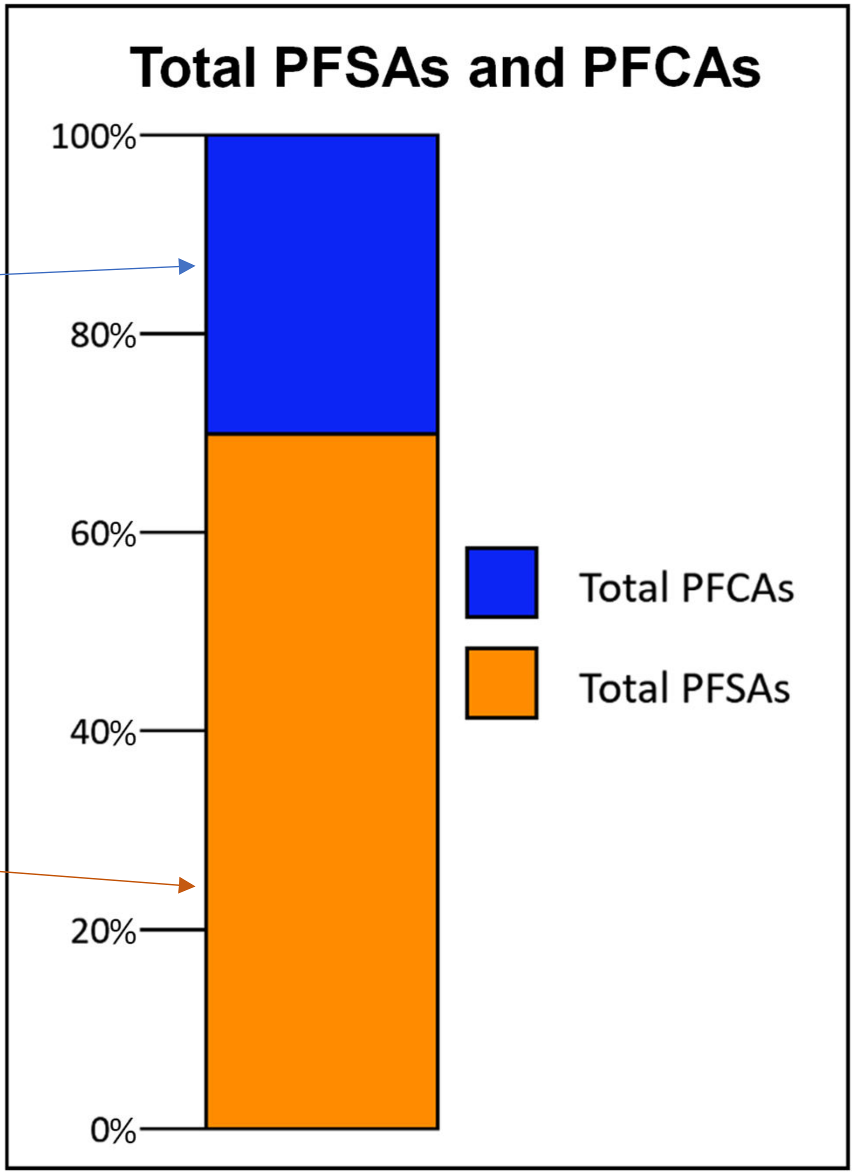


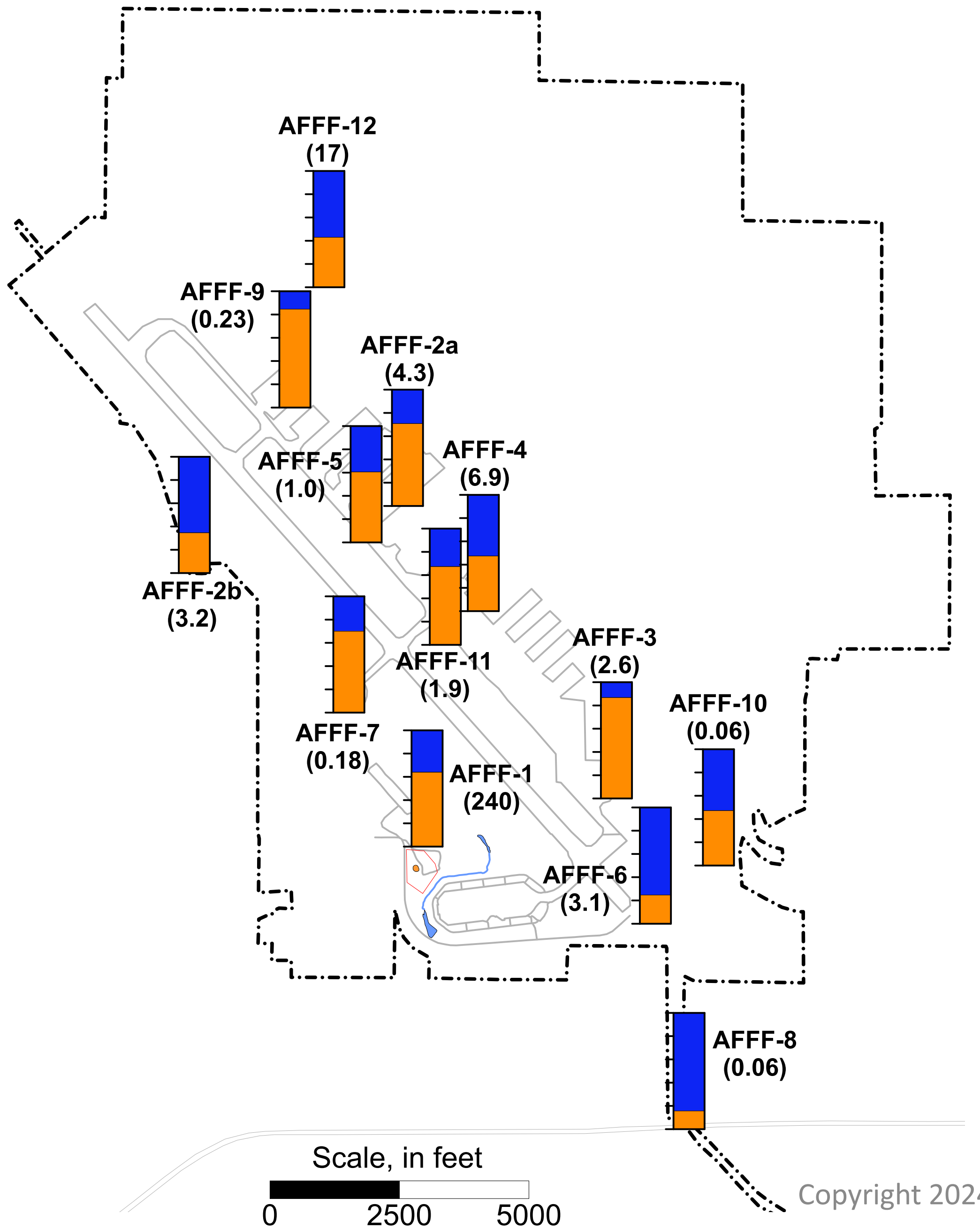
Stacked Bar Chart Example

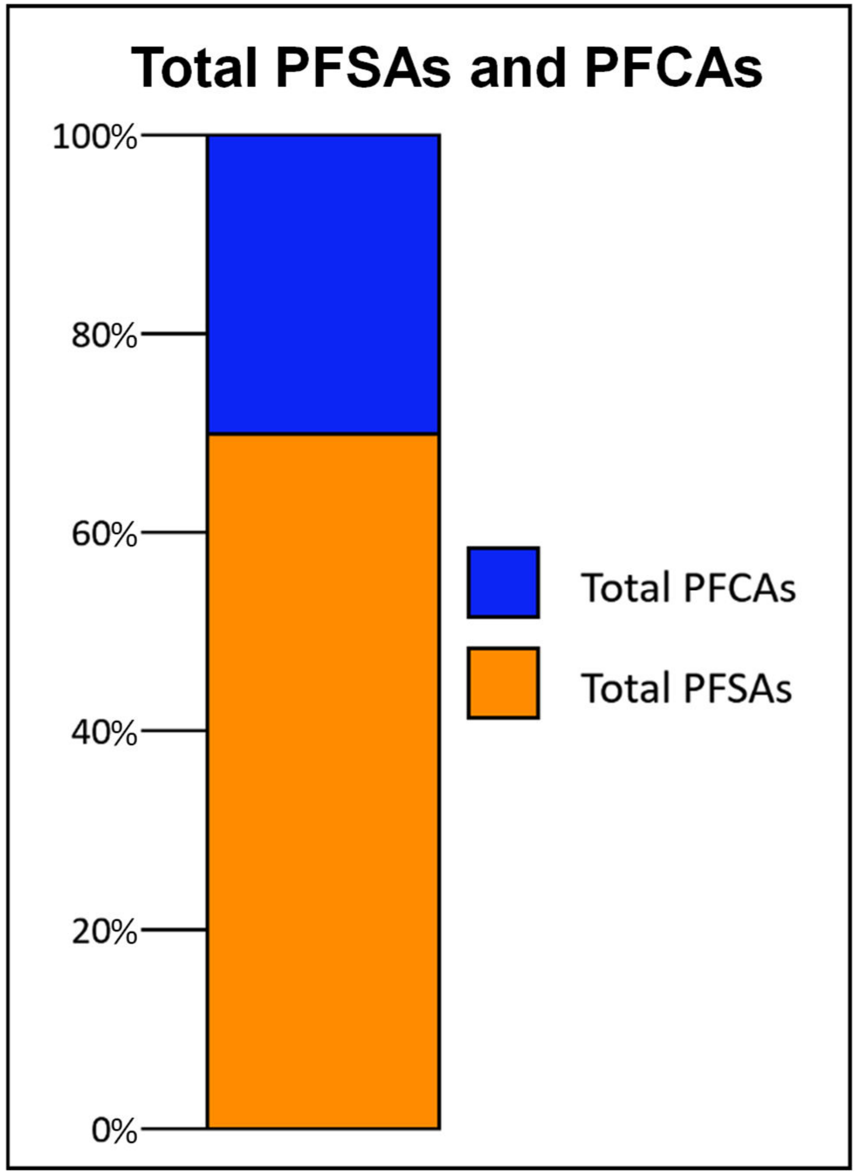
AFFF Product:
Fluorotelomerization
(FT) Process

