Fate and Transport of PFAS in the vadose zone: *controlling processes, mathematical formulation, and practical modeling approaches*

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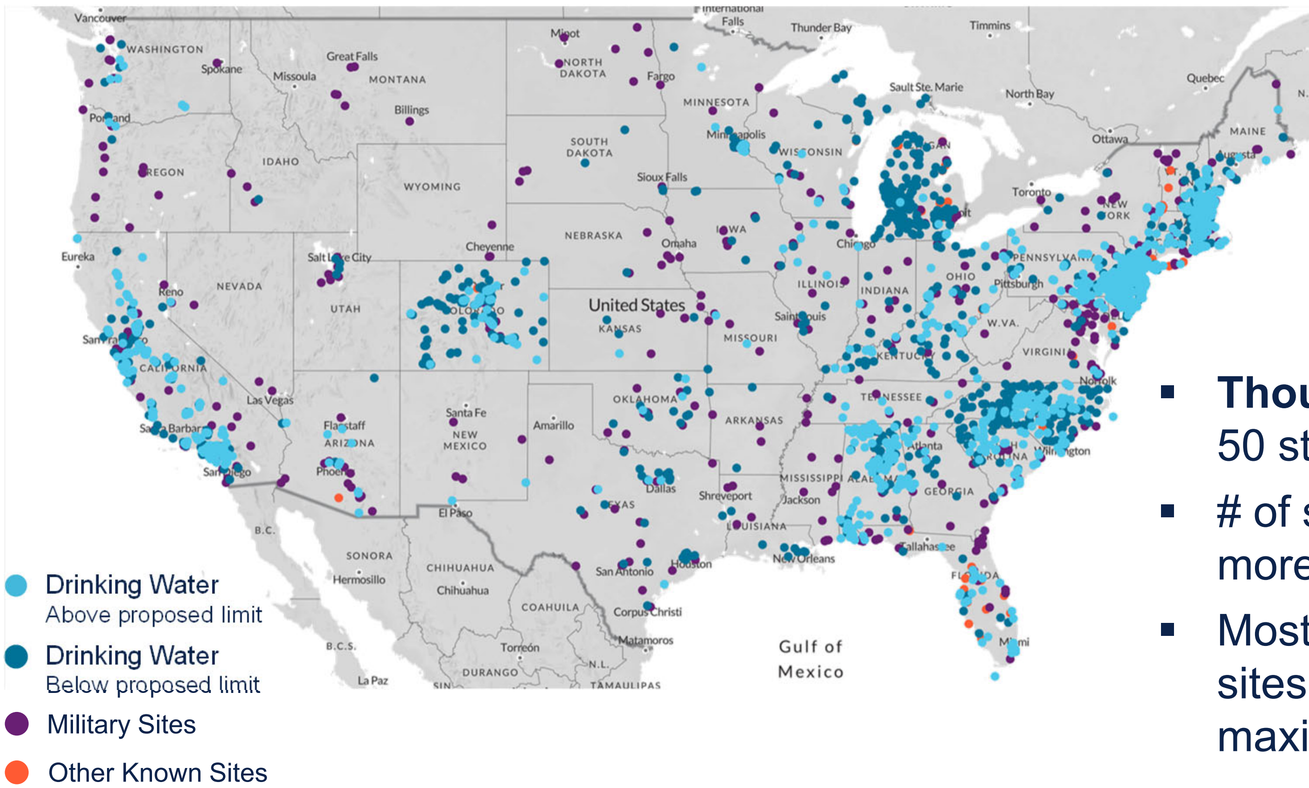
REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 3-5, 2023