AFFF Product:
Electrochemical Fluorination
(ECF) Process

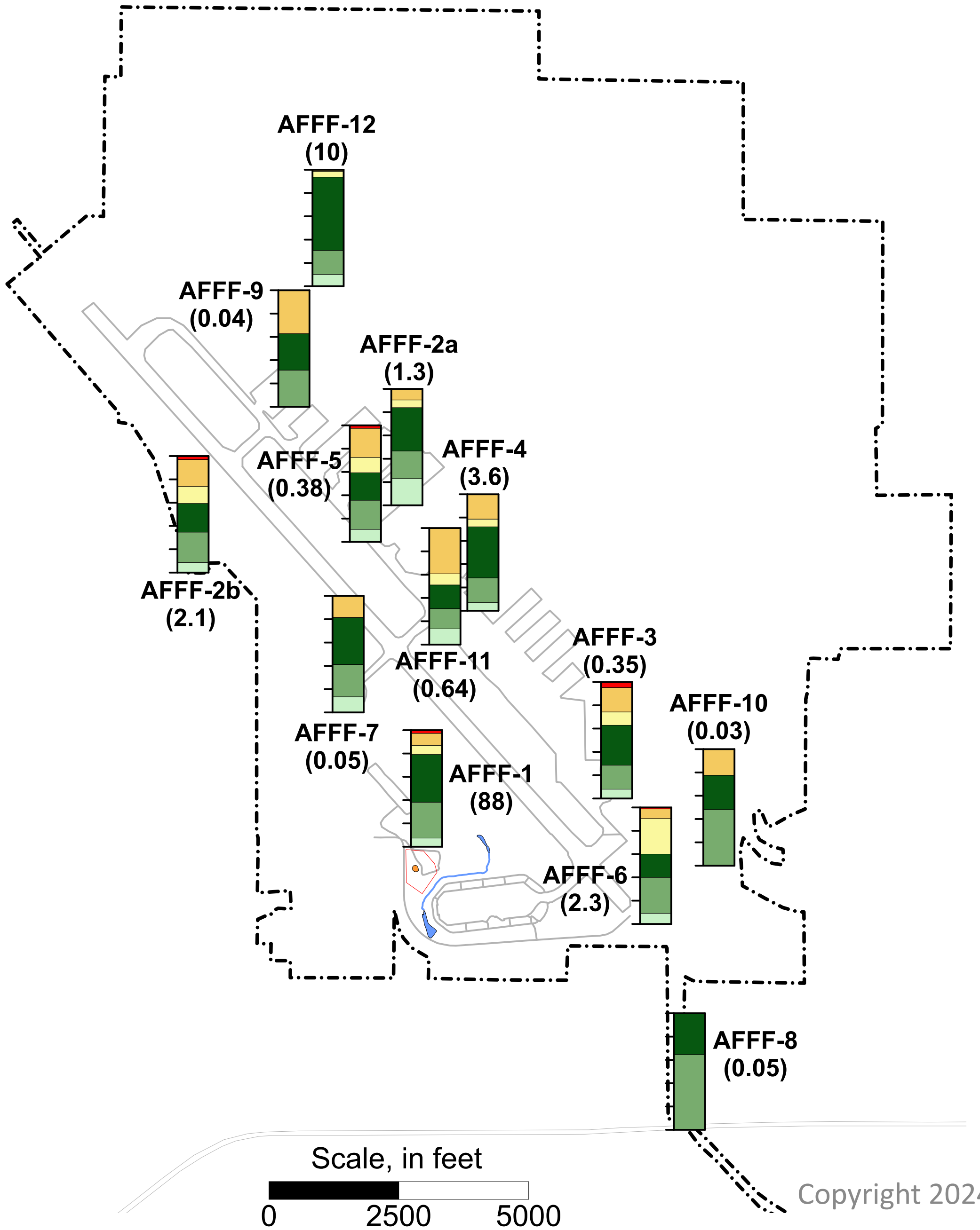


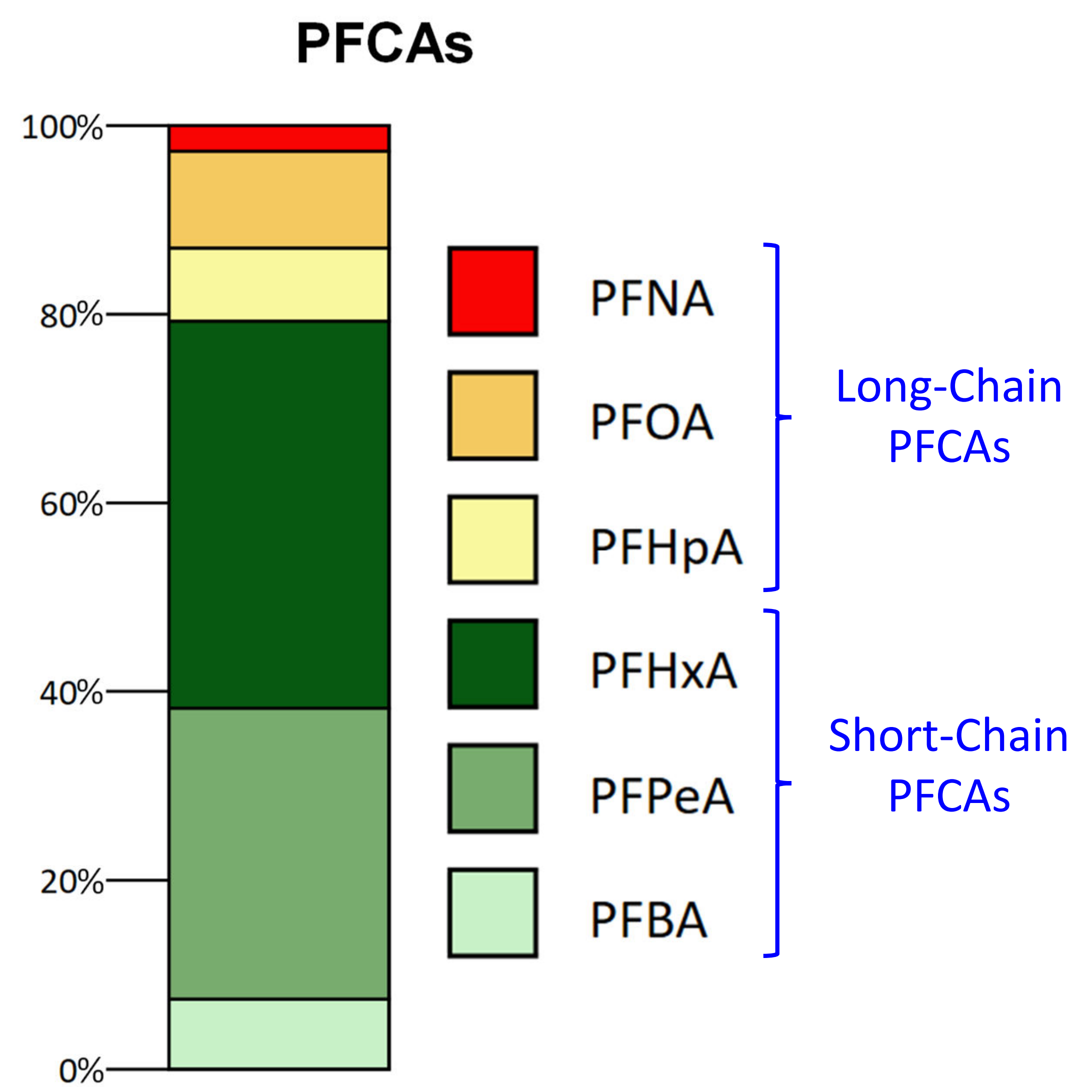
Stacked Bar Chart Example



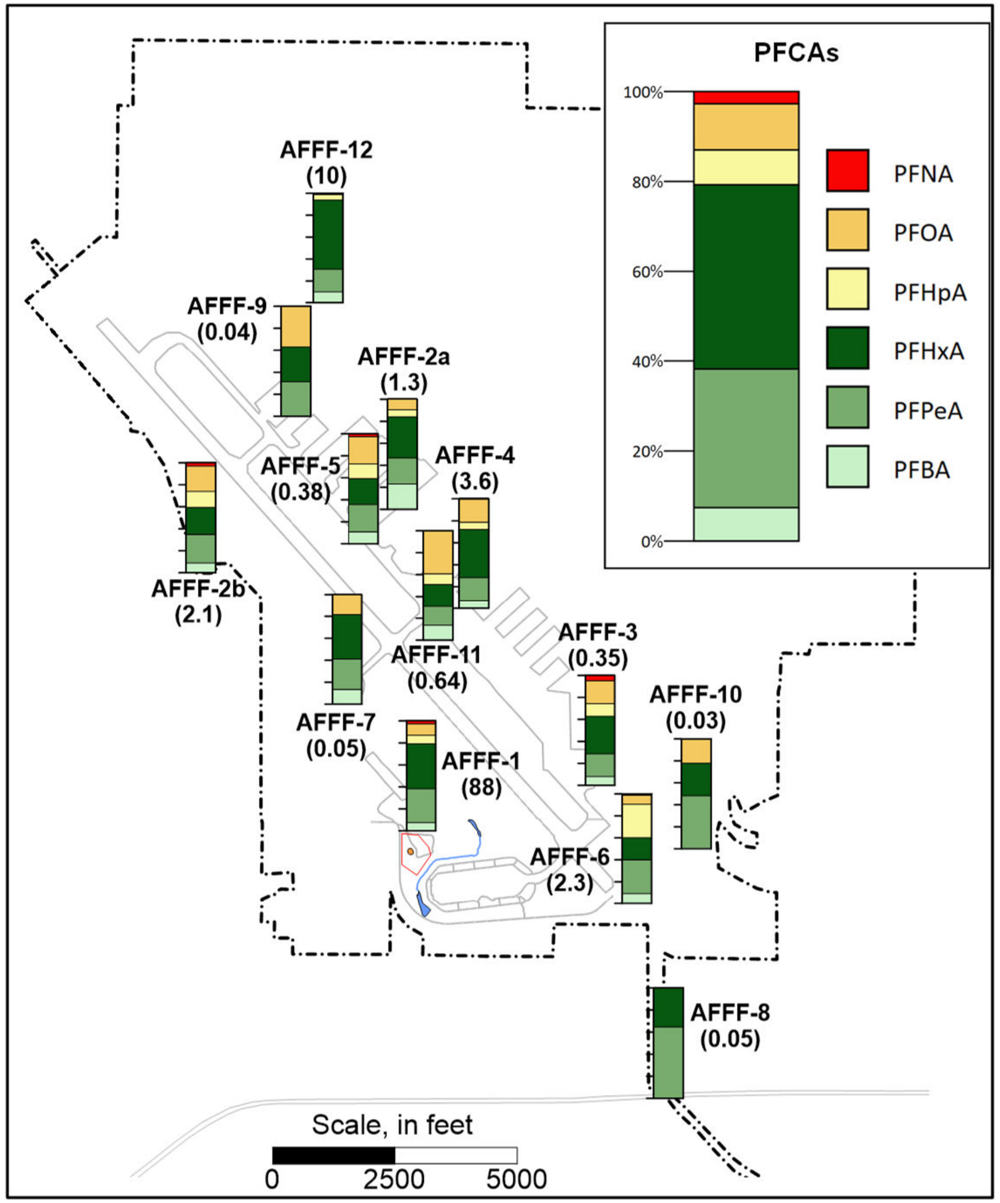


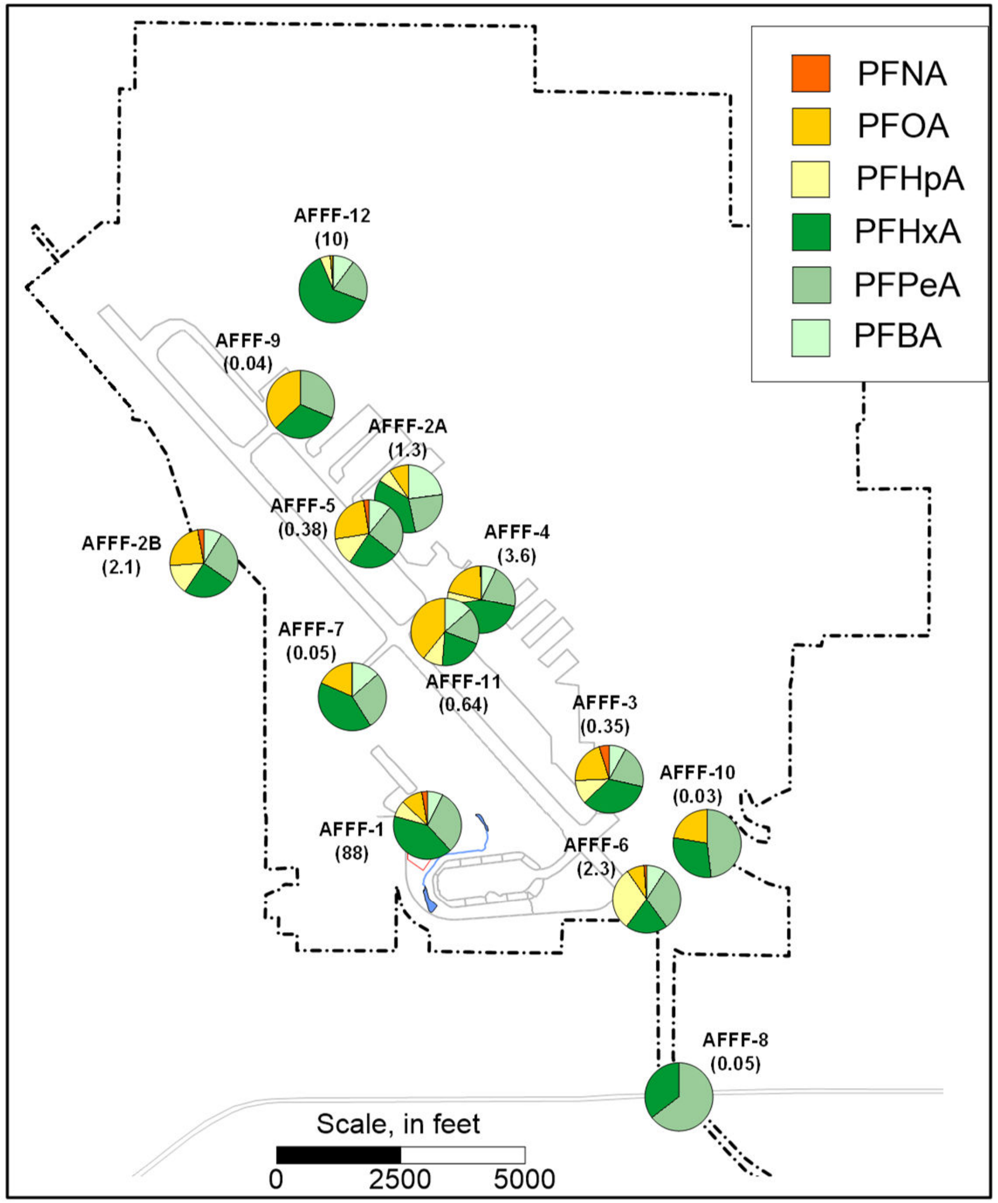
Source Area Short vs Long-Chain PFCAs





Stacked Bar vs Pie Chart Maps



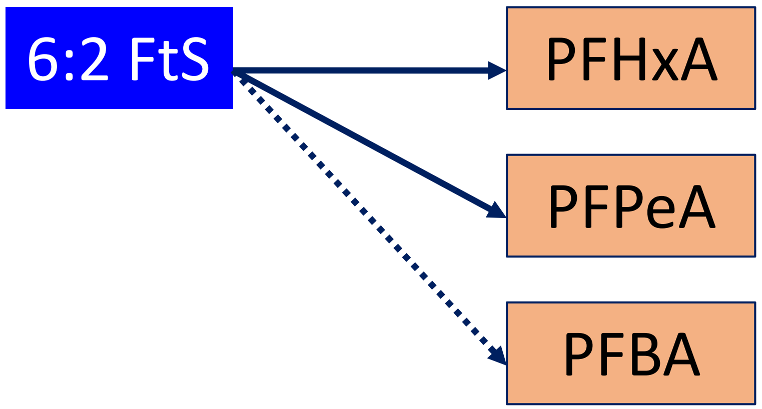


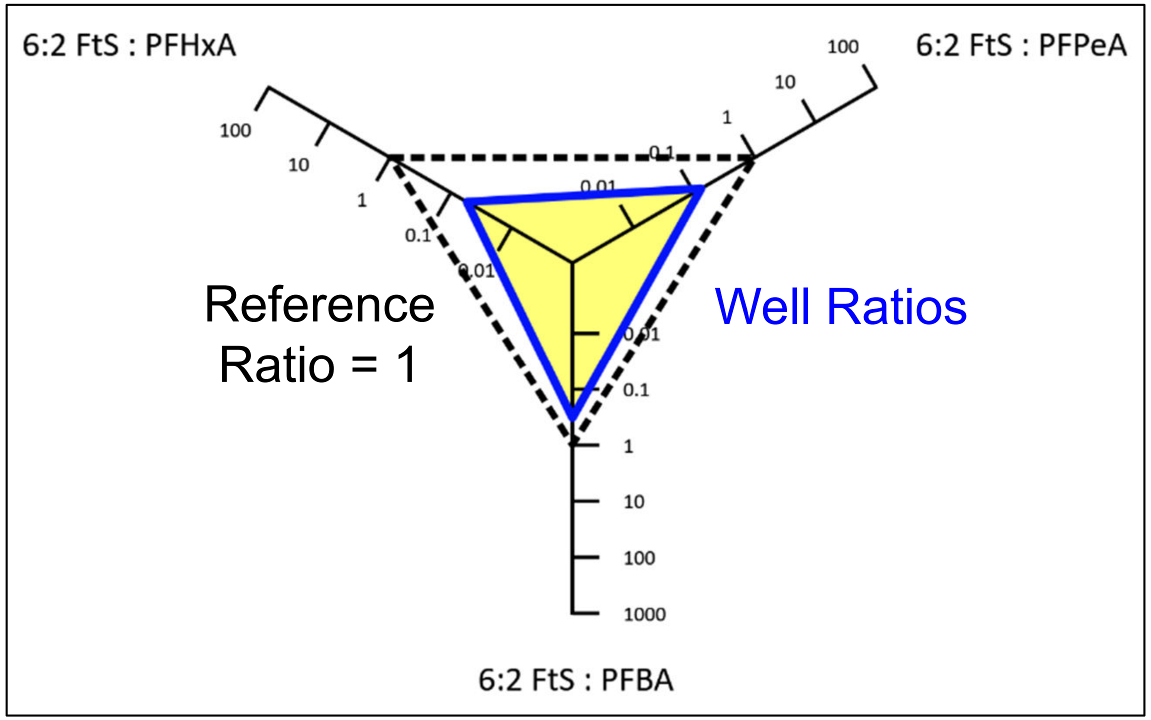
Advantages of Stacked Bar Maps:

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

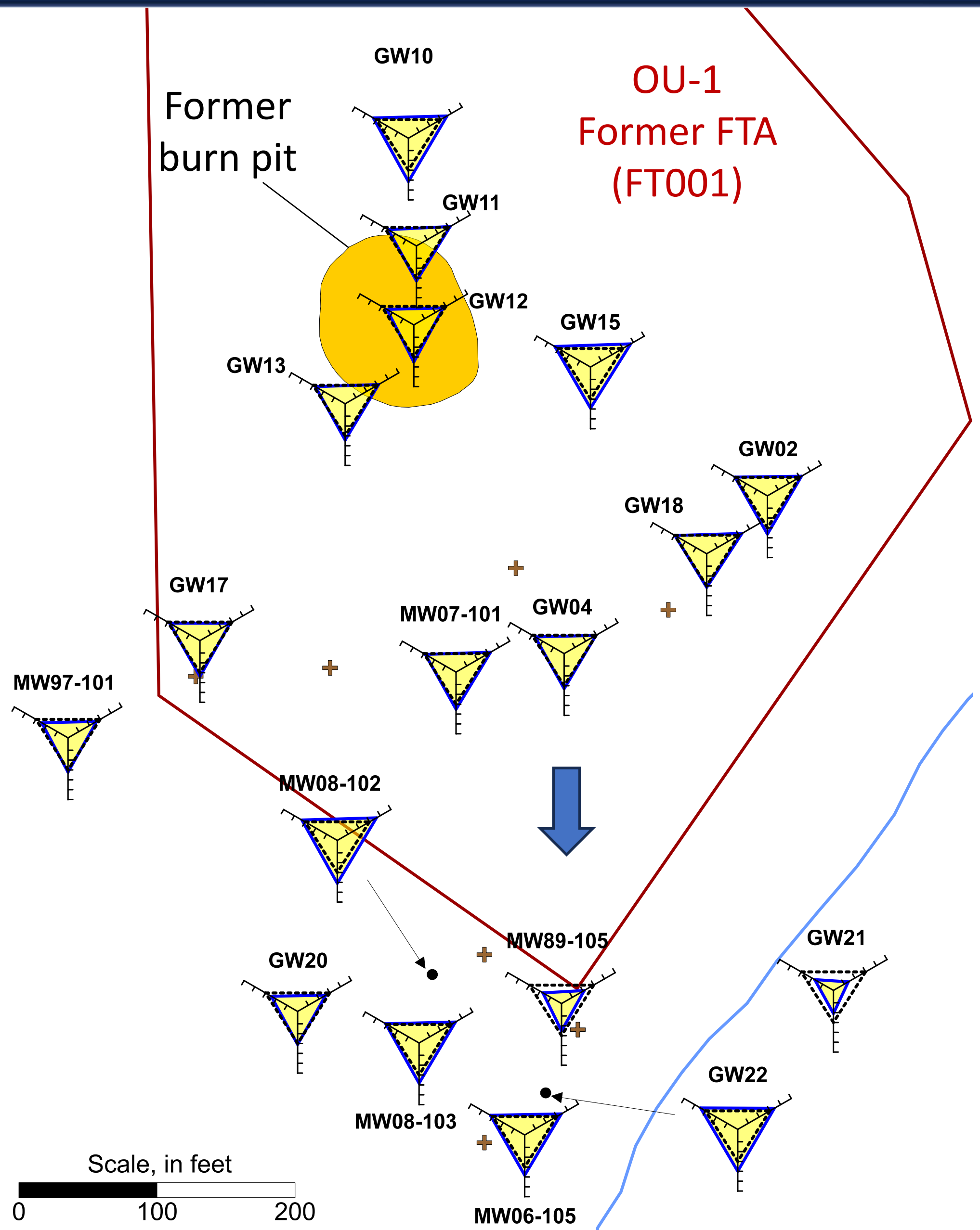
OU-1 (Former FTA): 6:2 FtS Ratios

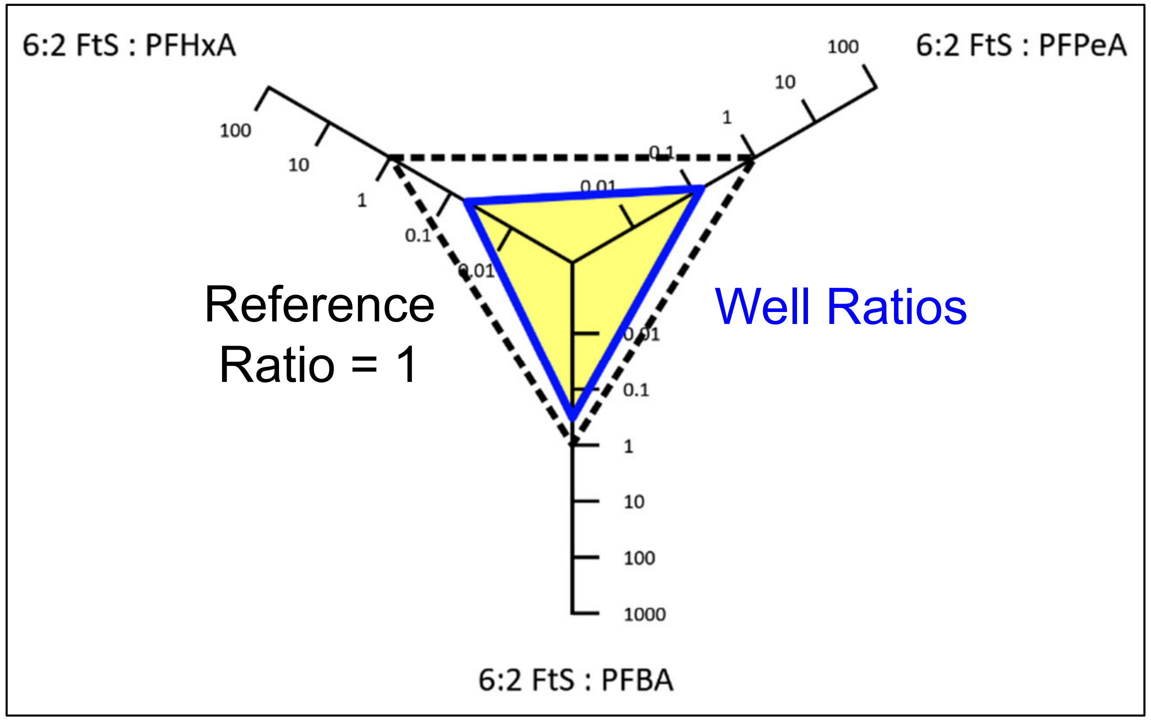
Precursor Transformation Pathways





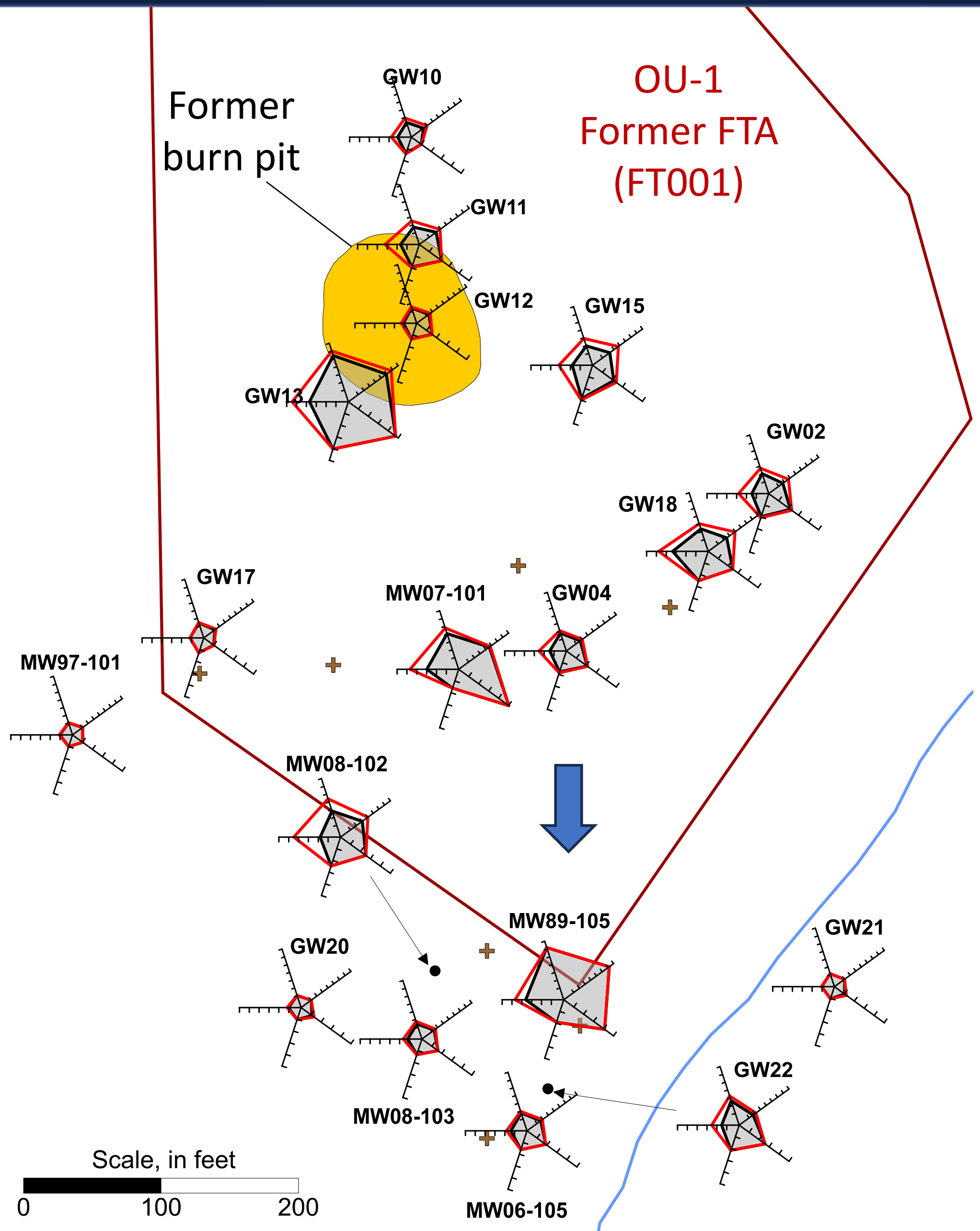
OU-1 (Former FTA): 6:2 FtS Ratios

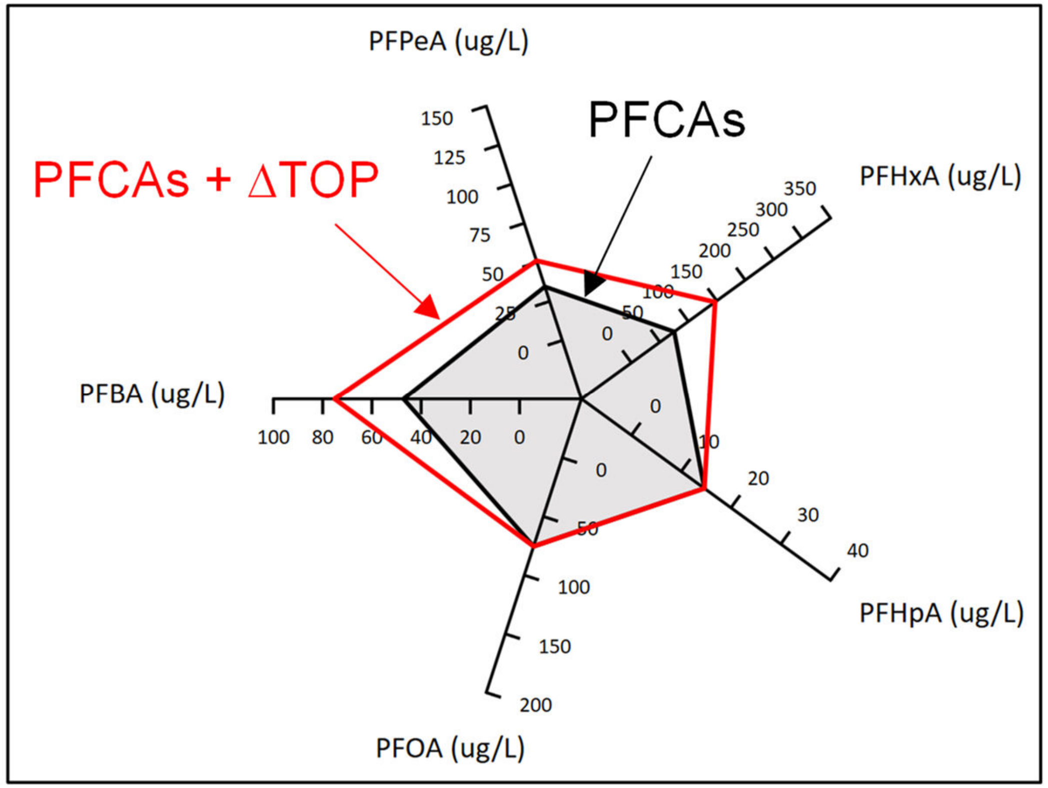




+ DO Infusion Well

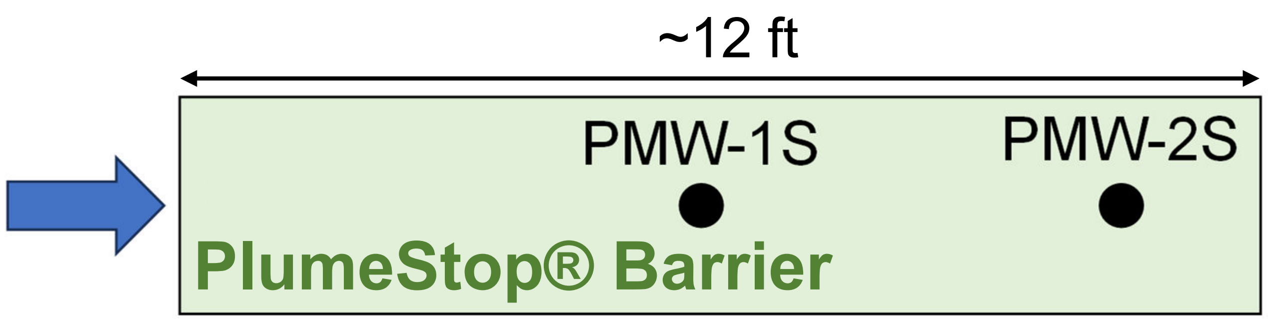
OU-1 (Former FTA): TOP Assay Results

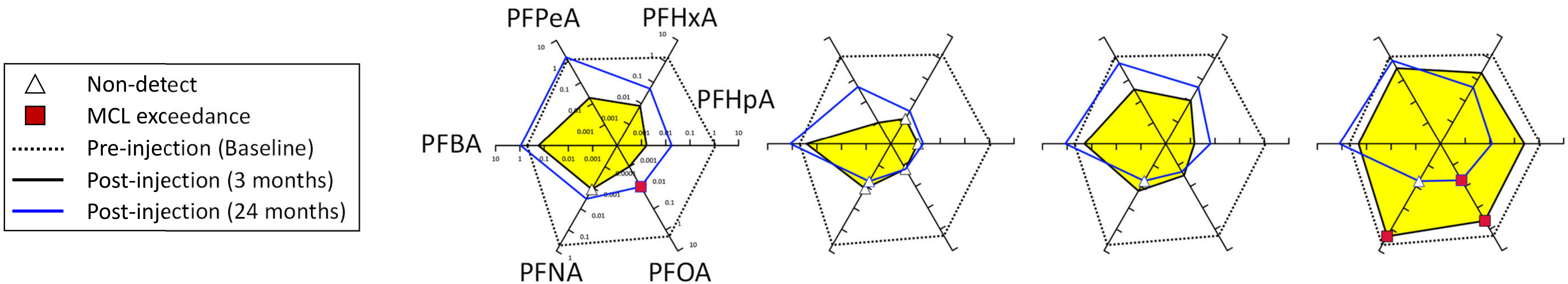




PFAS Remediation (PlumeStop®) Navy Site

Section 2





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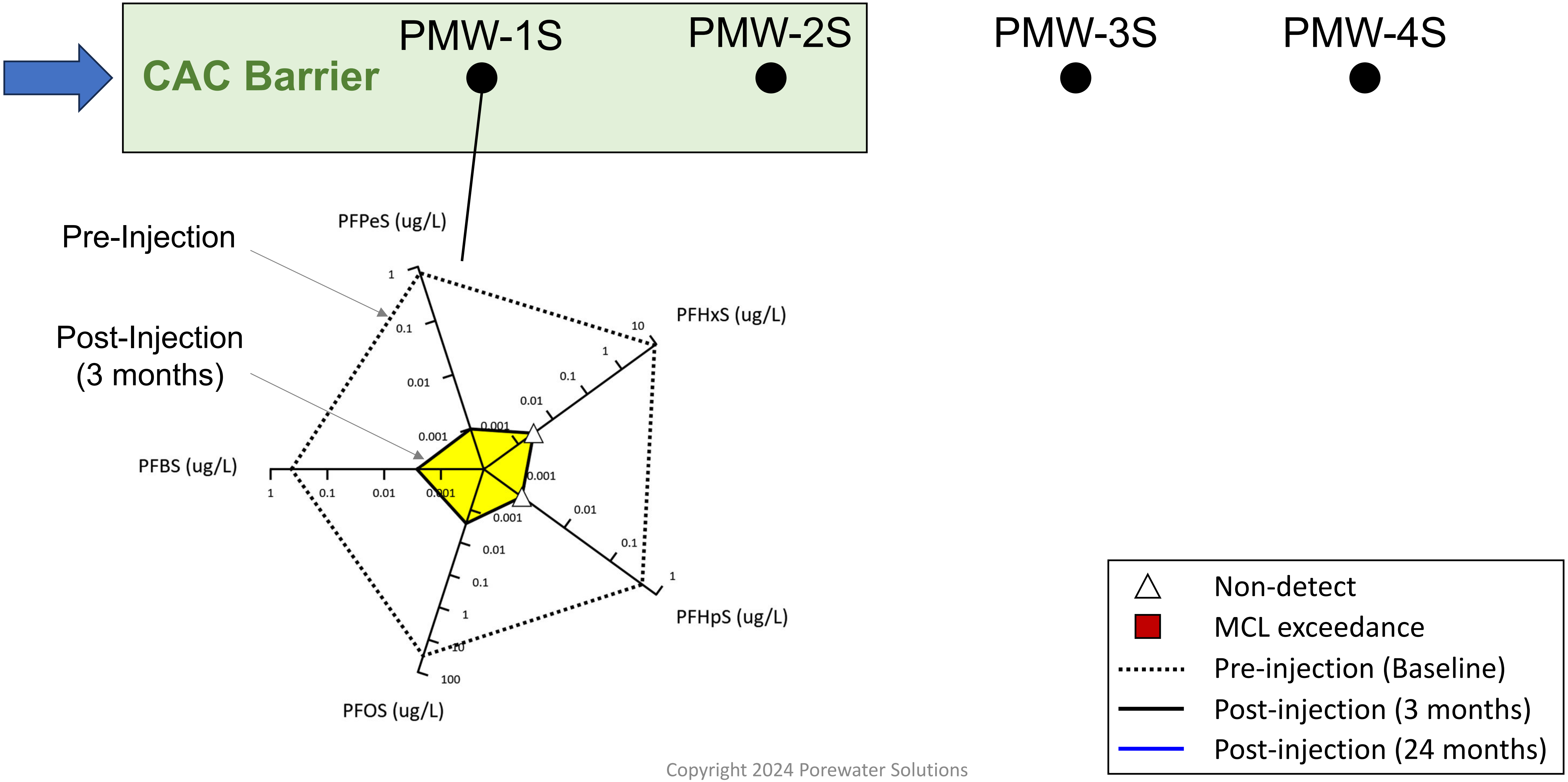
Dr. Paul Hatzinger, Graig Lavorgna, David Lippincott
APTIM