PFAS are widely spread in the environment

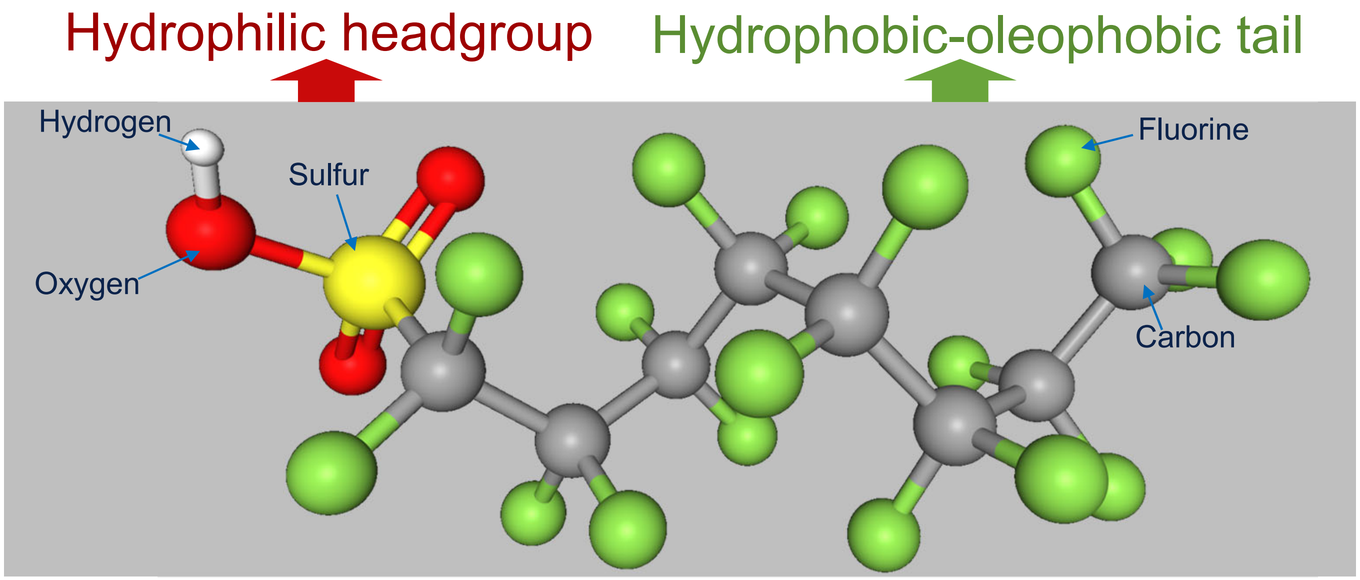


- **Thousands** of contamination sites in 50 states.
- # of sites are rapidly **growing** as more investigations are carried out.
- Most drinking water contamination sites are **above** the proposed maximum contaminant level (**MCL**).

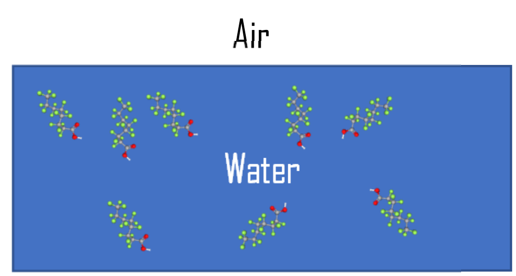
https://www.ewg.org/interactive-maps/pfas_contamination/map/

What are PFAS (Per- and poly-FluoroAlkyl Substances)?

PFAS molecule (e.g., PFOS)



- Surfactant (**Surf**ace **act**ive ag**ent**)
- Persistent (**C-F** bond)
- Toxic at **ppt** levels
- More than **9,000** compounds



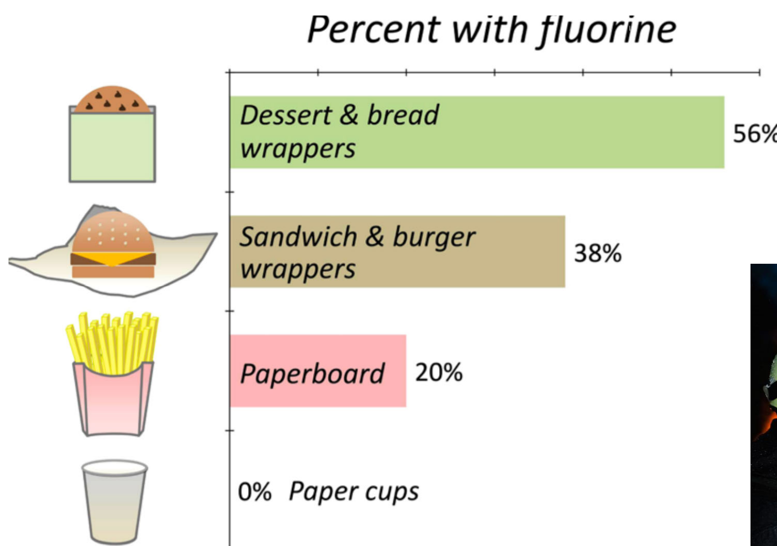
Adsorb at air–water interfaces

Used in our daily life and at military sites

"Perfect" chemicals if NOT toxic

Non-stick, stain- and water-resistant coating

Food packaging

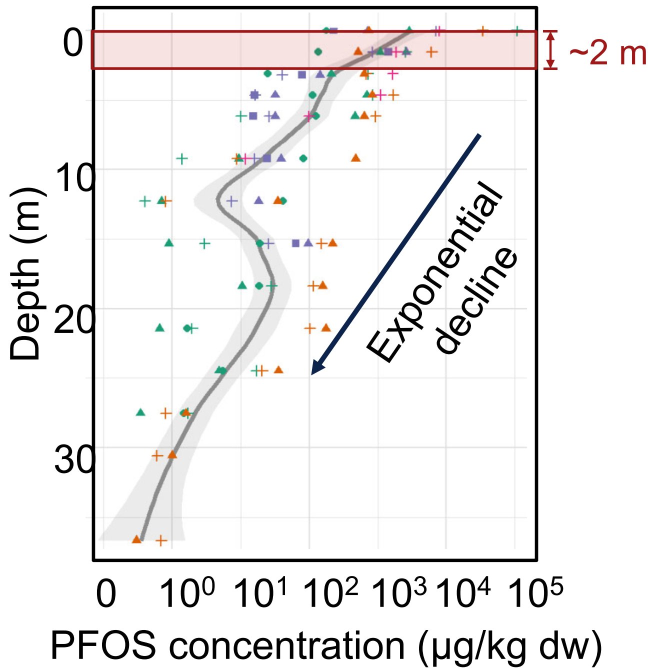


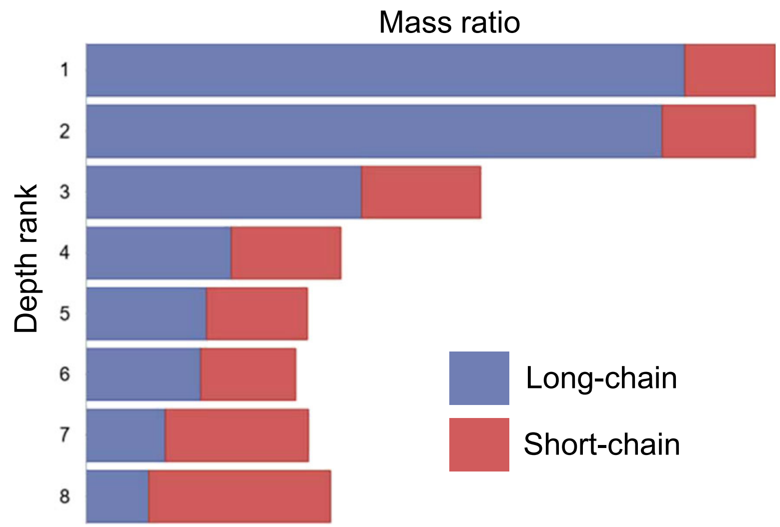
Schaider et al (2017)

Fire fighting foam

http://www.safetynews.co.nz/fire-fighting-foams-causing-sparks-fly/

Field data: spatial variation of concentrations in the soil





Anderson et al. 2019
Brusseau, Anderson, Guo. 2020.