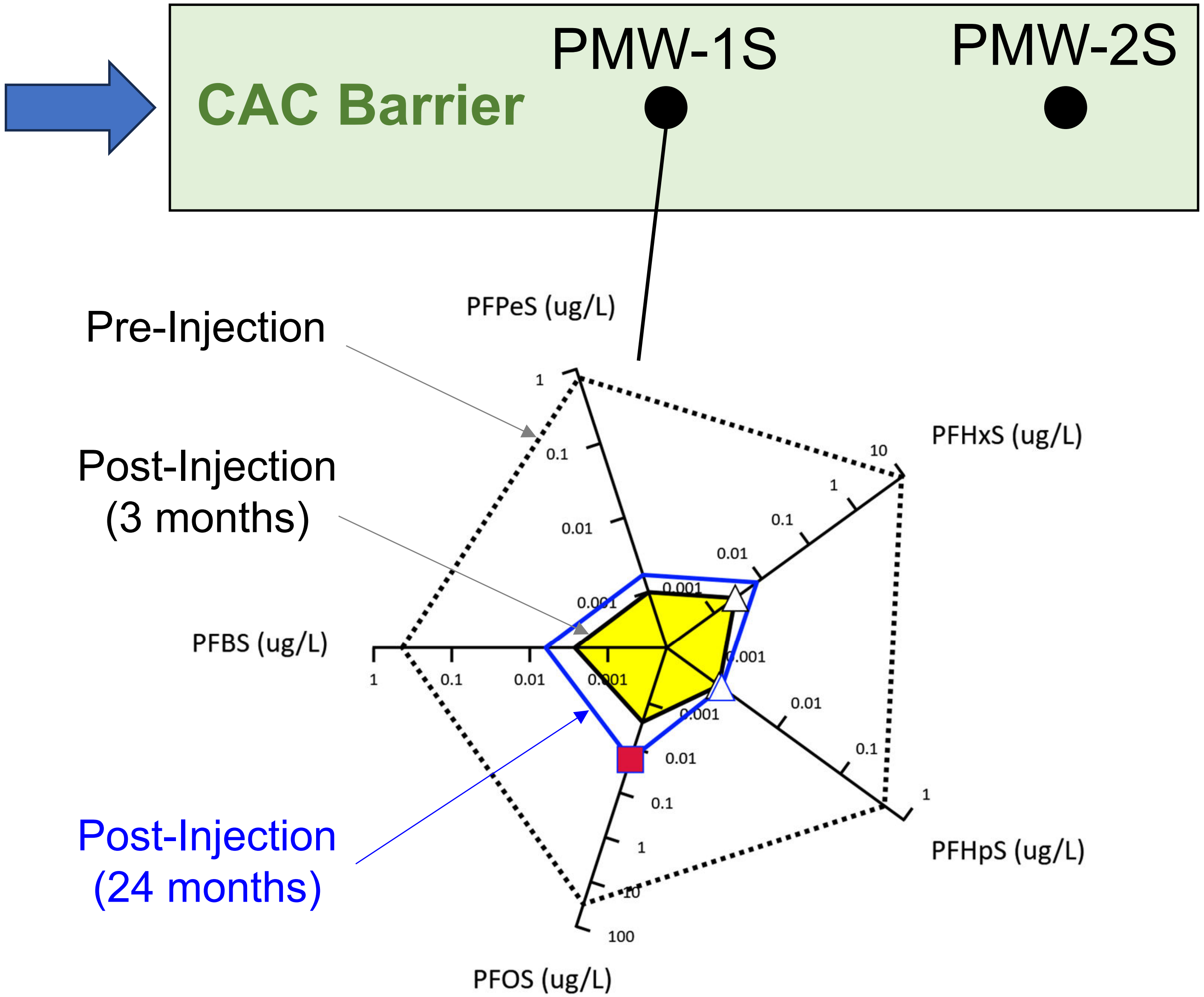
Dr. Anthony Danko
NAVFAC EXWC

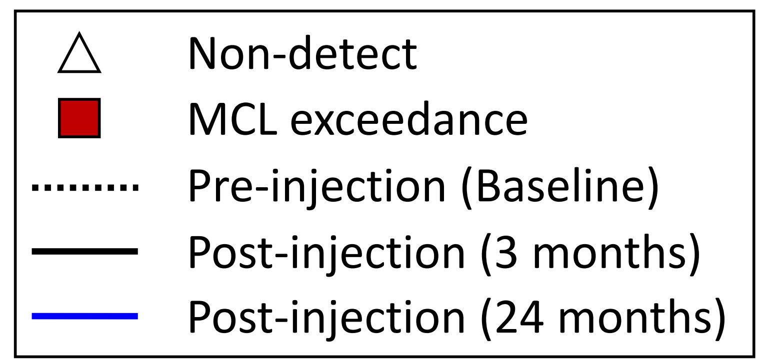
Dr. Brent Sleep
University of Toronto

NESDI PRB Performance: PFSAs

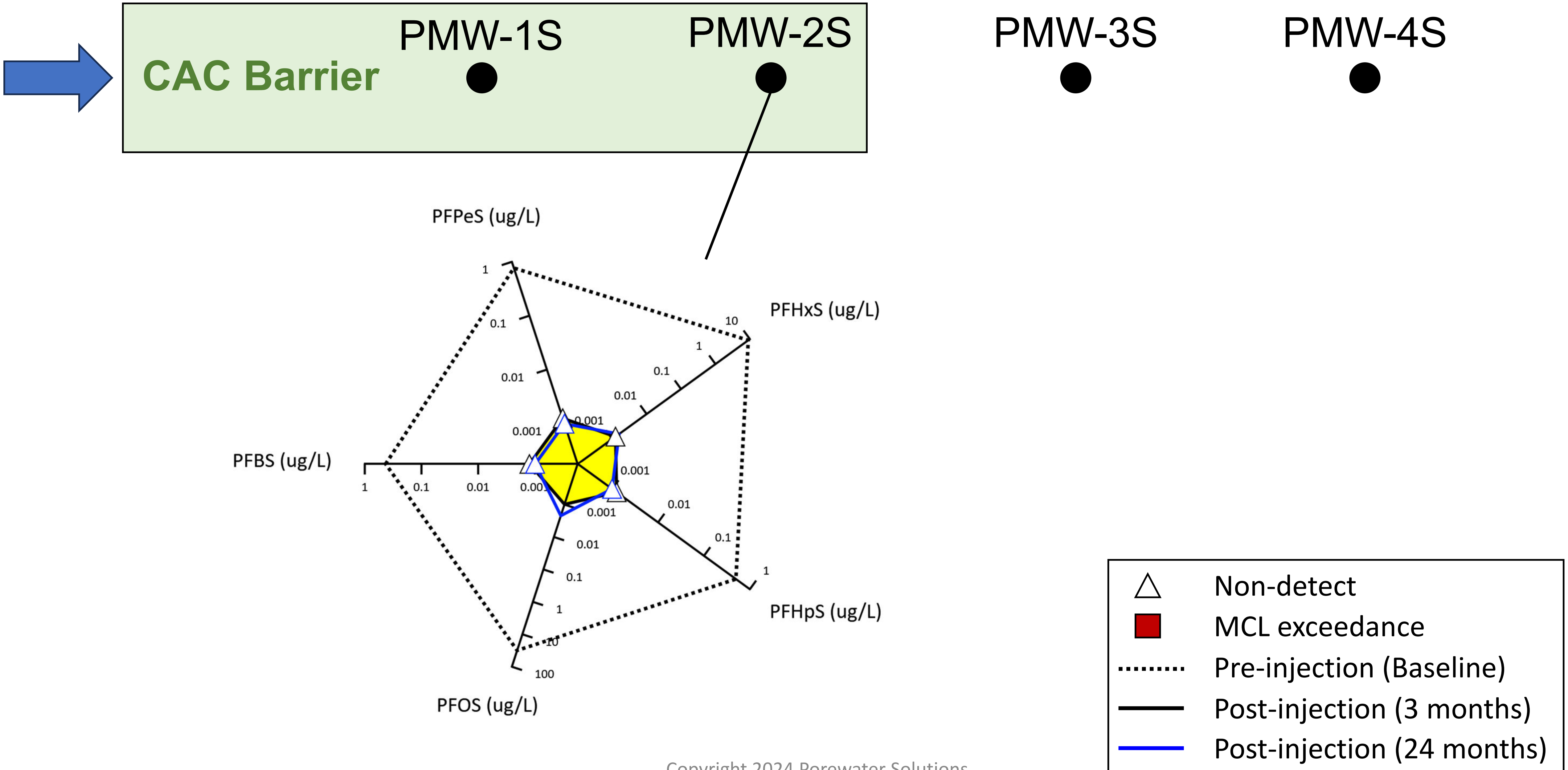


NESDI PRB Performance: PFSAs

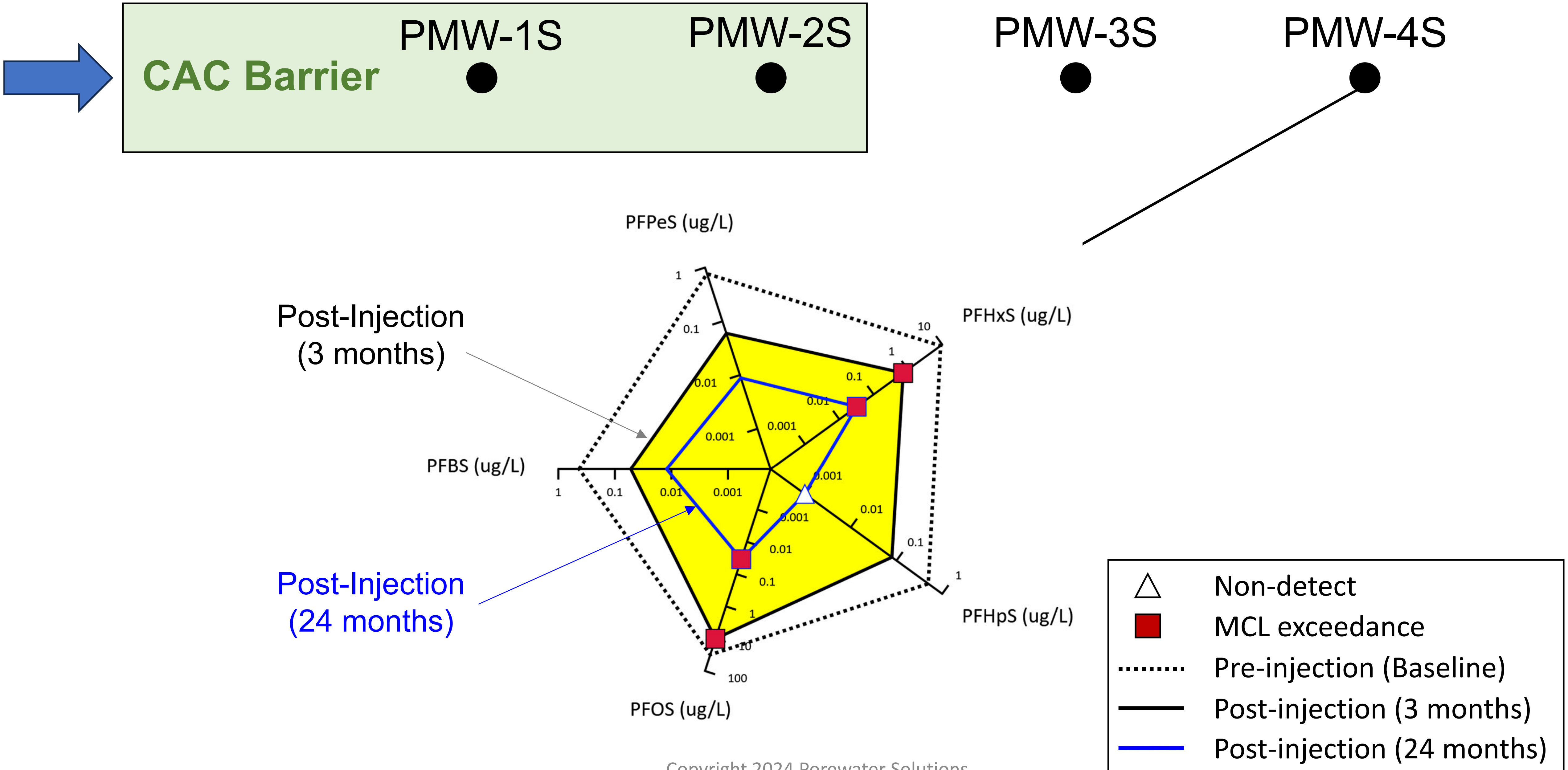




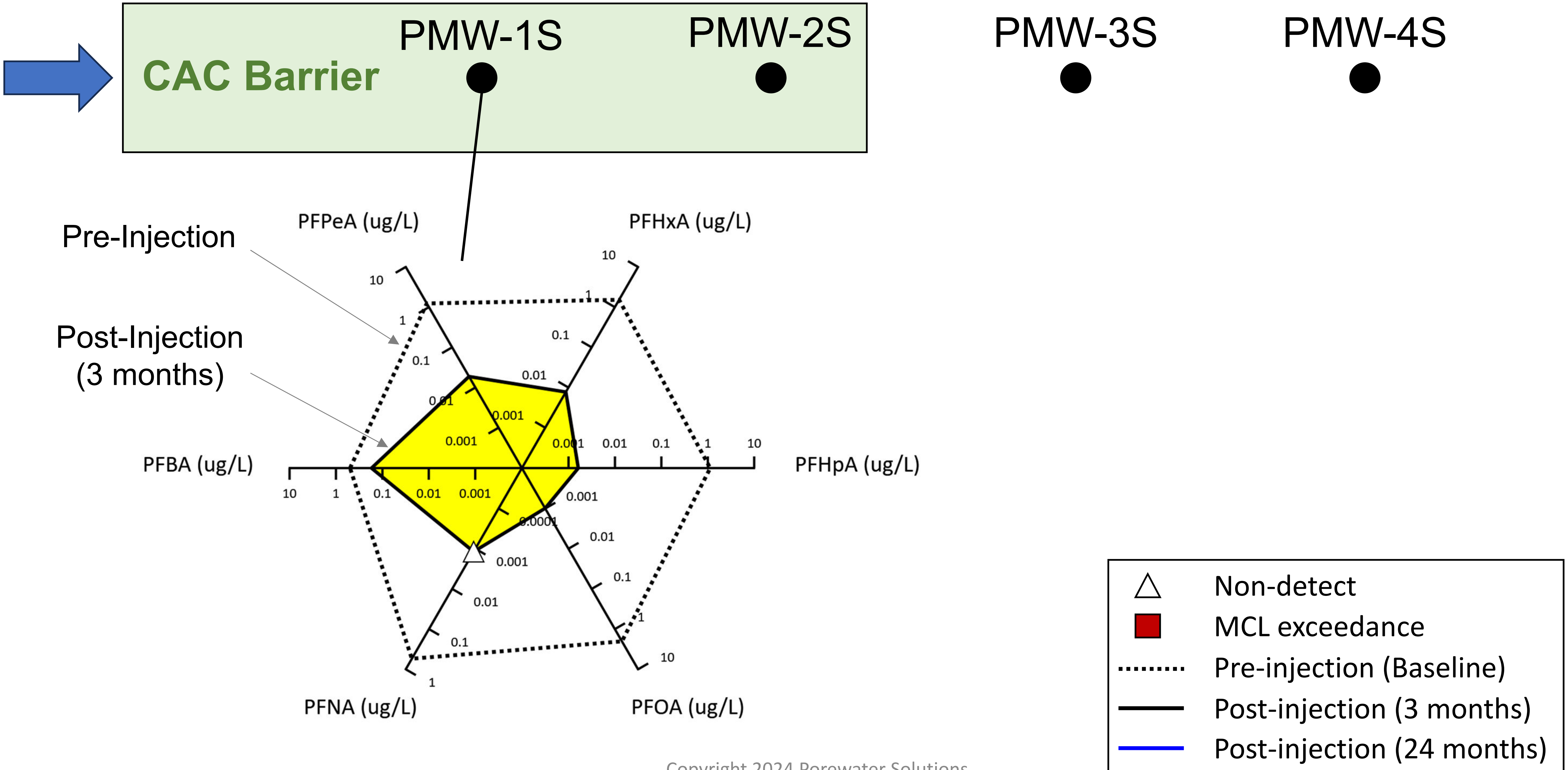
NESDI PRB Performance: PFSAs



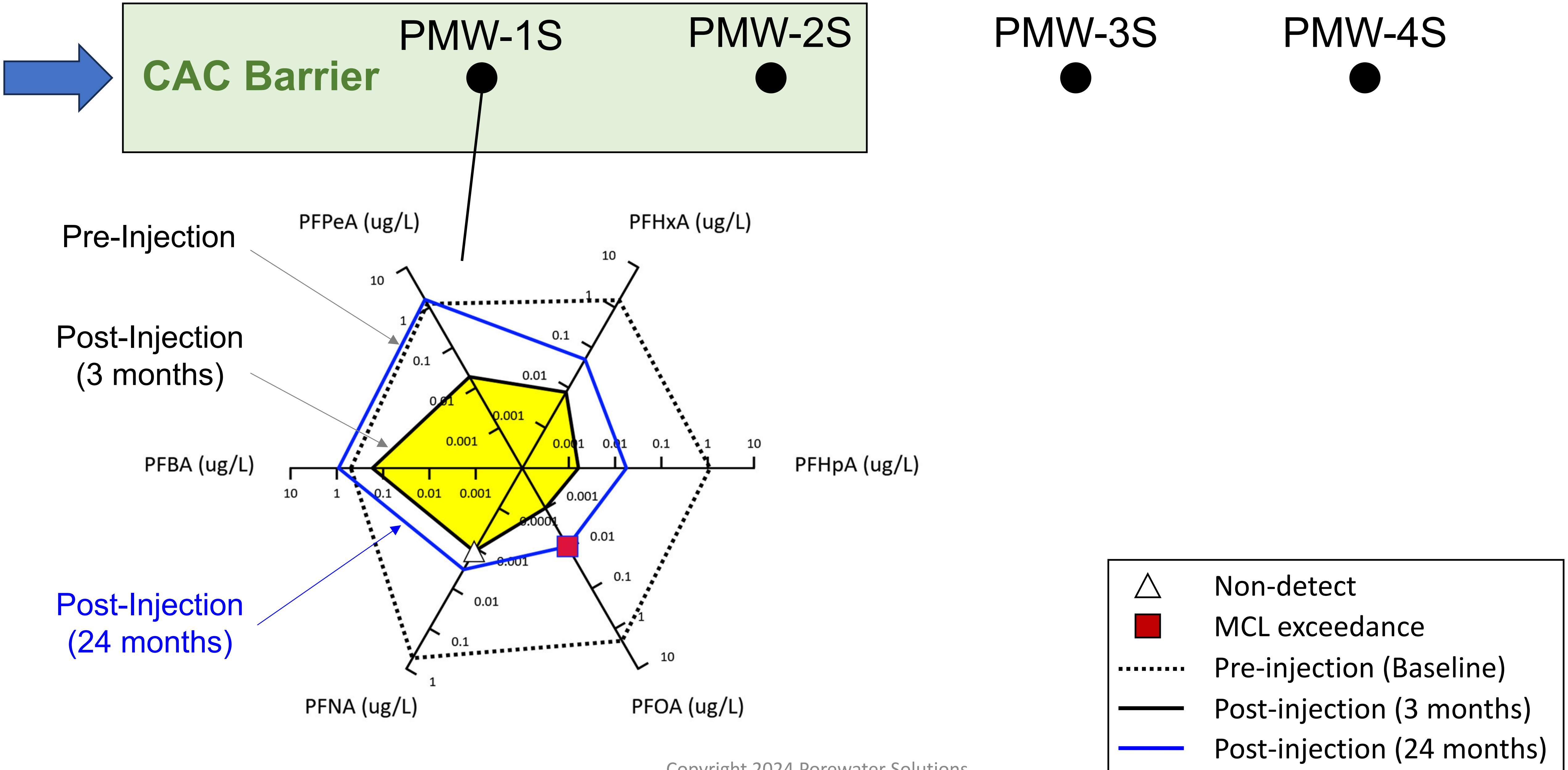
NESDI PRB Performance: PFSAs



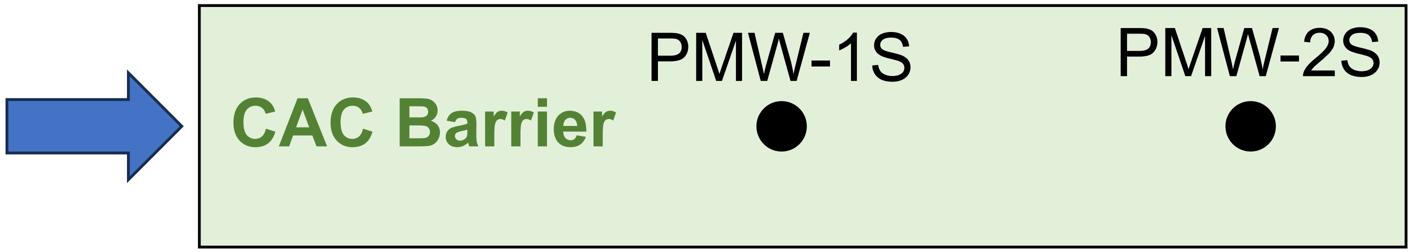
NESDI PRB Performance: PFCAs

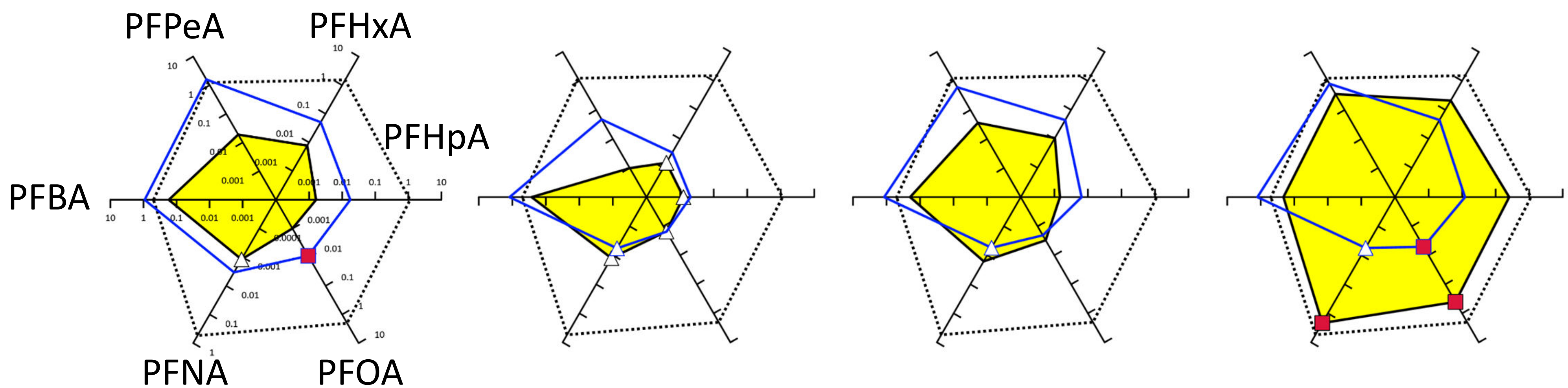


NESDI PRB Performance : PFCAs



NESDI PRB Performance : PFCAs



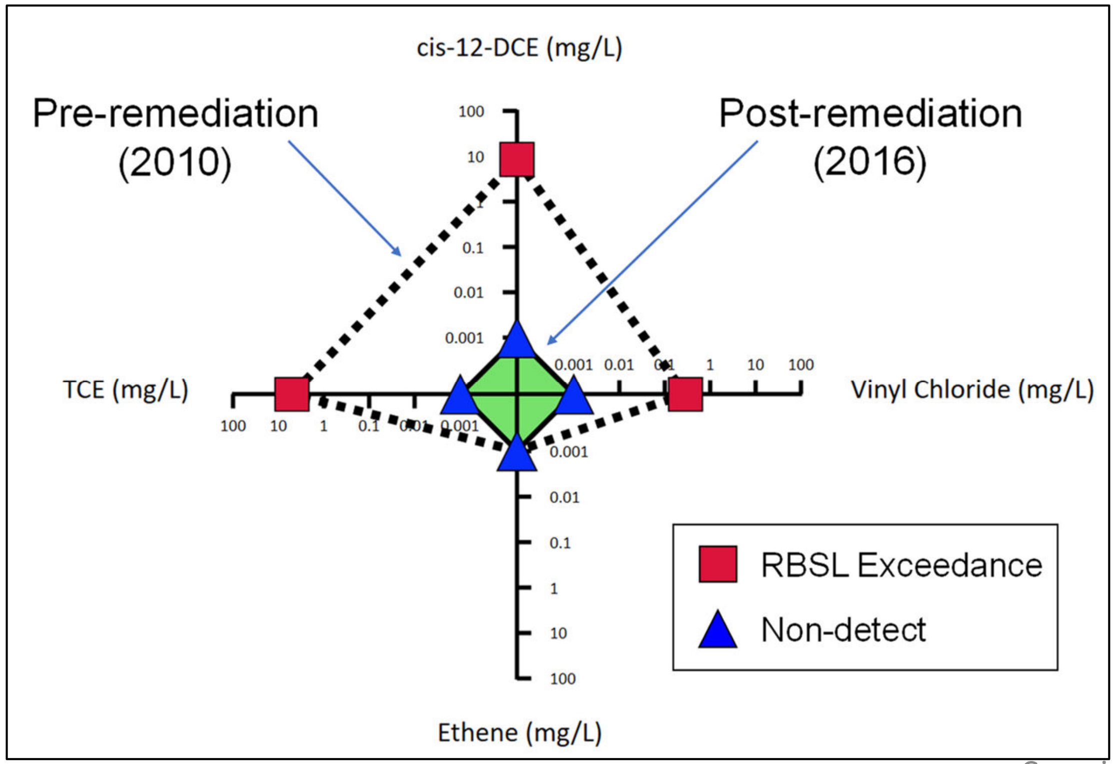


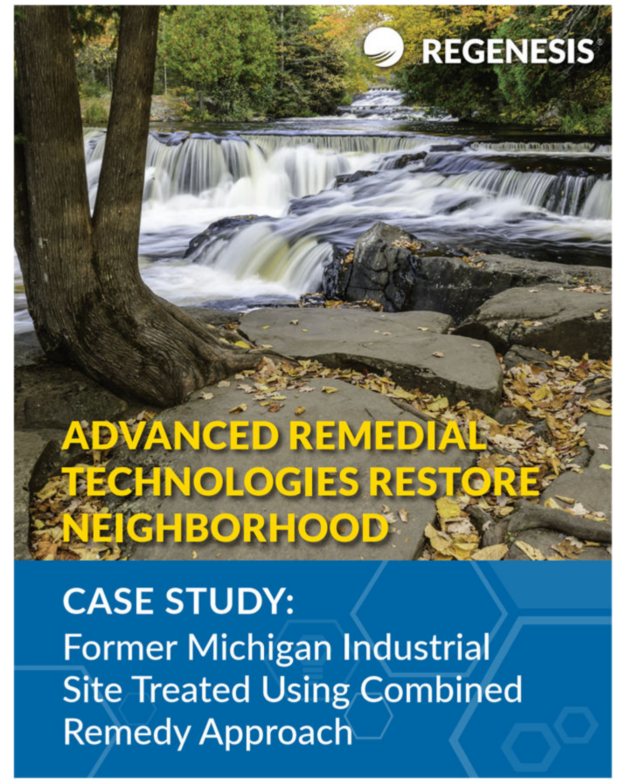
△ Non-detect
■ MCL exceedance
Pre-injection (Baseline)
Post-injection (3 months)
Post-injection (24 months)

Michigan Case Study
Regenesis Remediation

Section 3

www.Regenesis.com





Acknowledgements

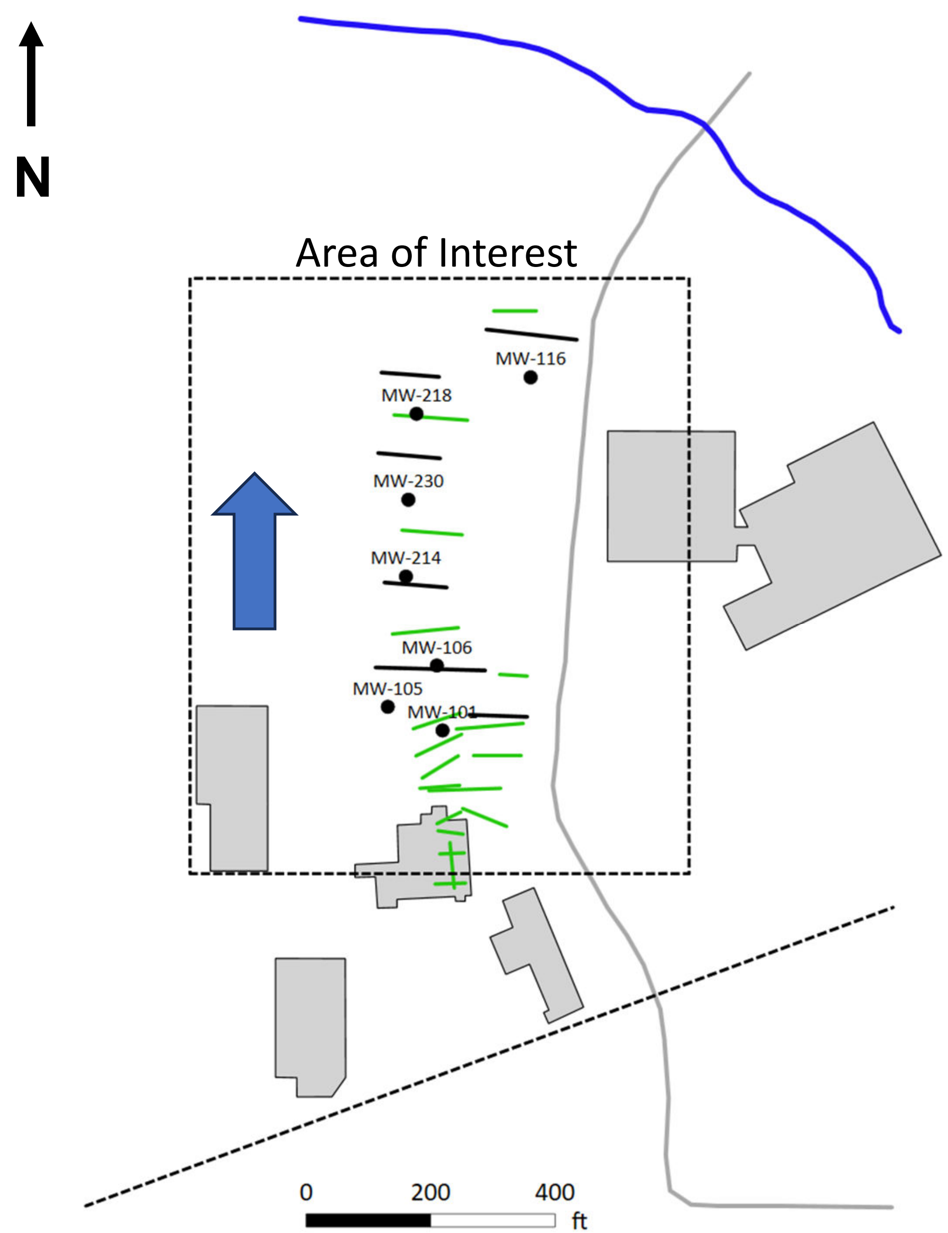
REGENESIS

Douglas Davis, Dr. Paul Erickson

microbial insights
www.microbe.com

Dora Taggart

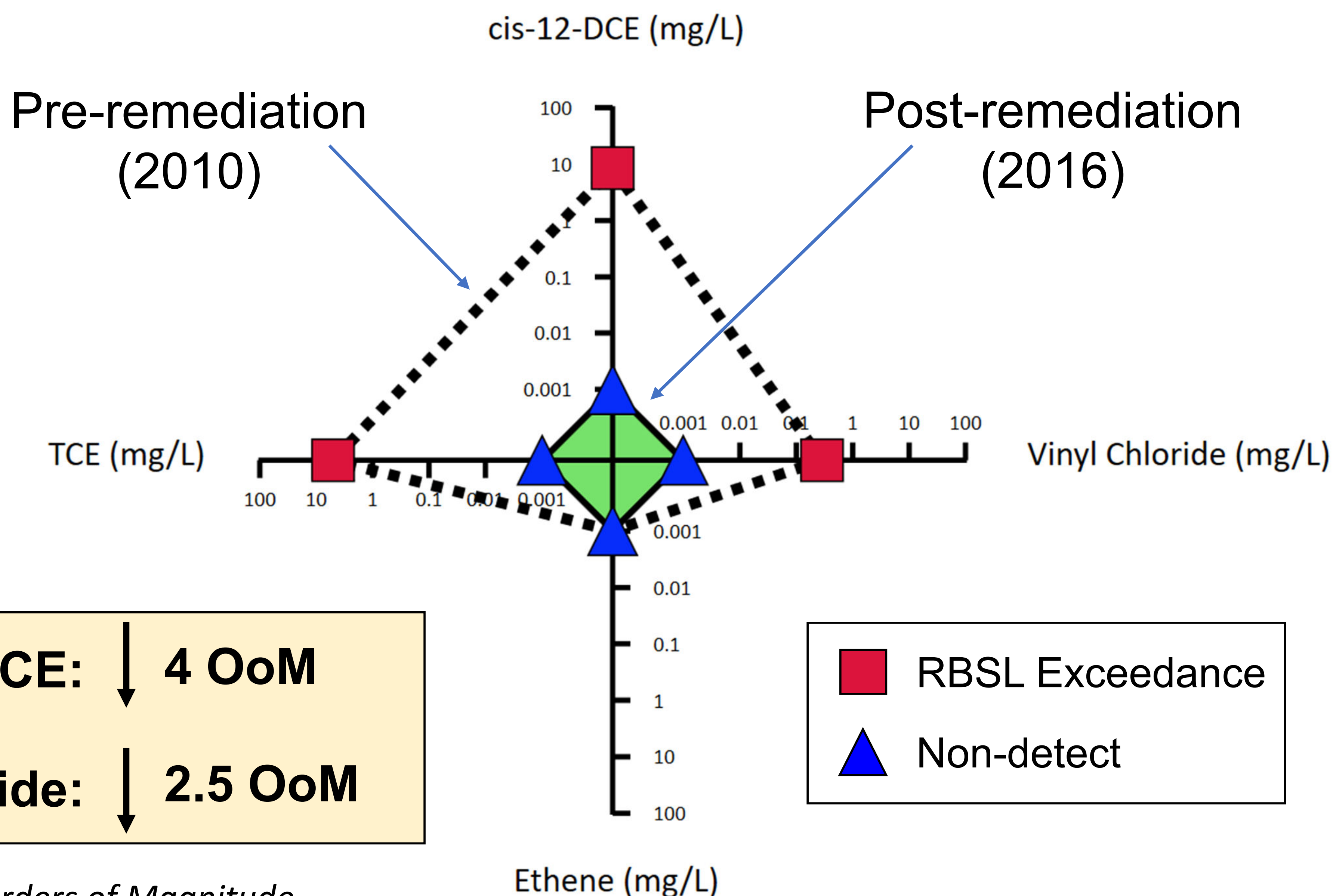
Site Setting



2011, 2013	Source & Plume Transects 3DMe Average well spacing: 15 feet
2015	Plume Transects PlumeStop®, HRC, BDI+ Average well spacing: 10 feet

3DMe: 3-D Microemulsion®
PlumeStop®: Colloidal activated carbon
HRC: Hydrogen Release Compound
BDI+: Bio-Dechlor Inoculum Plus®

CAH Radial Diagram (MW-230)