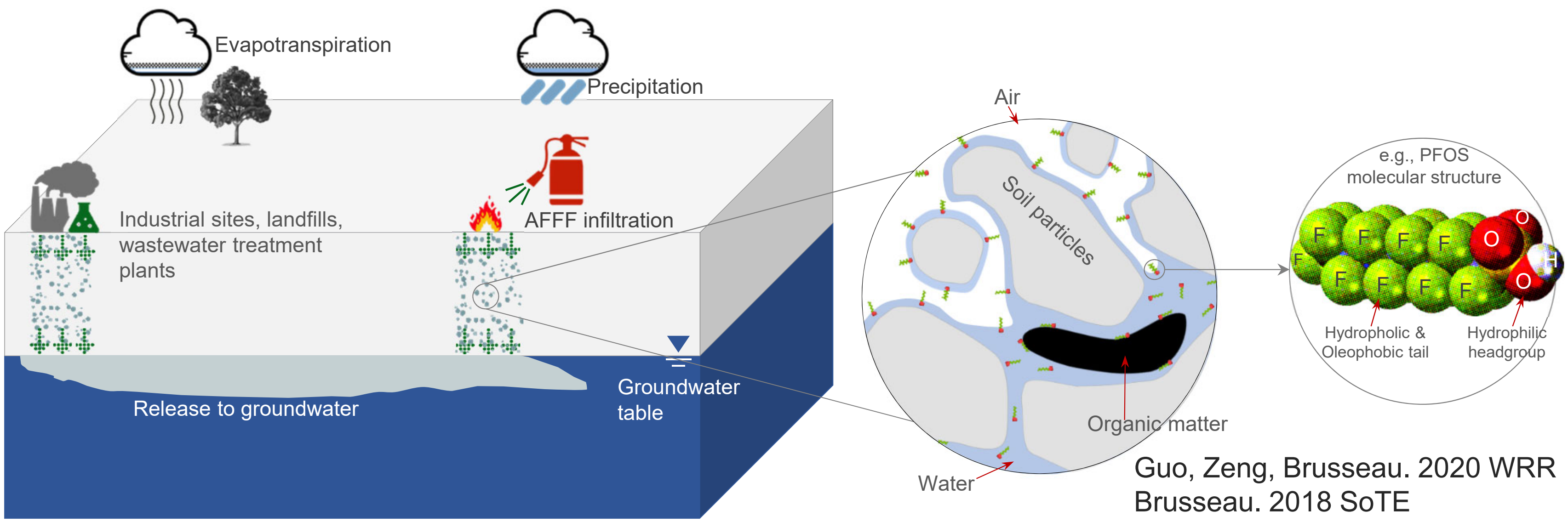
- Soils appear to act as significant source zones of PFAS.
- Long-chain PFAS tend to retain in shallow soil, while short-chain PFAS migrate to deeper depth.

Overarching Questions

What are the primary processes controlling PFAS leaching in soils?

What are the long-term mass discharge rates to groundwater?

PFAS transport in the vadose zone : physical & chemical processes



Guo, Zeng, Brusseau. 2020 WRR
Brusseau. 2018 SoTE

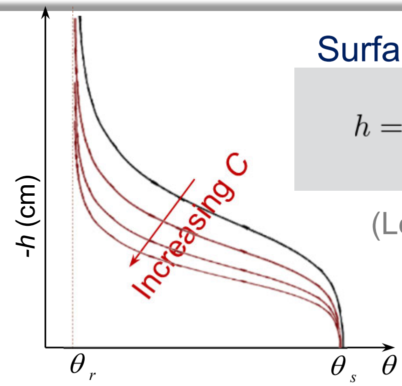
Unique physicochemical properties:

- ➢ As surfactants
  - ✓ PFAS accumulate at solid surfaces and air-water interfaces in soils.
  - ✓ PFAS present in pore water can modify surface tension.

PFAS transport in the vadose zone: mathematical formulation

Variably saturated flow:

$$\frac{\partial \theta}{\partial t} - \nabla \cdot [\boldsymbol{K}(\theta)\nabla(h - z)] = 0$$



Surfactant-induced flow

$$h = \frac{\sigma(C)\cos\gamma(C)}{\sigma_0 \cos\gamma_0} h_0$$

(Leverett J scaling)

PFAS transport:

$$\frac{\partial(\theta C)}{\partial t} + \rho_b \frac{\partial C_s}{\partial t} + \frac{\partial C_{aw}}{\partial t} + \nabla \cdot (\theta \boldsymbol{v} C) - \nabla \cdot \left(\theta \boldsymbol{D} \frac{\partial C}{\partial z}\right) = 0$$

Advection | Dispersion

Nonlinear and rate-limited solid-phase adsorption (SPA)

$$C_{s,1} = F_s K_f C^N$$

Instantaneous

$$\frac{dC_{s,2}}{dt} = \alpha_s[(1 - F_s)K_f C^N - C_{s,2}]$$

Kinetic

Nonlinear and rate-limited air-water interfacial adsorption (AWIA)

$$C_{aw} = F_{aw} A_{aw} K_{aw} C$$

Instantaneous

$$\frac{dC_{s,aw}}{dt} = \alpha_{aw}[(1 - F_{aw})A_{aw}K_{aw}C - C_{aw,2}]$$

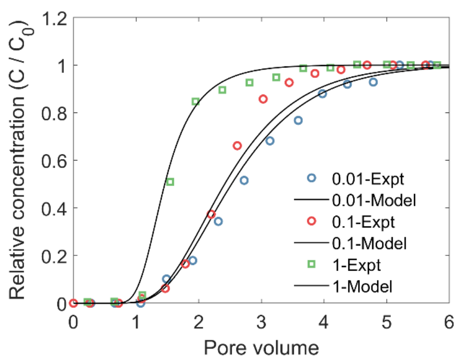
Kinetic

Guo, Zeng, Brusseau. 2020 WRR
Zeng & Guo. 2021 AWR

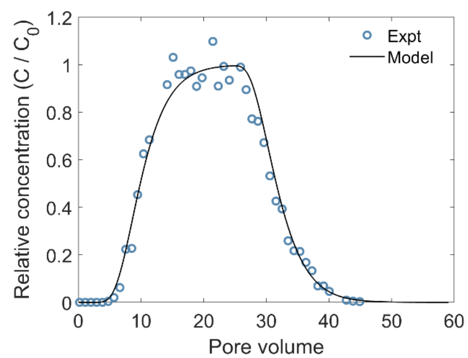
θ	Water content
σ	Surface tension
h	Pressure head
K	Hydraulic conductivity
γ	Contact angle
v	Pore-water velocity
D	Dispersion coefficient
C	Aqueous concentration
$C_{s,1}$	Instantaneous SPA
$C_{s,2}$	Kinetic SPA
$C_{aw,1}$	Instantaneous AWIA
$C_{aw,2}$	Kinetic AWIA
K_f, N	Freundlich parameters
F_s	Fraction of instantaneous sites
A_{aw}	Air-water interfacial area
K_{aw}	AWIA coefficient
F_{aw}	Fraction of instantaneous sites

Model validation: vs. miscible-displacement experiments

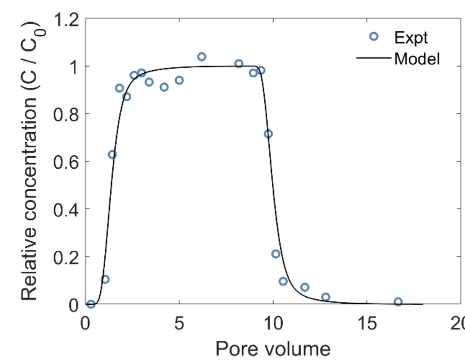
Experimental data set #1
PFOA (1 mg/L, 0.1 mg/L, 0.01 mg/L)
Measured data: Lyu et al., 2018



Experimental data set #2
PFOS (0.1 mg/L)
Measured data: Brusseau et al., 2021



Experimental data set #3
GenX (10 mg/L)
Measured data: Yan et al., 2021

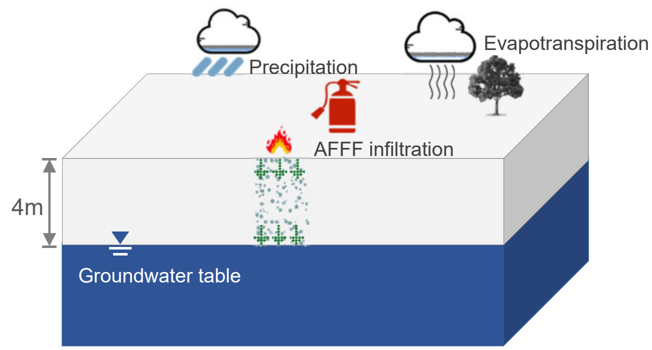


➢ Independent model predictions match well with experimental data.