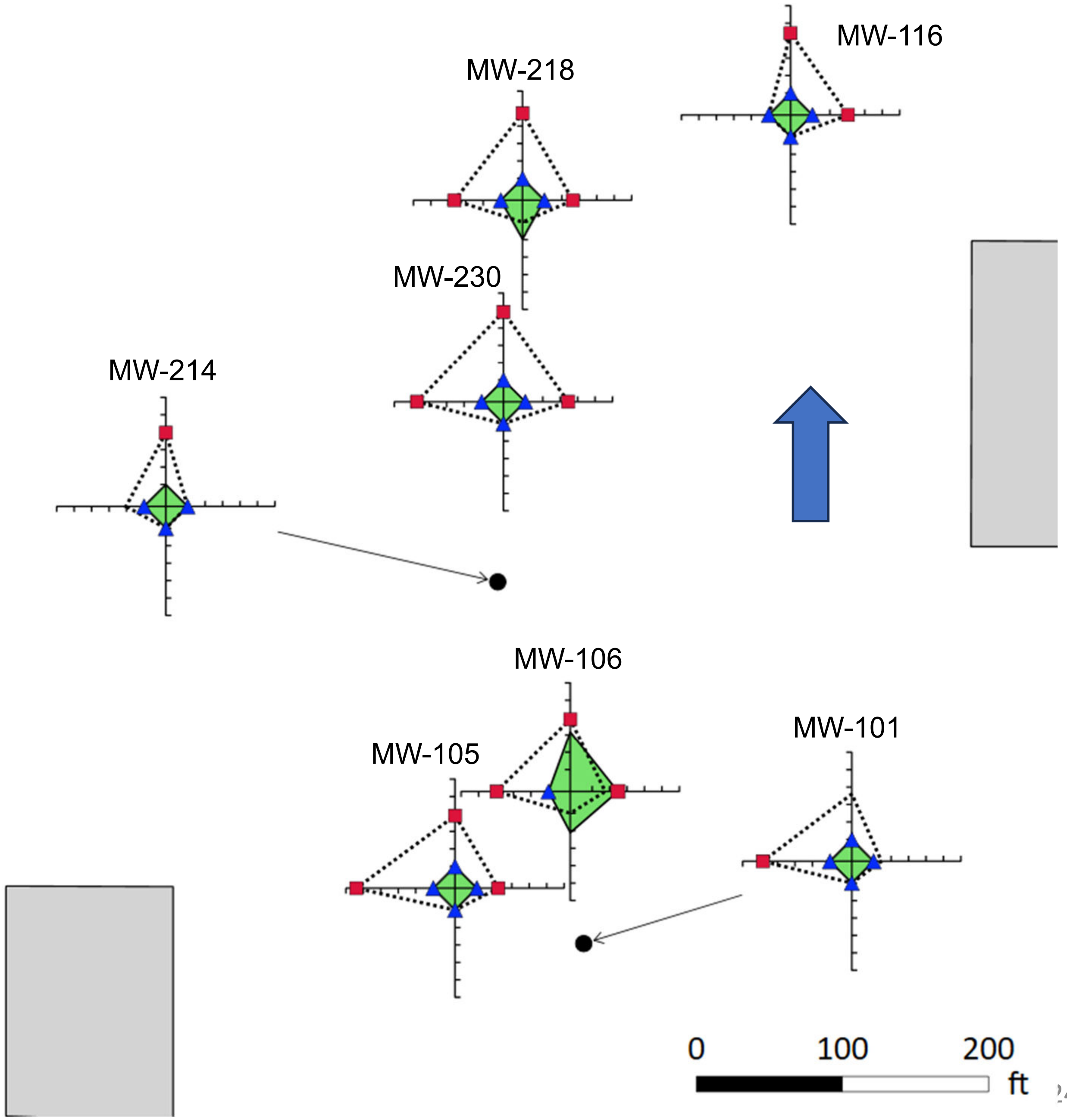


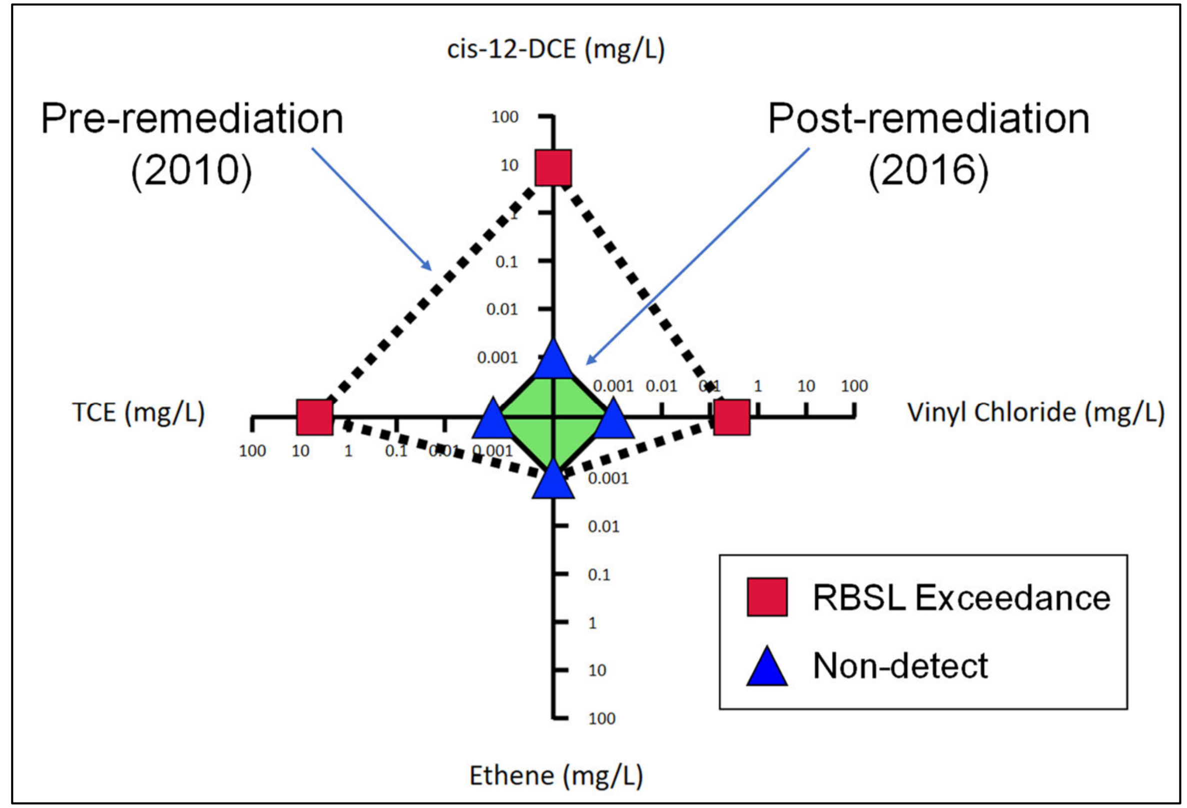
TCE, cis-DCE: ↓ 4 OoM

Vinyl Chloride: ↓ 2.5 OoM

OoM: Orders of Magnitude

CAH Radial Diagram Map

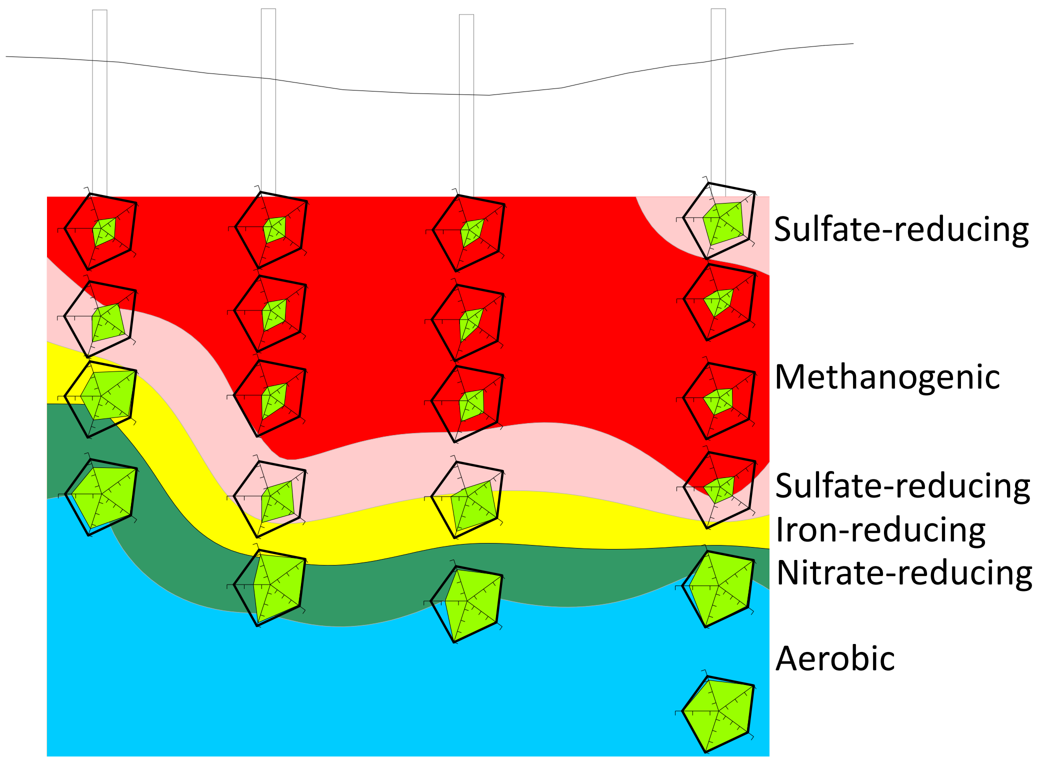


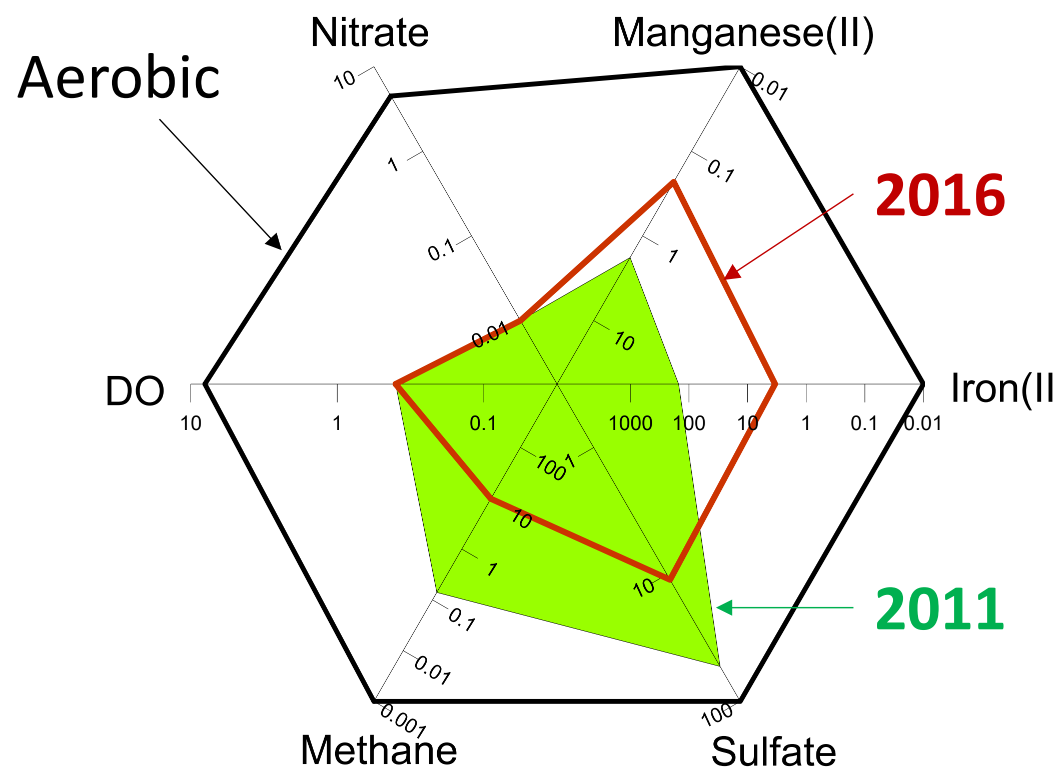


Unique Redox Radial Diagram Method

Section 4

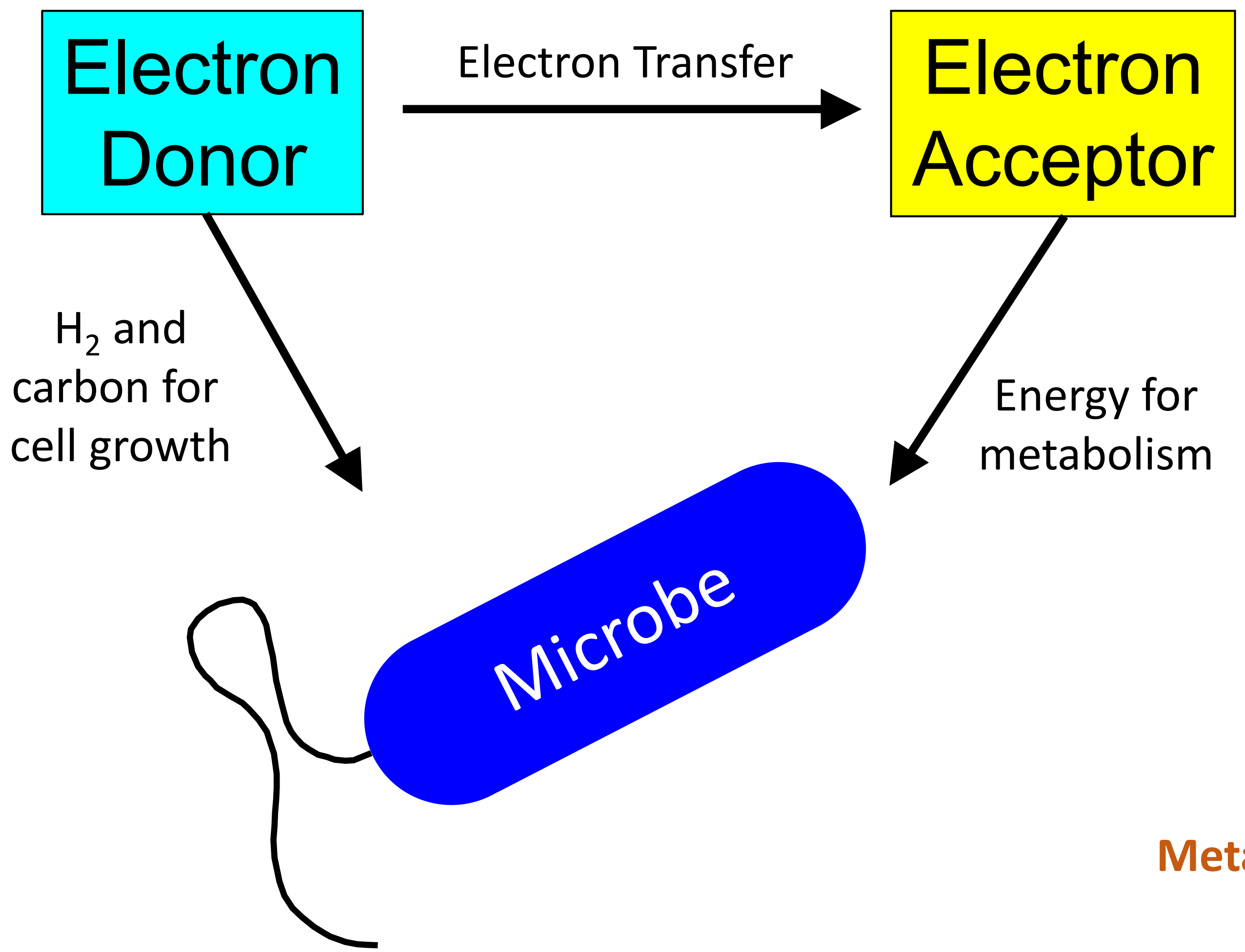
Wurtsmith AFB, MI





Note: all concentrations in mg/L.

Biogeochemical Processes

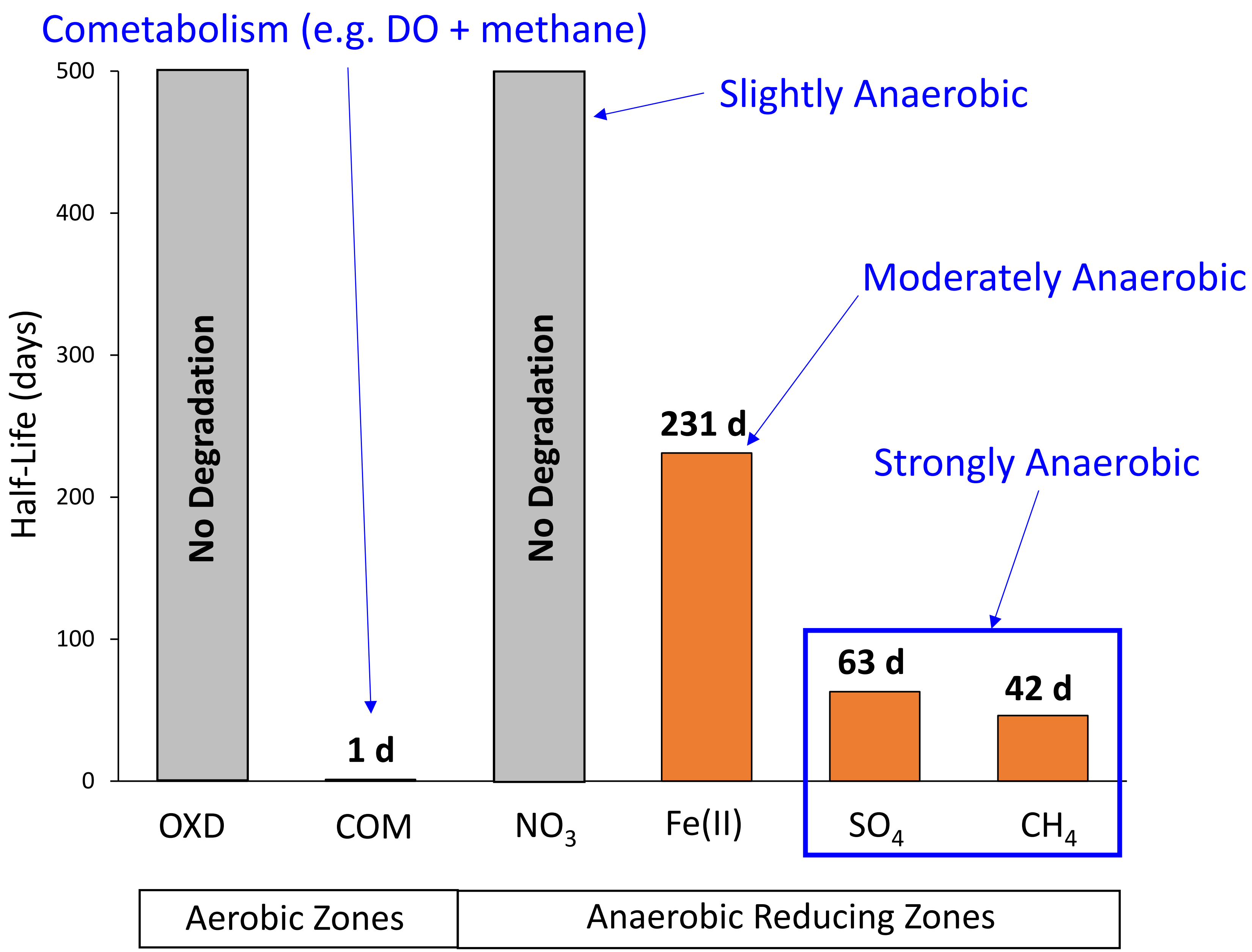


Inorganic Electron Acceptors:

- O_2
- NO_3
- $Mn_{(s)} \rightarrow Mn^{2+}$
- $Fe_{(s)} \rightarrow Fe^{2+}$
- SO_4
- $CO_2 \rightarrow CH_4$

Metabolic Byproducts

TCE Degradation by Redox Zone



Redox Radial Diagrams: MI Superfund Site

Proceedings of the API/NGWA Petroleum Hydrocarbons and Organic Chemicals in Groundwater Conference, Houston, Texas, November 1996

APPLICATION OF AN INNOVATIVE VISUALIZATION METHOD FOR DEMONSTRATING INTRINSIC REMEDIATION AT A LANDFILL SUPERFUND SITE

Grant R. Carey*, Michael G. Mateyk, Glenn T. Turchan, Edward A. McBean, Frank A. Rovers, J. Richard Murphy

Conestoga-Rovers & Associates, Waterloo, Ontario, Canada

James R. Campbell

Engineering Management, Inc., Pittsburgh, Pennsylvania, USA

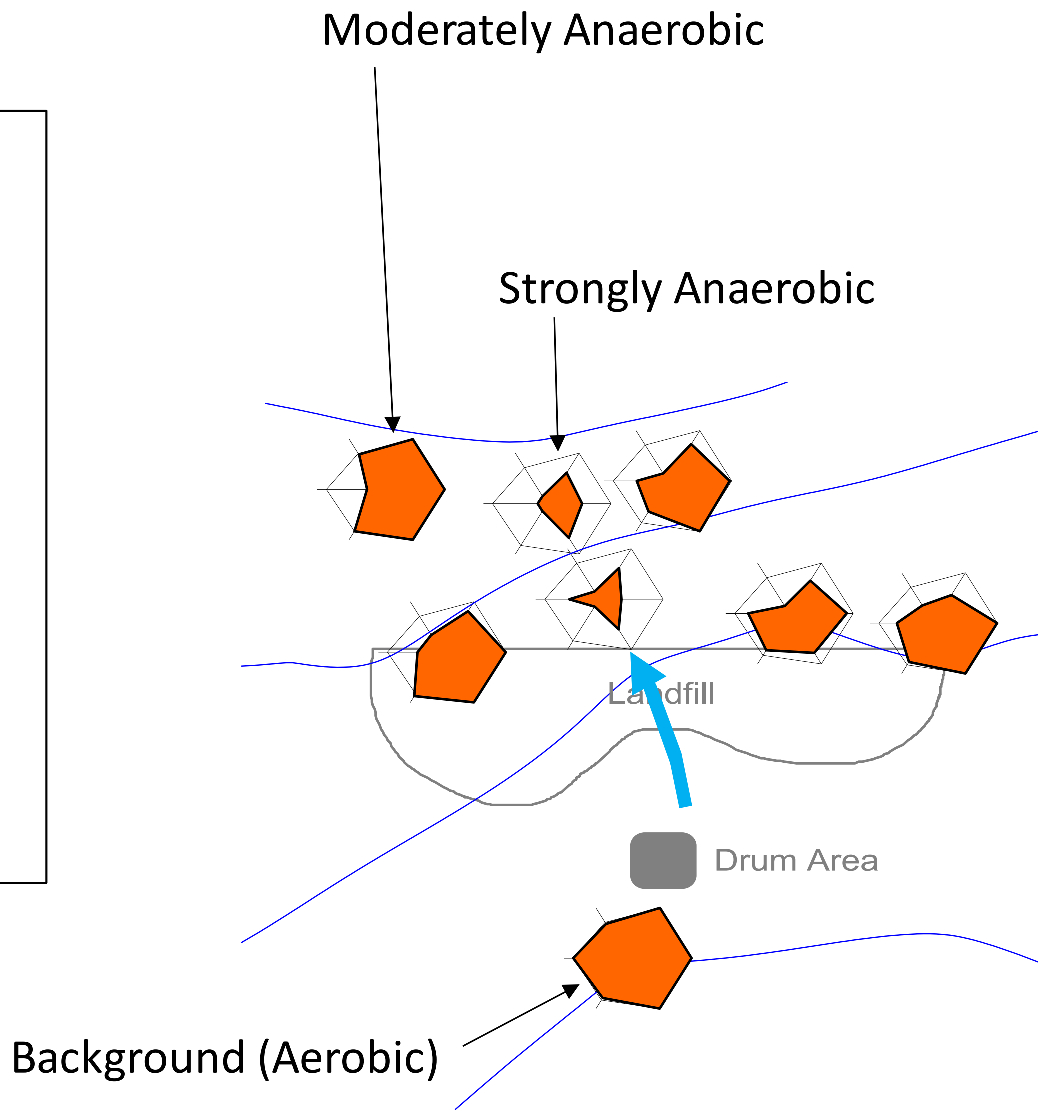
ABSTRACT

A visualization method is utilized as part of the assessment of intrinsic remediation for a landfill Superfund Site. Radial diagrams aligned in the same sequence as the preferentially-reduced electron acceptors are employed to depict spatial variations in redox potential relative to background conditions. Radial diagrams are also employed to simultaneously depict spatial and temporal variations for trichloroethane, 1,2-dichloroethane, 1,1-dichloroethane, and chloroethane. This visualization approach provides a more simple and illustrative demonstration of the effectiveness of intrinsic remediation than can be realized using contour maps or tabulated data. Guidance is provided for selecting the configurations of the axes for the radial diagrams.

INTRODUCTION

The utilization of intrinsic remediation requires that sound technical documentation, clearly illustrating the effectiveness of this measure, be presented to regulatory agencies and concerned citizens. Assessment of the distributions of multiple chemicals that are co-dependent on each other (such as redox indicators of biodegradation, or parent compounds and daughter products of biodegradation) can be complex and cumbersome to document. Scientific documentation of intrinsic remediation may also be difficult for a non-technical audience (e.g. the community) to understand. Incorporating visual aids as part of these assessments will provide a more convincing demonstration of the effectiveness of intrinsic remediation.

* Now with Environmental Software Solutions, Ottawa, Ontario, Canada



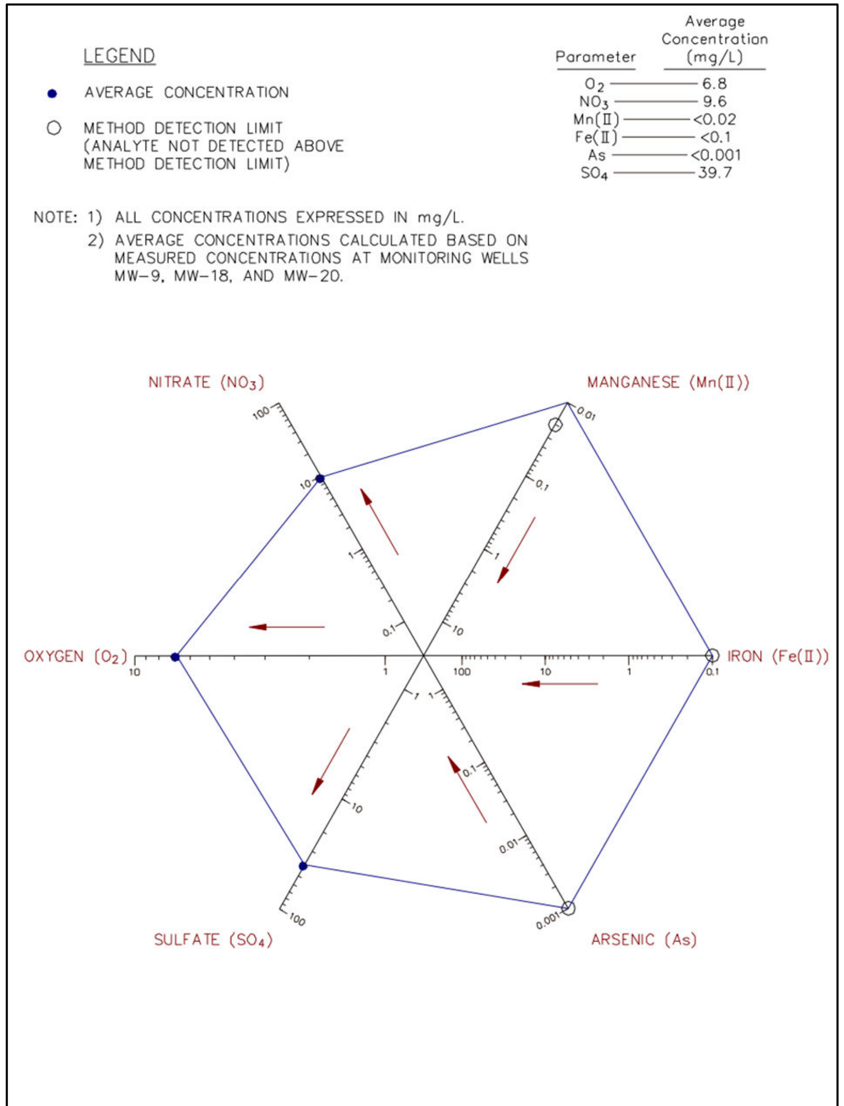
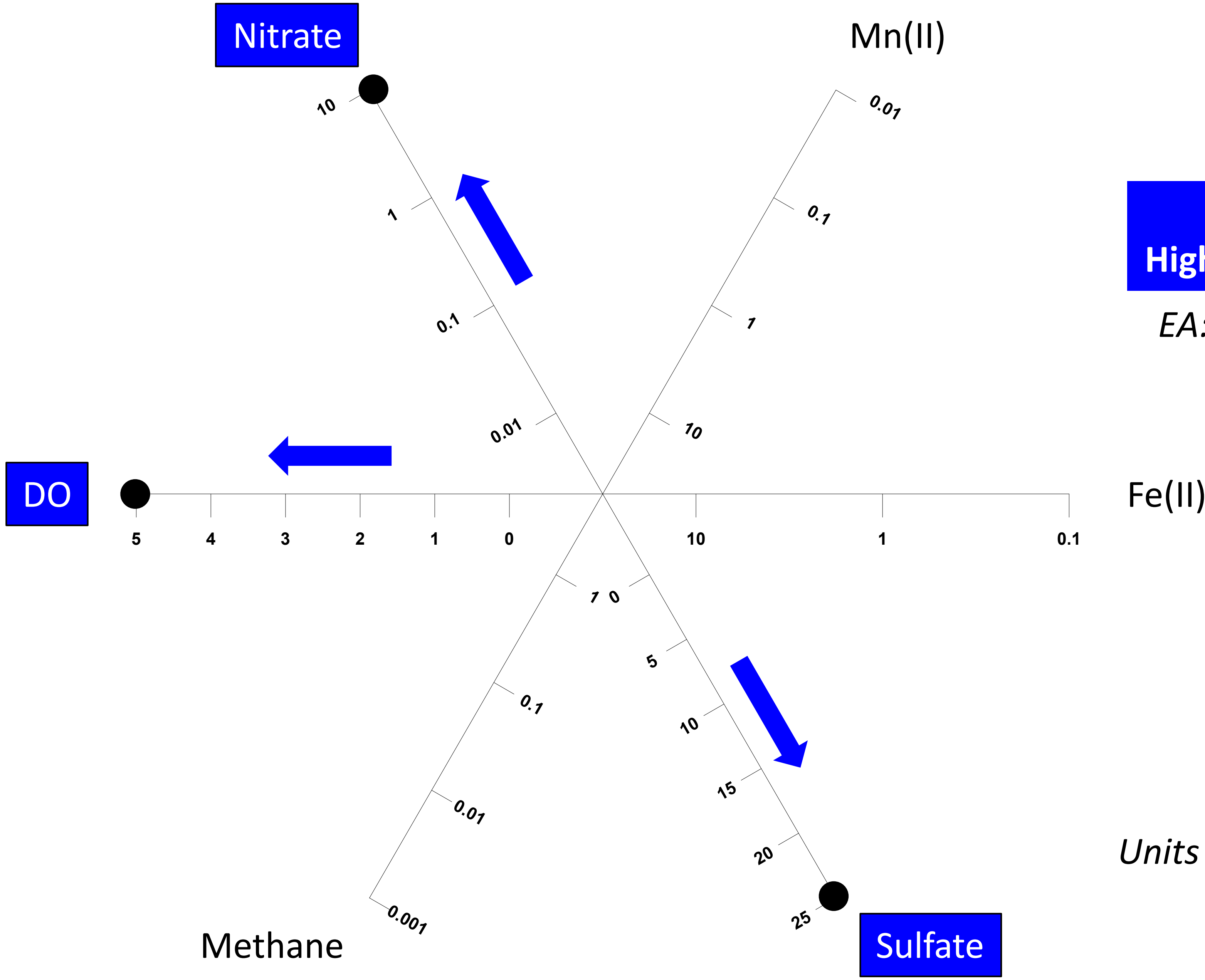


Figure 2 – BACKGROUND REDOX CONCENTRATIONS

Redox Diagram: Electron Acceptors (EA)

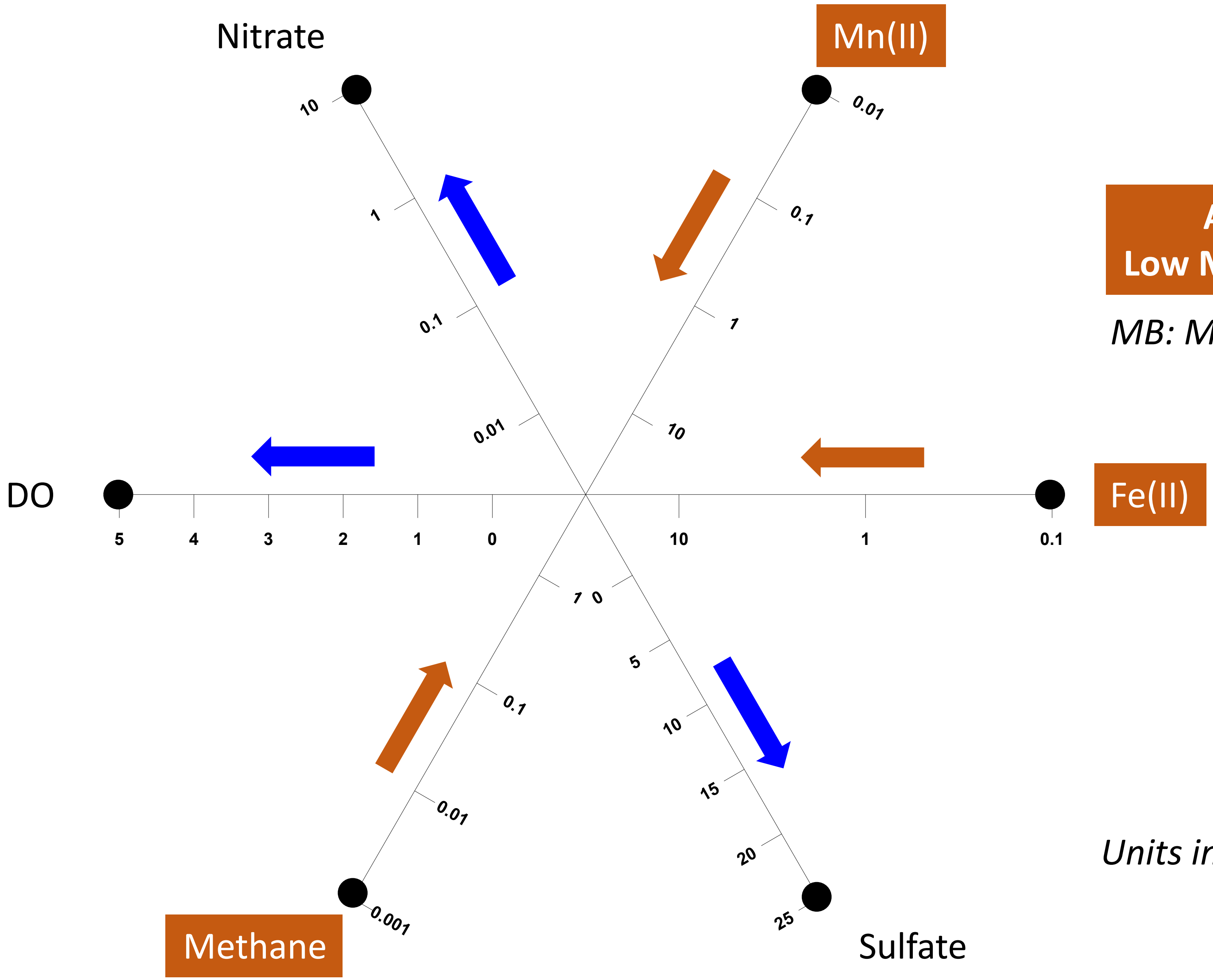


Aerobic zone:
High EA concentrations

EA: Electron Acceptor

Units in mg/L

Redox Diagram: Metabolic By-Products (MB)

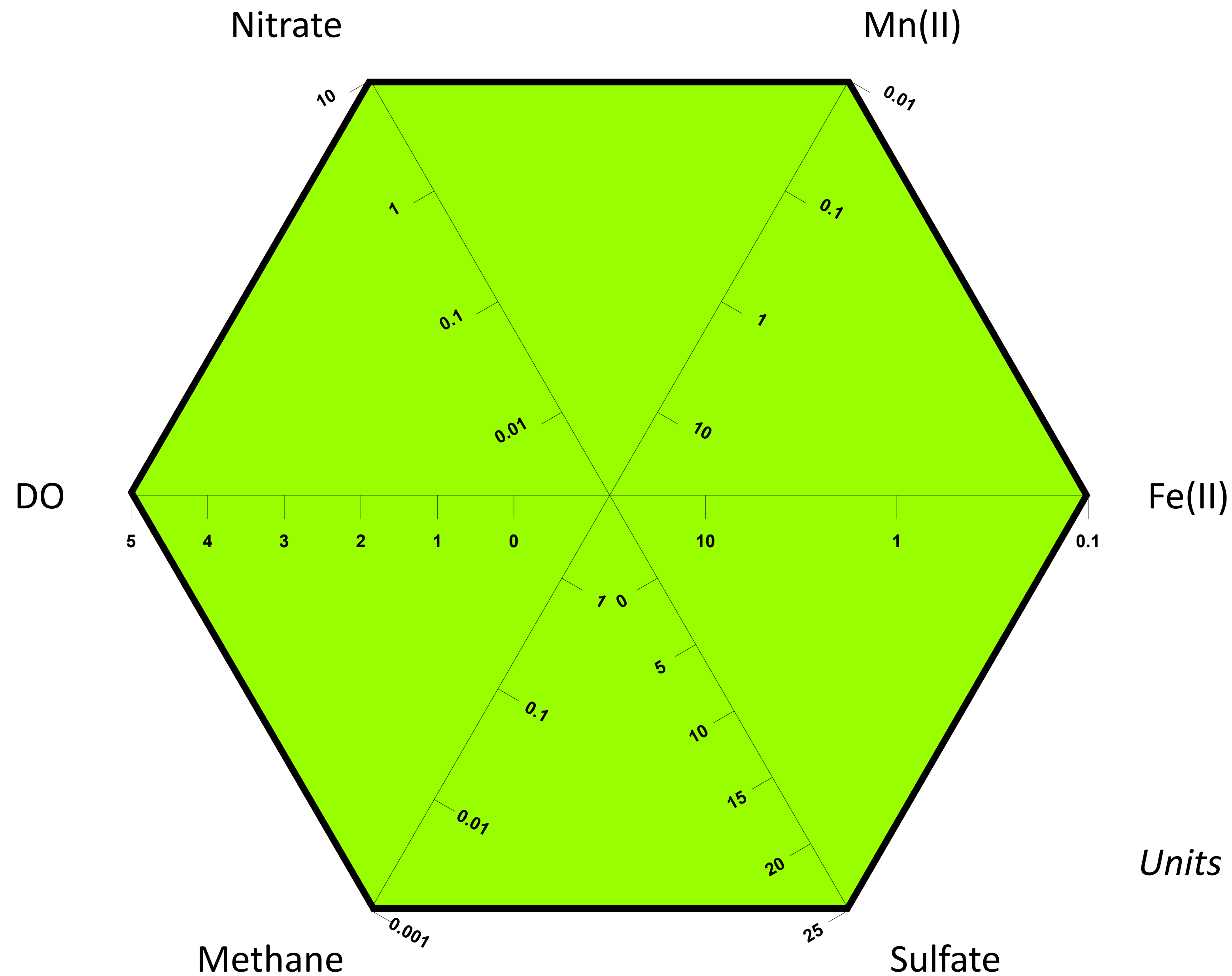


Aerobic zone: Low MB concentrations

MB: Metabolic Byproduct

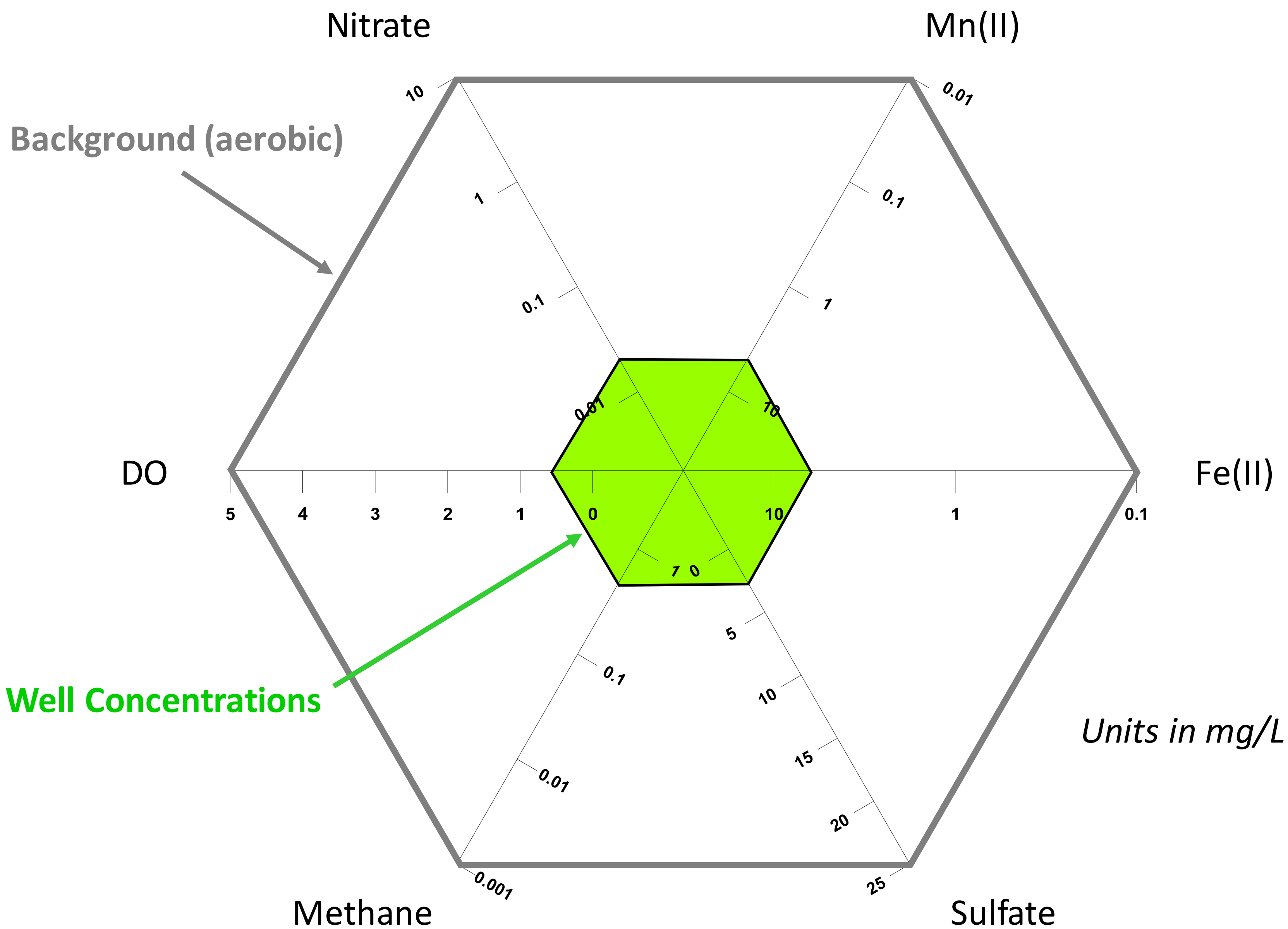
Units in mg/L

Redox Diagram: Aerobic (Background)

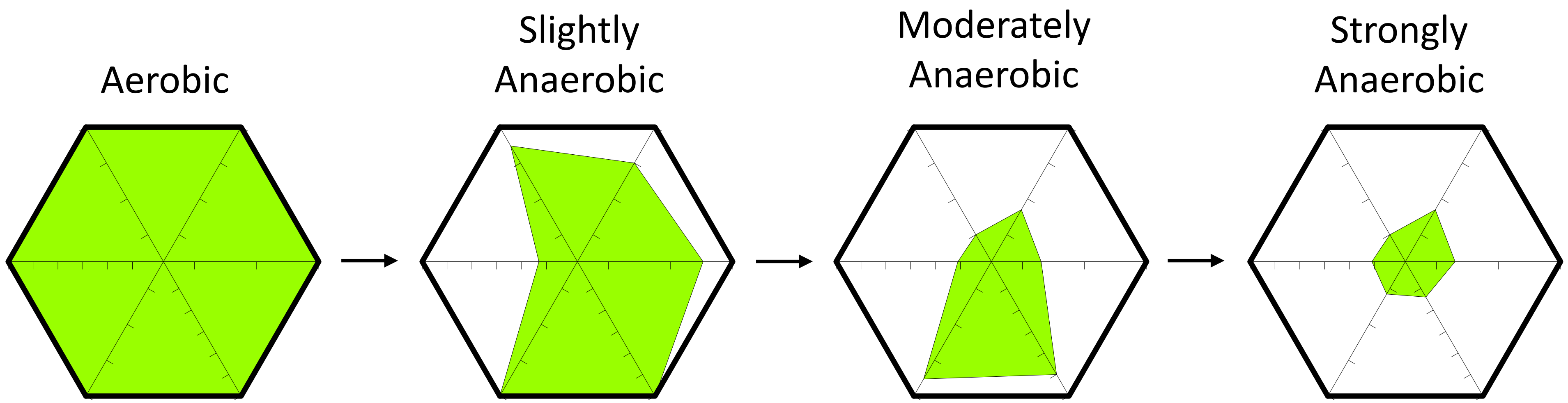


Units in mg/L

Redox Diagram: Strongly Anaerobic at Well



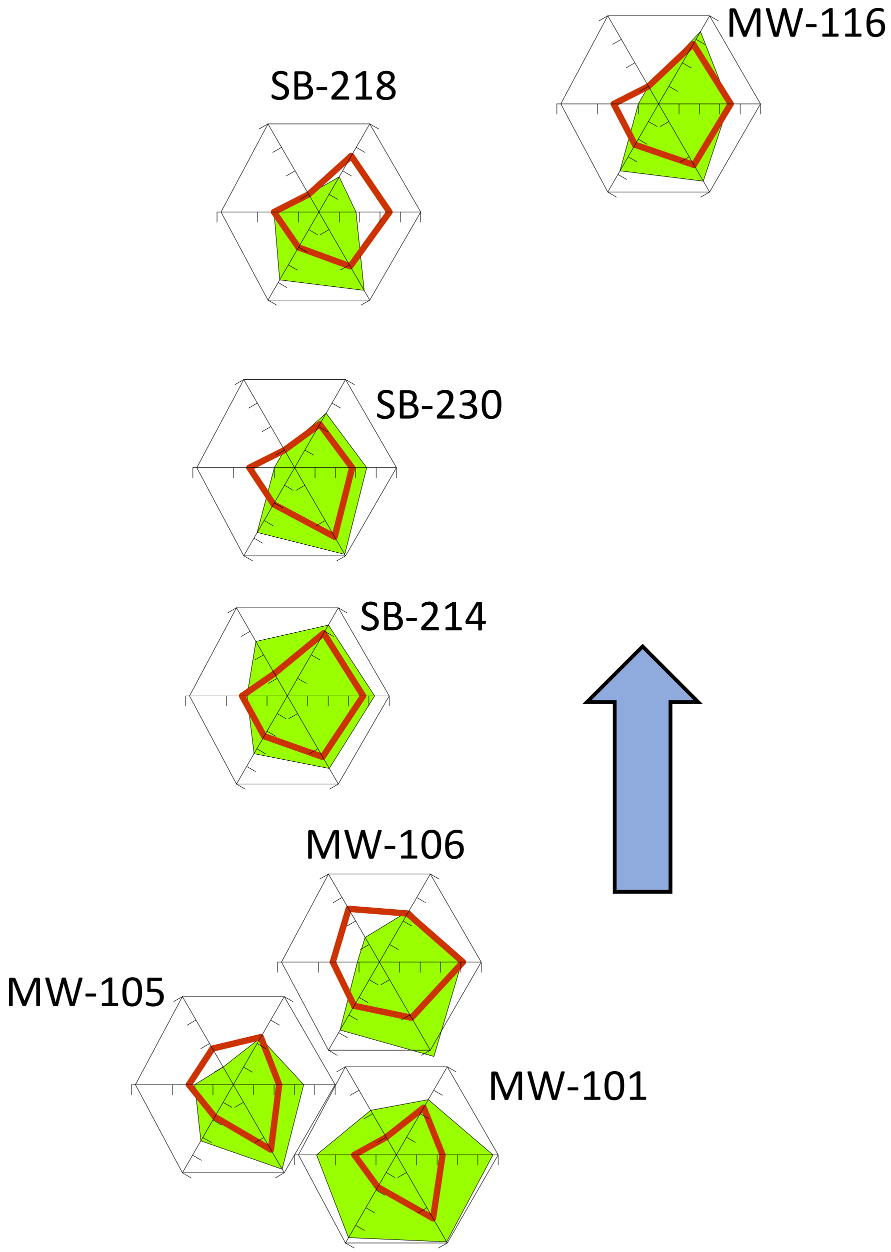
Redox Zone Transition

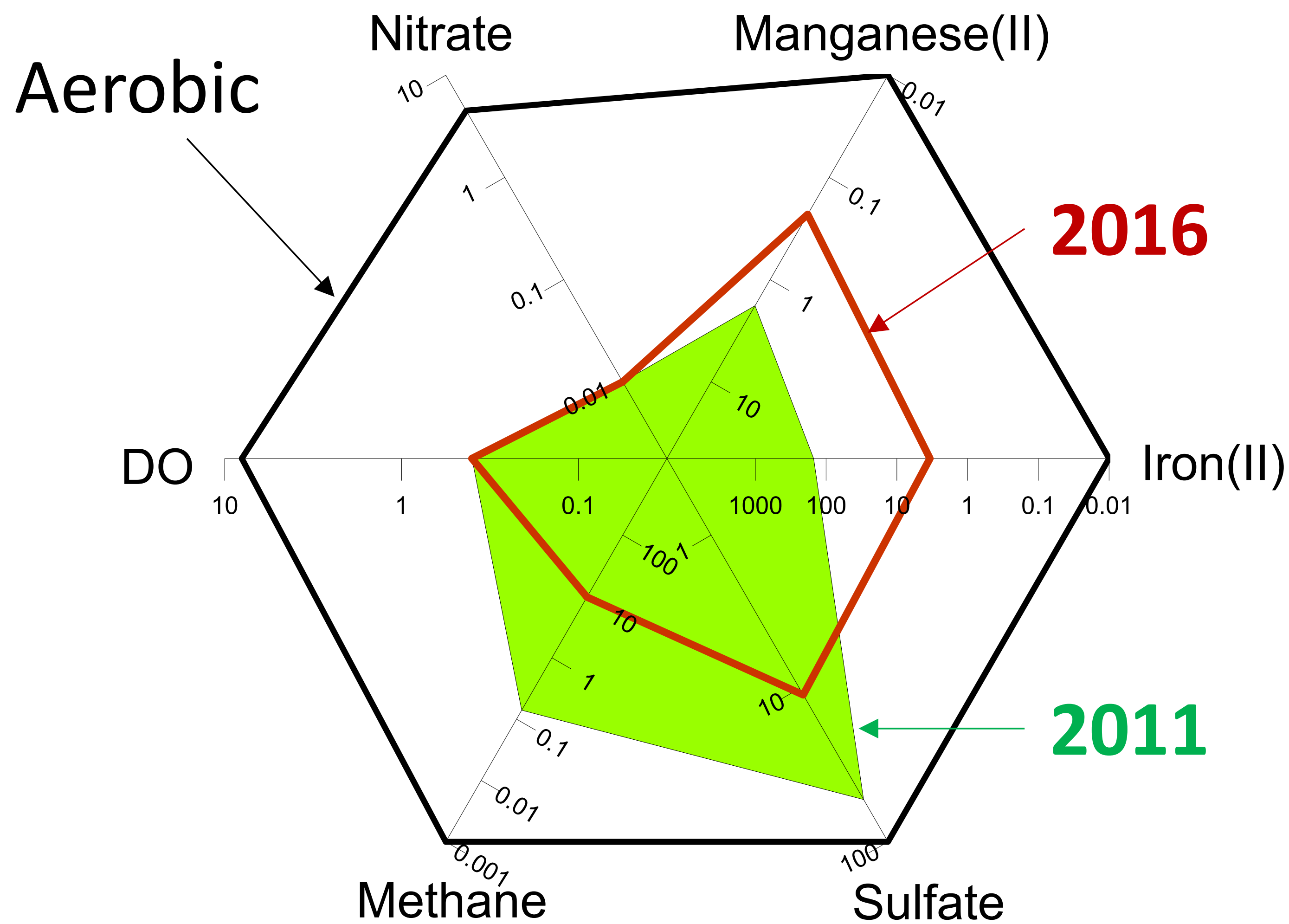


Radial diagrams are ideal for plotting relationships between redox indicators at each monitoring well.