Zeng, Brusseau, Guo. 2021 JH
Guo, Zeng, Brusseau, Zhang. 2022 AWR

Numerical simulation: PFAS migration at a fire training area

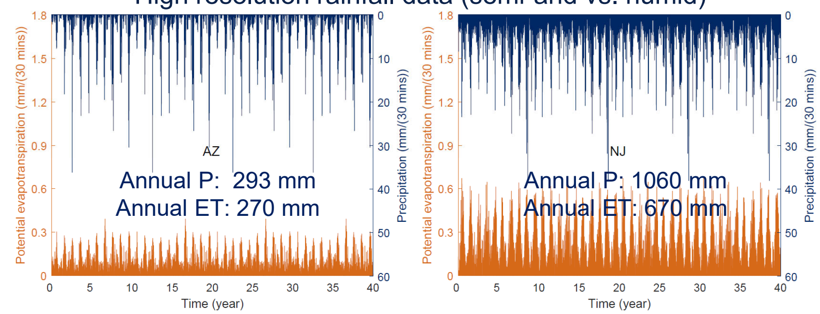
- PFAS contamination scenario at an AFFF-impacted fire training area site



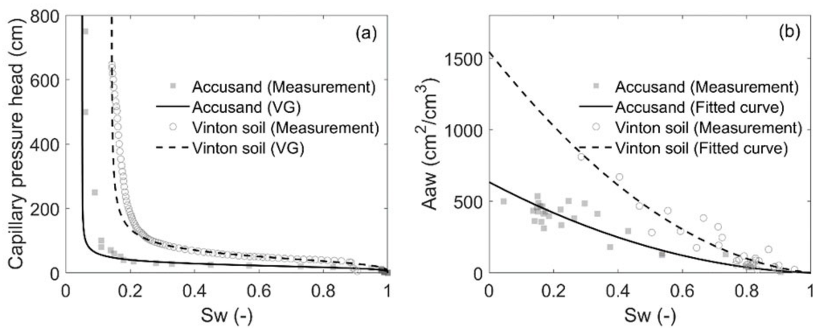
✓ Fire training: one session every 10 days lasting for 30 years

✓ Representative PFAS mixture in 1% diluted AFFF solution
PFOS: 100 mg/L, PFHxS: 7.1 mg/L, PFBS: 1.4 mg/L

High resolution rainfall data (semi-arid vs. humid)



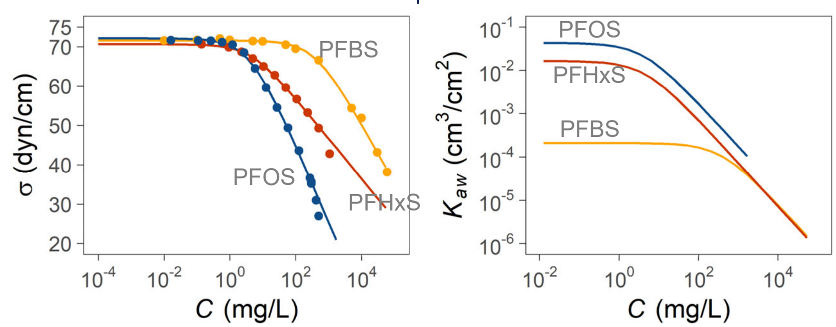
Two soil types (Accusand vs. Vinton)