Location	DO (mg/L)	Nitrate (mg/L)	Mn(II) (mg/L)	Fe(II) (mg/L)	Sulfate (mg/L)	Methane (mg/L)
Aerobic	5	10	<0.01	<0.1	25	<0.001
Slightly Anaerobic	0.3	3	0.1	0.3	25	<0.001
Moderately Anaerobic	0.1	<0.01	2	5	18	0.01
Strongly Anaerobic	0.1	<0.01	2	5	2	0.7

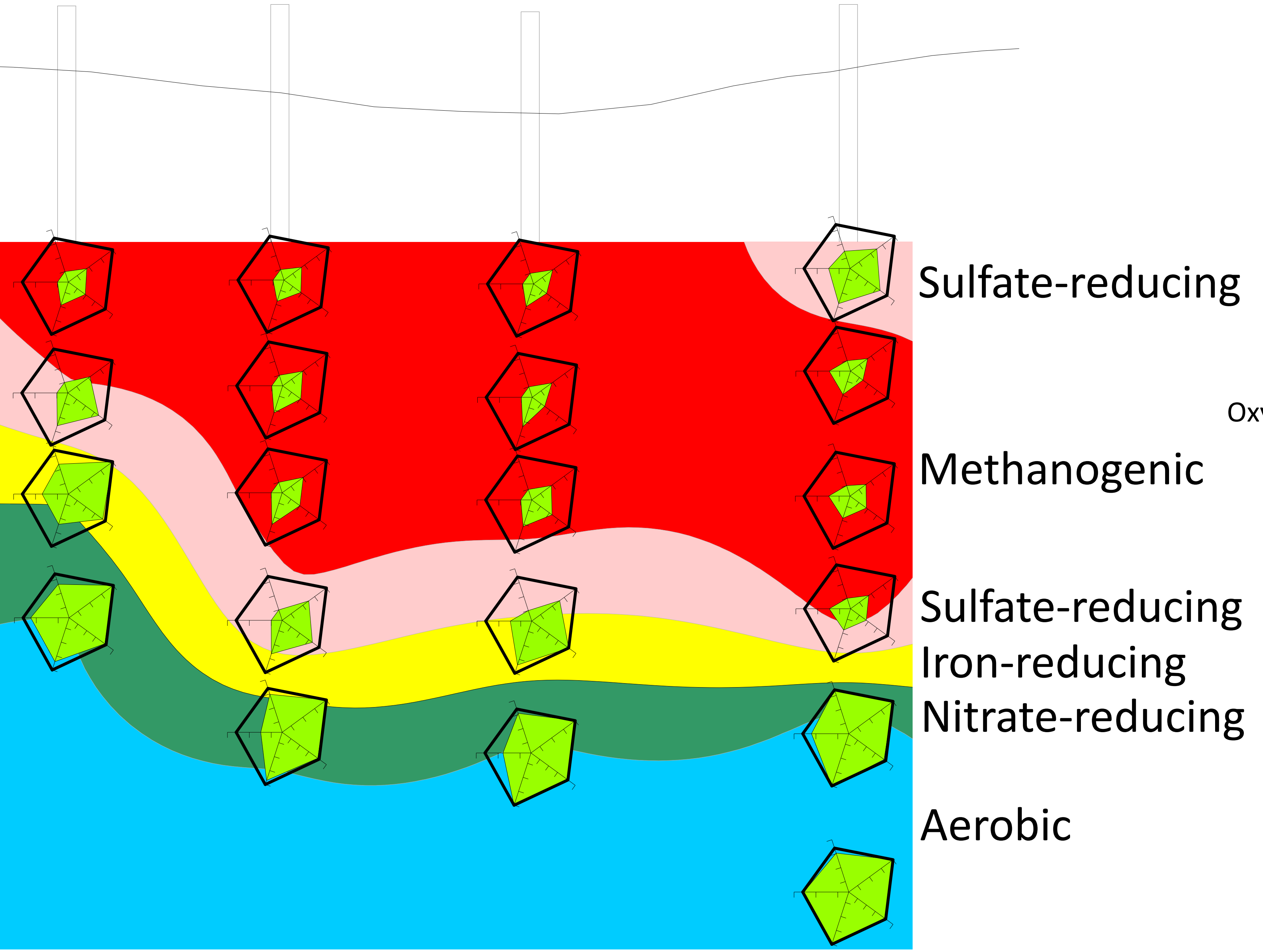
Redox Radial Diagram Map (Regenesis site)

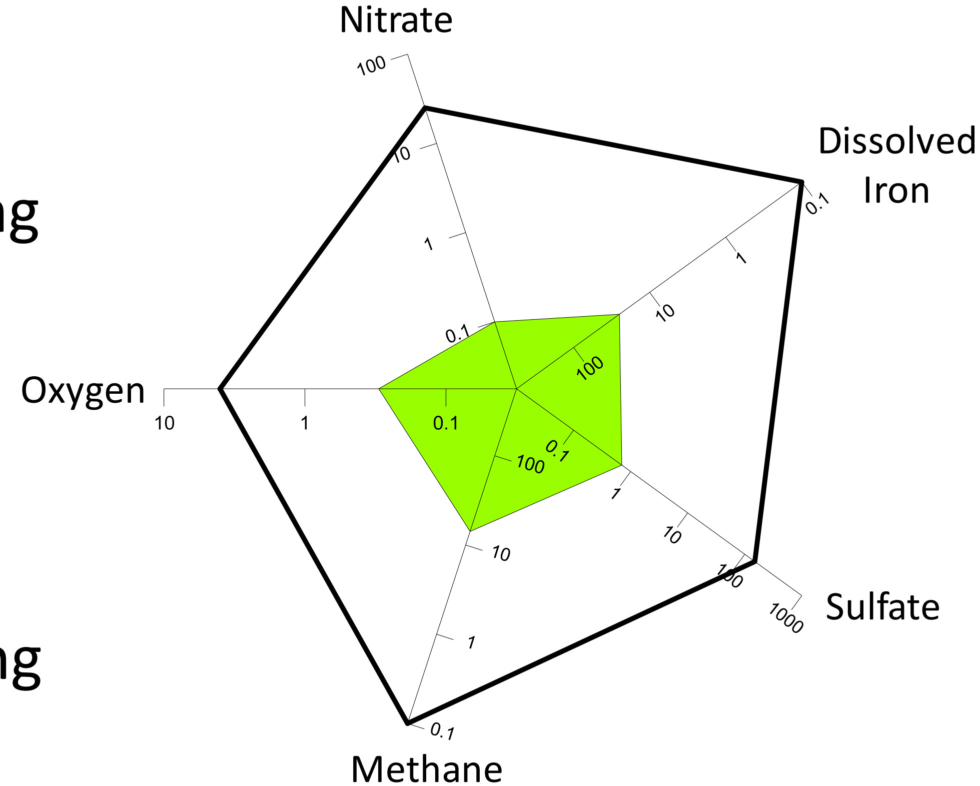




Note: all concentrations in mg/L.

Redox Zone Case Study: Wurtsmith AFB, MI

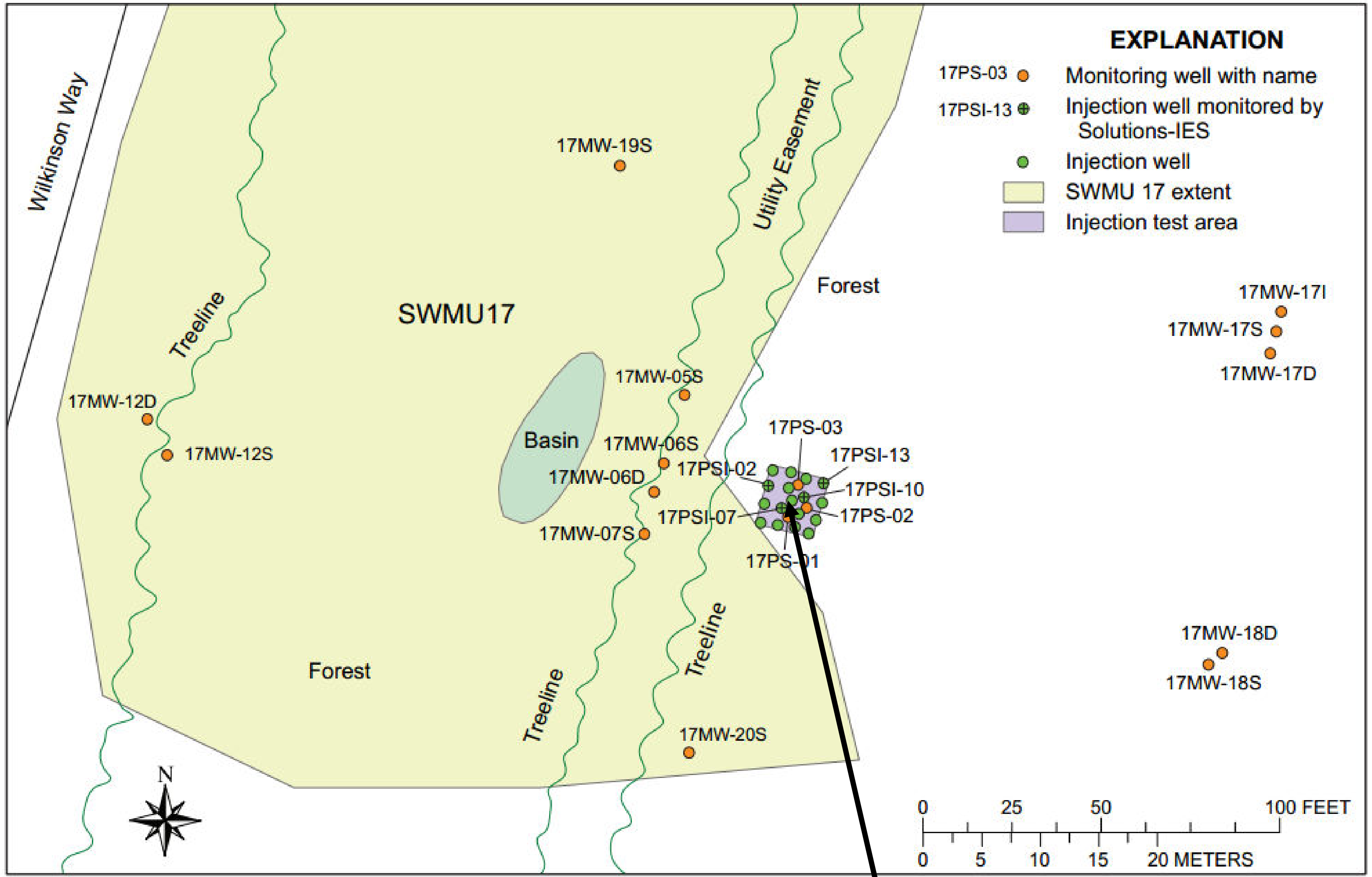




All concentrations in mg/L.

Data Reference: Chapelle et al. (1996)

Charleston Naval Weapons Station, South Carolina



USGS, 2009

Emulsified Oil
Pilot Test Area

Redox Indicators

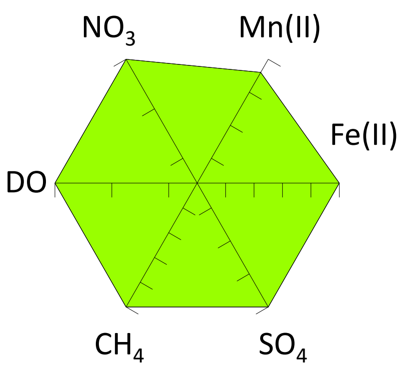
- 7 wells
- 6 redox indicators
- 12 events

→ 500 data points

Charleston NWS Relative Redox Area by Zone

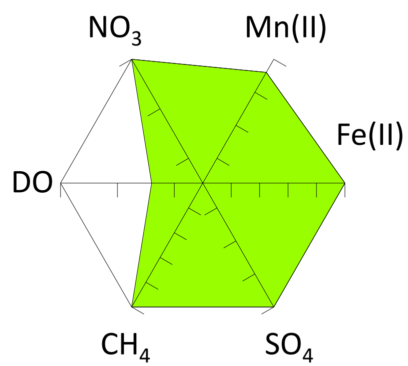
RRA = Relative Redox Area

Aerobic



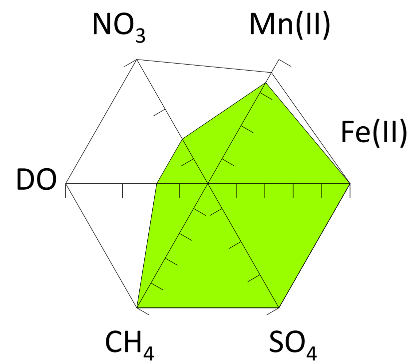
RRA=100%

NO_3-reduction



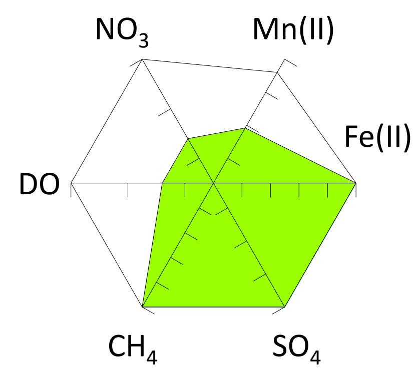
RRA=78%

Mn-reduction



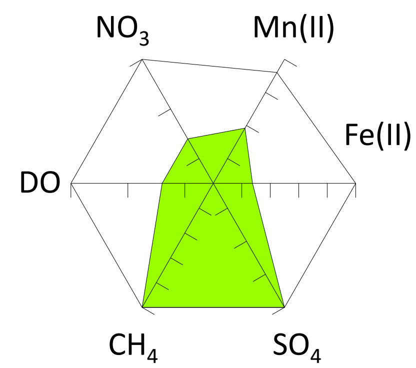
RRA=62%

Fe-reduction



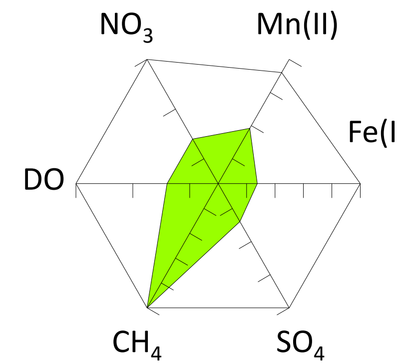
RRA=53%

SO_4-reduction



RRA=35%

Methanogenesis



RRA=20%

RRA=100% | **RRA=78%** | **RRA=60%** | **RRA=42%** | **RRA=24%**

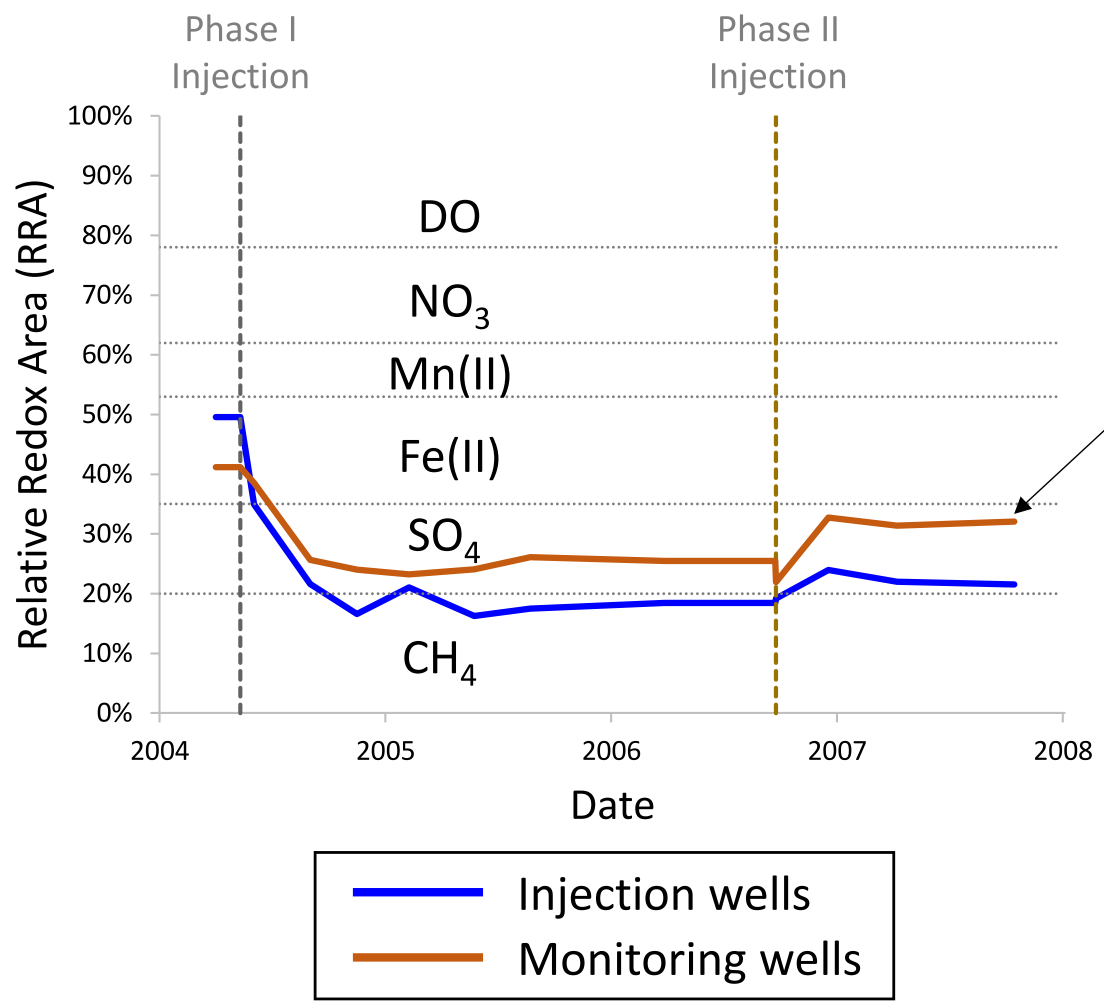
Wurtsmith AFB redox zone thresholds (p. 1.57):

Redox Zone Case Study: Charlseton, SC

Location	Days Since Injection 5/13/2004	Sample Date	Dissolved Oxygen (mg/L)	Nitrate (mg/L)	Manganese (mg/L)	Dissolved Iron (mg/L)	Sulfate (mg/L)	Methane (µg/L)
17PSI-02	-43	3/31/04	1.48	<0.5	0.390	33	91.5	53.2
17PSI-02	20	6/2/04	0.39	<0.5	0.570	150	18.0	47.4
17PSI-02	111	9/1/04	0.42	<0.5	0.510	160	<0.5	42.6
17PSI-02	188	11/17/04	0.14	<0.5	0.530	210	<0.5	256.3
17PSI-02	271	2/8/05	0.44	1.0/1.0	0.550	210	0.95	429.6
17PSI-02	377	5/25/05	0.19	< 0.5	0.660	210	< 0.5	1135
17PSI-02	468	8/24/05	0.35	< 0.5	0.630	180	< 0.5	812.8
17PSI-02	684	3/28/06	0.68	<0.5	0.590	210	<0.5	1933.2
17PSI-02	865	9/25/06	0.62	<0.5	0.530	60	<0.5	1366.9
17PSI-02	951	12/20/06	NM	<0.5	0.100	6.9	28.3	2135.8
17PSI-02	1062	4/10/07	0.36	<0.5	0.300	0.6	32.8/35.8	9433.9
17PSI-02	1252	10/17/07	0.80	<0.5	0.230	1.5	<0.5	5269.8
17PSI-07	-43	3/31/04	3.93	<0.5	0.370	24	102.5	40.7
17PSI-07	20	6/2/04	0.60	<0.5	0.710	180	1.8	53.7
17PSI-07	111	9/1/04	0.13	<0.5	0.820	300	0.5	26.6
17PSI-07	188	11/17/04	0.09	<0.5	0.740	240	<0.5	156.3
17PSI-07	271	2/8/05	0.48	<0.5	0.790	320	<0.5	151.7
17PSI-07	377	5/25/05	0.26	< 0.5	0.810	310	< 0.5	1469.4
17PSI-07	468	8/24/05	0.39	< 0.5	0.710	260	< 0.5	1816.0
17PSI-07	684	3/28/06	0.61	<0.5	0.530	420	<0.5	2121.1
17PSI-07	865	9/25/06	1.81	<0.5	0.620	320	<0.5	2684.9
17PSI-07	951	12/20/06	0.62	<0.5	0.750	220	<0.5/0.7	5509.0
17PSI-07	1062	4/10/07	0.98	<0.5	0.700	250	<0.5	4086.0
17PSI-07	1252	10/17/07	1.00	<0.5	0.720	120	<0.5	5377.2
17PSI-10	-43	3/31/04	4.05	<0.5	0.400	29	58.7	35.5
17PSI-10	20	6/2/04	0.47	<0.5	0.920	150	53.5/52.6	16.9
17PSI-10	111	9/1/04	0.26	<0.5	0.700	130	0.7	20.1
17PSI-10	188	11/17/04	0.14	<0.5	0.940	190	<0.5	27.2
17PSI-10	271	2/8/05	0.41	<0.5	0.830	220	<0.5	851.9
17PSI-10	377	5/25/05	0.32	< 0.5	0.800	220	< 0.5	2626.4
17PSI-10	468	8/24/05	0.45	< 0.5	1.200	190	< 0.5	1884.3
17PSI-10	684	3/28/06	0.56	<0.5	0.640	240	<0.5	2152.8
17PSI-10	866	9/26/06	0.52	<0.5	0.720	210	<0.5	4147.0
17PSI-10	951	12/20/06	0.74	<0.5	0.590	170	0.7	5972.8
17PSI-10	1062	4/10/07	0.51	<0.5	0.750	200	<0.5	9990.4
17PSI-10	1252	10/17/07	0.80	<0.5	0.510	40	<0.5/0.6	6651.4
17PSI-13	-43	3/31/04	4.66	<0.5	0.610	53	102.6	13.4
17PSI-13	20	6/2/04	0.74	<0.5	0.920	120	82.6	17.5
17PSI-13	111	9/1/04	0.19	<0.5	0.840	200	<0.5	14.3
17PSI-13	187	11/16/04	0.10	<0.5/<0.5	0.920	210	<0.5/<0.5	78.7
17PSI-13	271	2/8/05	0.39	<0.5	0.880	190	<0.5	534.5
17PSI-13	376	5/24/05	0.29	<0.5/<0.5	0.800	160	<0.5/<0.5	3441.6
17PSI-13	468	8/24/05	0.35	< 0.5	0.990	160	< 0.5	2550.7
17PSI-13	684	3/28/06	NA	<0.5	0.880	260	<0.5	1105.7
17PSI-13	866	9/26/06	0.56	<0.5	0.830	180	<0.5	5069.7
17PSI-13	951	12/20/06	0.81	<0.5	0.850	260	1.1	5540.8
17PSI-13	1062	4/10/07	0.46	<0.5	0.840	280	<0.5	7879.1
17PSI-13	1252	10/17/07	0.60	<0.5	0.570	90	<0.5	9099.5
17PS-01	-42	4/1/04	0.67	<0.5	0.630	78	65.5	27.2
17PS-01	20	6/2/04	1.14	<0.5	0.720	120	44.1/44.6	25.8
17PS-01	111	9/1/04	0.15	<0.5	0.540	110	15.3	37.7
17PS-01	187	11/16/04	0.17	<0.5	0.780	130	23.4	33.1
17PS-01	271	2/8/05	0.23	<0.5	0.680	150	27.9	145.0
17PS-01	377	5/25/05	0.34	< 0.5	0.690	130	20.3	231.9
17PS-01	468	8/24/05	0.33	< 0.5	0.570	190	21.6	92.2
17PS-01	685	3/29/06	0.49	<0.5	0.490	210	30.9	261.2
17PS-01	866	9/26/06	0.81	<0.5	0.690	110	<0.5	1232.6
17PS-01	951	12/20/06	NA	<0.5	0.190	7.2	1.4	7415.3
17PS-01	1062	4/10/07	0.72	<0.5	0.050	1.0	<0.5	11308.5
17PS-01	1252	10/17/07	0.20	1.3	0.230	2.1	0.5	7759.2
17PS-02	-42	4/1/04	1.50	<0.5	0.560	50	58	30.8
17PS-02	20	6/2/04	3.36	<0.5	0.740	81	5.4	30.6
17PS-02	111	9/1/04	0.14	<0.5	0.570	170	15.0	36.7
17PS-02	187	11/16/04	0.16	<0.5	0.590	150	2.8	66.0
17PS-02	271	2/8/05	0.20	<0.5/<0.5	0.520	120	10.0	1144.8
17PS-02	377	5/25/05	0.47	< 0.5	0.660	92	6.7	1176.5
17PS-02	468	8/24/05	0.32	< 0.5	0.540	150	20.8	1681.8
17PS-02	685	3/29/06	0.50	<0.5	0.550	130	14	3639.3
17PS-02	866	9/26/06	0.48	<0.5	0.620	170	2.8	2133.3
17PS-02	951	12/20/06	NA	<0.5	0.180	1.10	9.6	9880.6
17PS-02	1062	4/10/07	0.75	<0.5	0.260	12.0	<0.5/0.57	8896.9
17PS-02	1252	10/17/07	0.40	1.1	0.075	0.41	<0.5	9148.4
17PS-03	-42	4/1/04	0.40	<0.5	0.680	69	77.5	36.0
17PS-03	20	6/2/04	1.22	<0.5	0.810	110	10.0	50.7
17PS-03	111	9/1/04	0.14	<0.5	0.460	130	<0.5	173.3
17PS-03	187	11/16/04	0.18	<0.5/<0.5	0.800	200	0.5/<0.5	2062.5
17PS-03	271	2/8/05	0.25	<0.5	0.570	180	<0.5	7737.5
17PS-03	377	5/25/05	0.31	< 0.5	0.700	180	< 0.5	4425.3
17PS-03	468	8/24/05	0.37	< 0.5	0.470	190	2.10	3136.5
17PS-03	685	3/29/06	0.44	<0.5	0.430	370	1.6	3522.2
17PS-03	866	9/26/06	0.57	<0.5	0.580	96	1.9	4852.4
17PS-03	951	12/20/06	NA	<0.5	0.170	1.1	9.6/9.5	9839.1
17PS-03	1062	4/10/07	0.68	<0.5	0.055	0.38	5.0	4281.3
17PS-03	1252	10/17/07	0.40	1.3	0.120	0.58	<0.5	10127.1