Soil water characteristics

Air-water interfacial area

Three representative PFAS

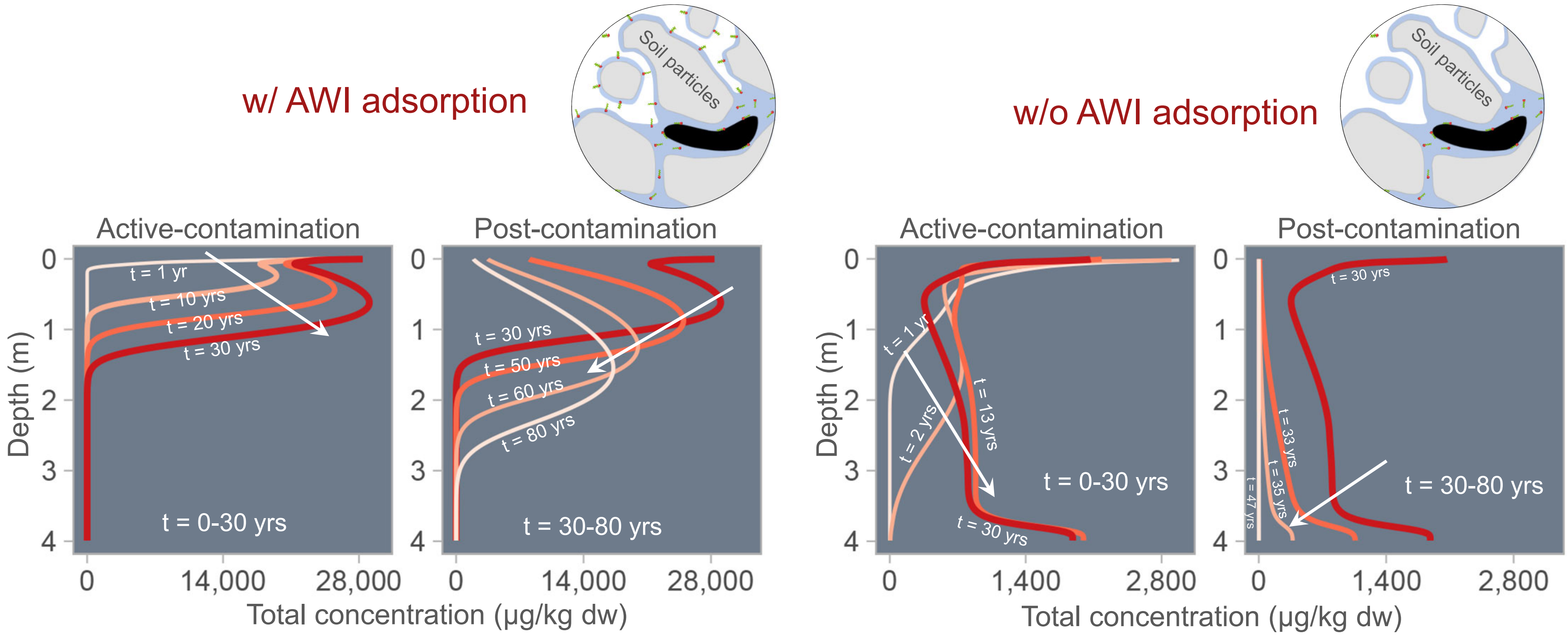


Surface tension data

Air-water interfacial adsorption coeff.