Average RRA versus time in Pilot Test Area (IWs)

RRA: Relative Redox Area



Iron depletion in soil?

Benefits of Radial Diagram & Stacked Bar Maps

- **Powerful tool for visualizing chemical inter-relationships**
  - Parent/daughters, short-chain/long-chain, PFSAs vs PFCAs
  - One radial diagram map may replace 5-10 chemical maps
- **Visualize OoM reductions along flow path, and over time**
  - Natural and enhanced remediation trends
- **Quickly show where chemicals exceed cleanup criteria**
- **Unique method for redox zone delineation**

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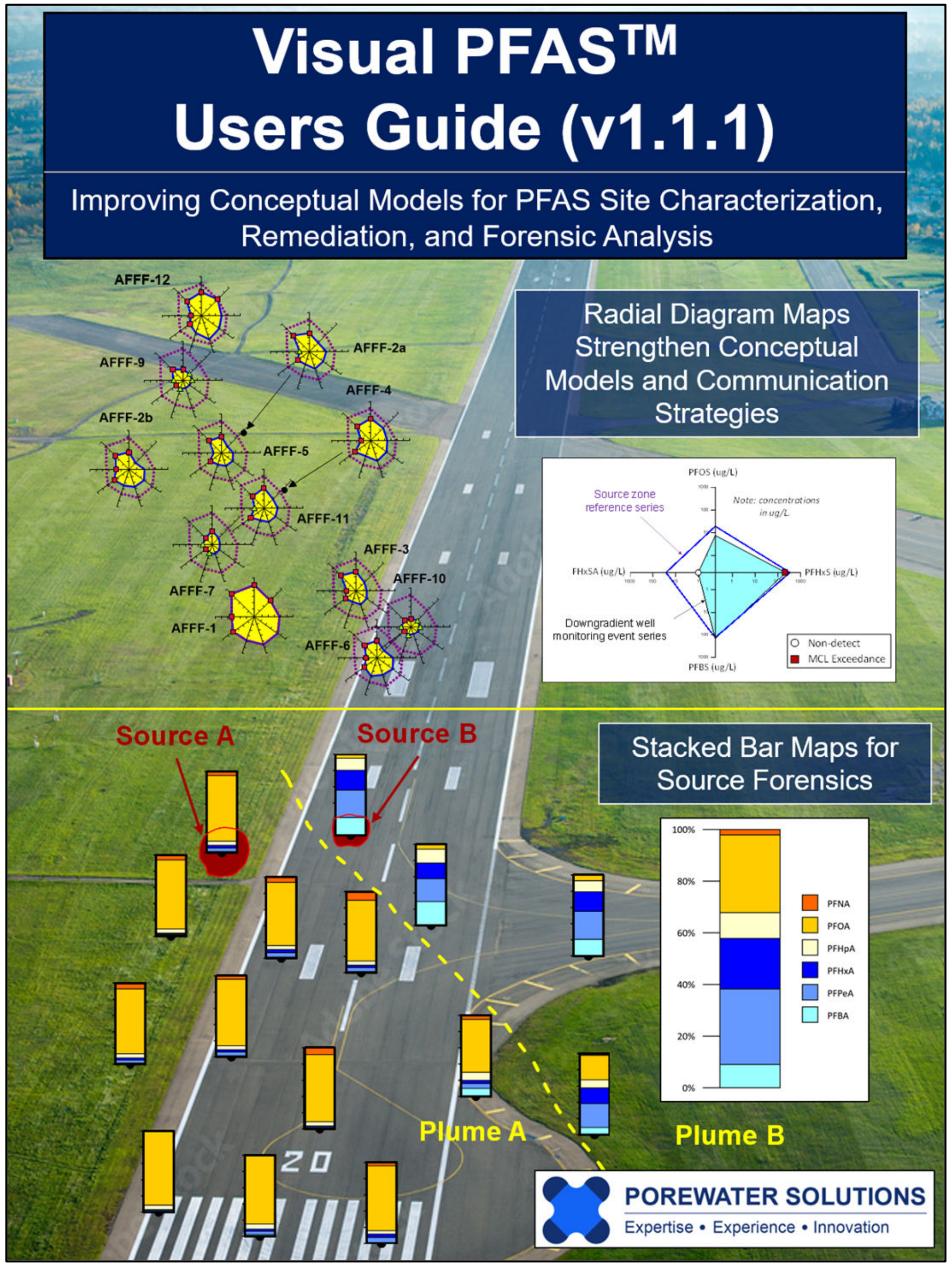

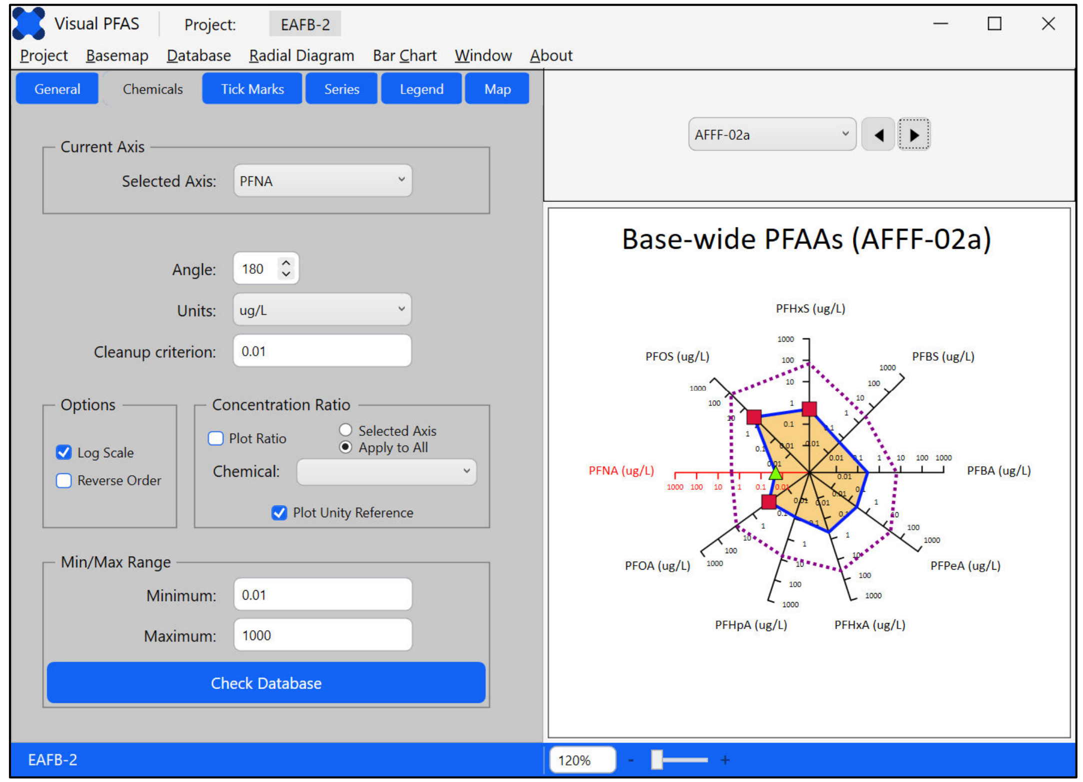

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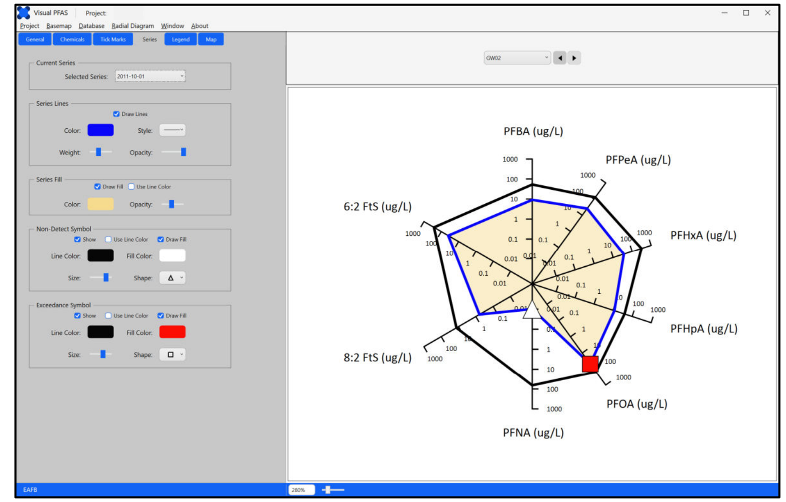
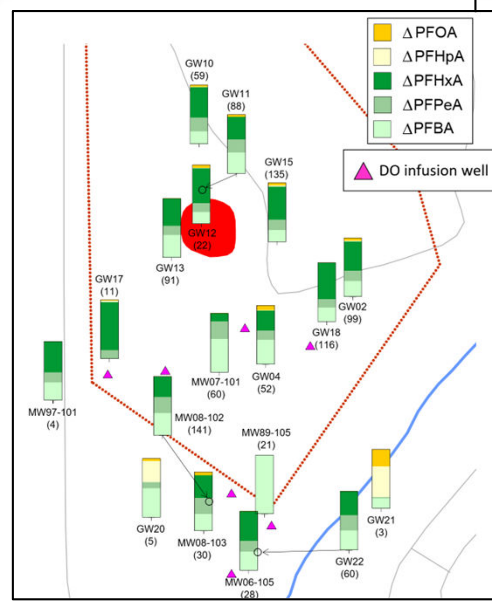
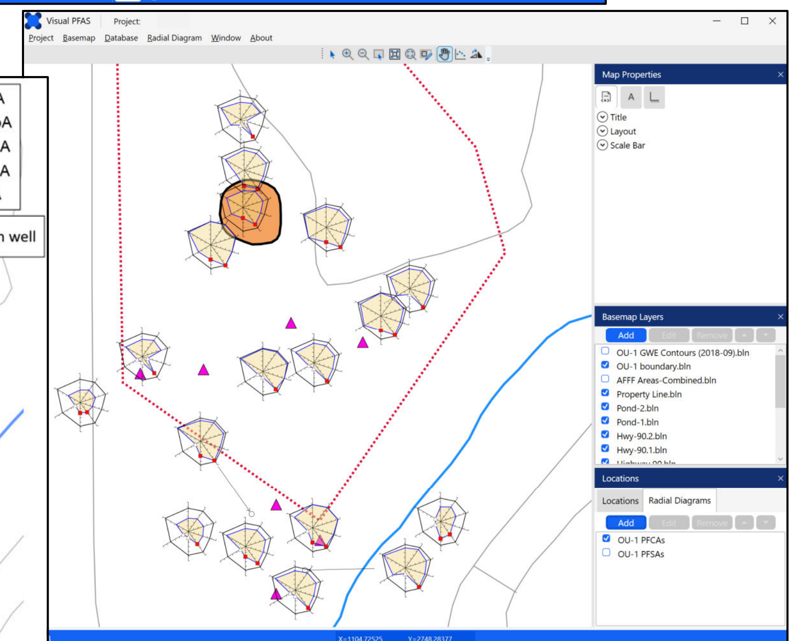
Phone: 613-890-2286



www.porewater.com/PFAS.html





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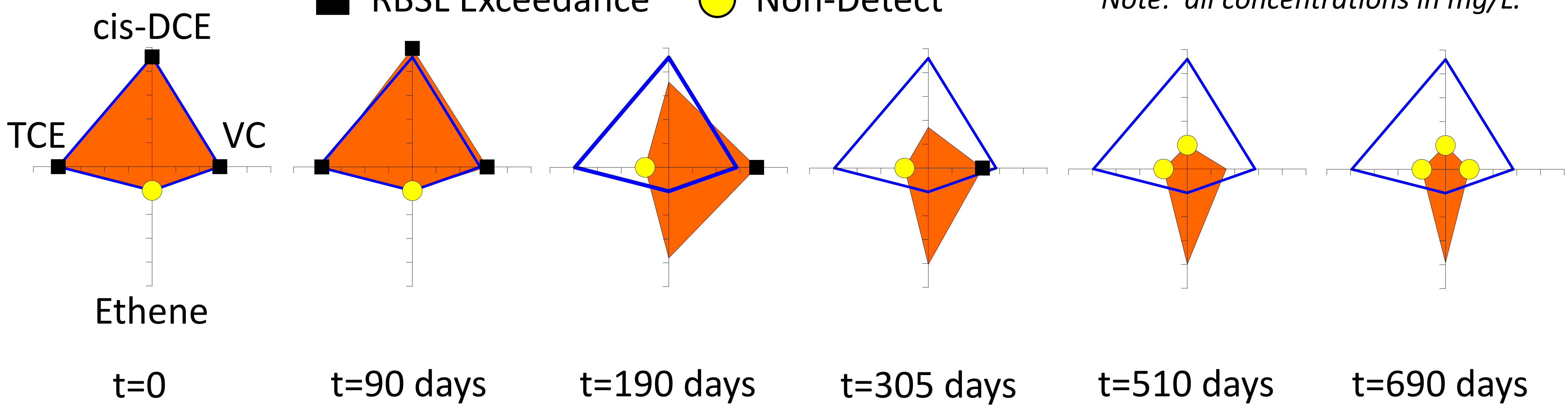
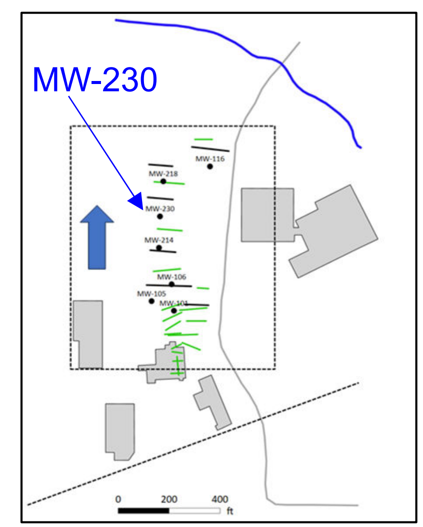
MW-230 CAH Trends Over Time

RBSL Exceedance Non-Detect

Note: all concentrations in mg/L.





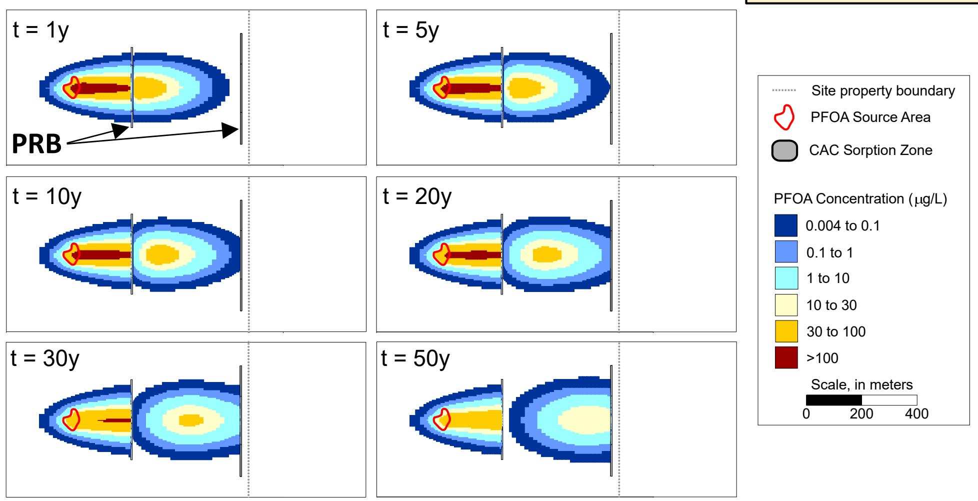
In-Situ Remediation Model (ISR Model)

- Originally developed in 1998 as BioRedox-MT3DMS
- Field and research projects since 2017
- PFAS-related functionality
  - ✓ PFAS adsorption to CAC
  - ✓ Kinetic sorption
  - ✓ Competitive adsorption
  - ✓ CAC aging
  - ✓ Colloid transport
  - ✓ Branched decay chains

In progress

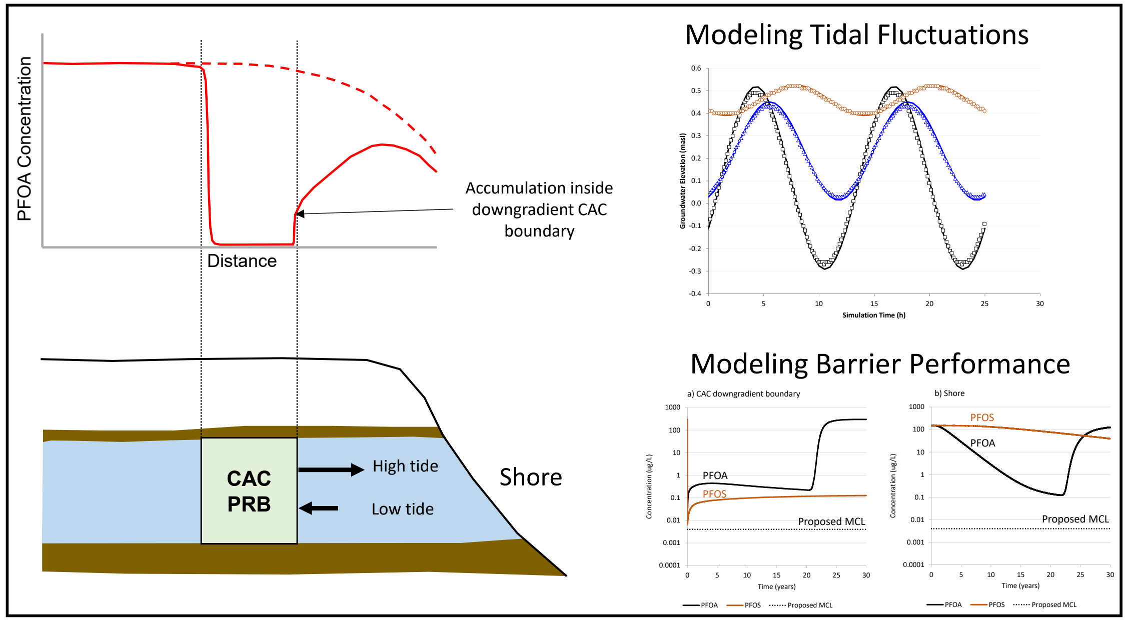
South Dakota Air Force Base

Carey et al. (2023)



Navy Coastal Site

Carey et al. (2024)



U.S. DoD SERDP/ESTCP Project Involvement

ESTCP ER21-3959 — An Investigation of Factors Affecting *In Situ* **PFAS Immobilization by Activated Carbon**

ESTCP ER20-5182 — **Validation of Colloidal Activated Carbon** for Preventing the Migration of PFAS in Groundwater

ESTCP ER21-1070 — Hydraulic, Chemical, and Microbiological Effects of *In Situ* Activated **Carbon Sorptive Barrier** for PFAS Remediation in Coastal Sites

ESTCP ER24-8200 — **Two PFAS Remediation Models** for Understanding and Managing PFAS in the Saturated Zone

ESTCP ER25-8483 — **SERDP-ESTCP e-learning Modules: PFAS In-Situ Remediation**