Numerical simulation: PFAS migration at a fire training area

- Retention and leaching of PFOS: temporal evolution of spatial profiles

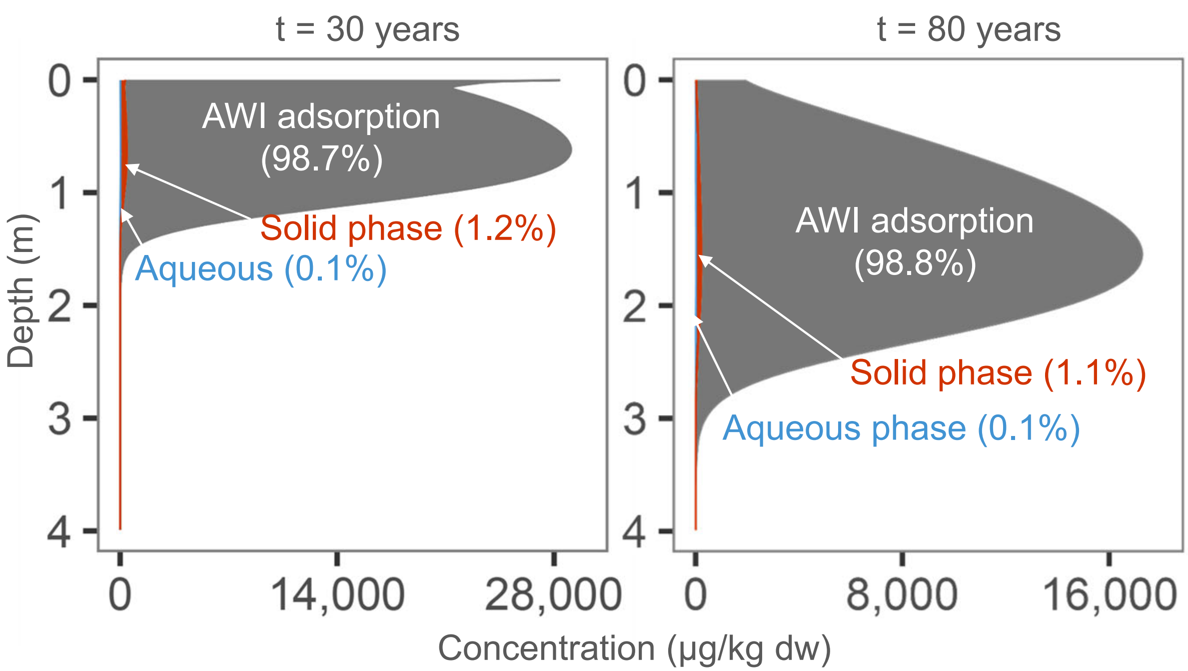


➢ Air-water interfacial adsorption significantly reduces the PFOS leaching in soils.

Guo, Zeng, Brusseau. 2020 WRR

Numerical simulation: PFAS migration at a fire training area

- Retention and leaching of PFOS: mass distribution in soils

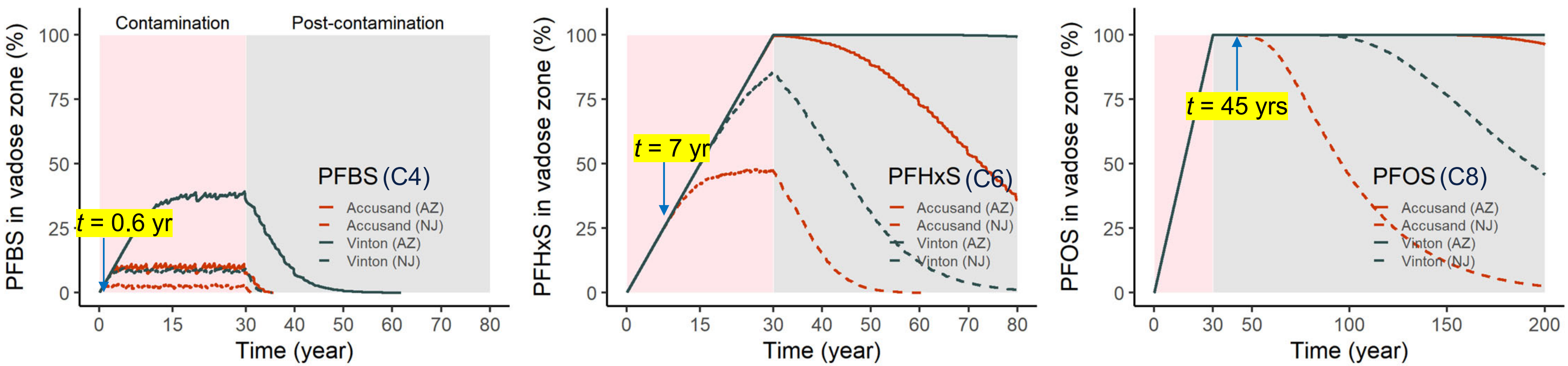


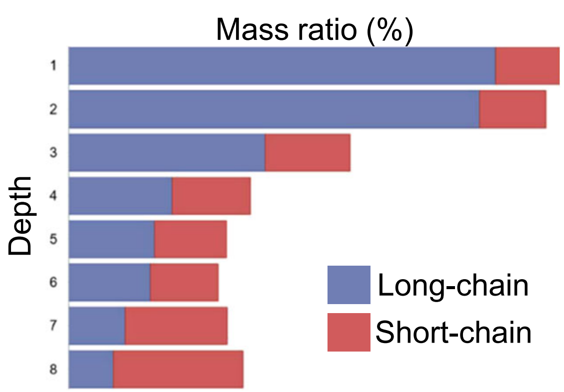
- The majority (>98%) of PFOS in the soil is adsorbed at the air-water interfaces.
- Only 0.1% and ~1% of PFOS in aqueous and solid phase.
- C in soils >> C in groundwater.

Guo, Zeng, Brusseau. 2020 WRR

Numerical simulation: PFAS migration at a fire training area

- Short-chain vs. long-chain



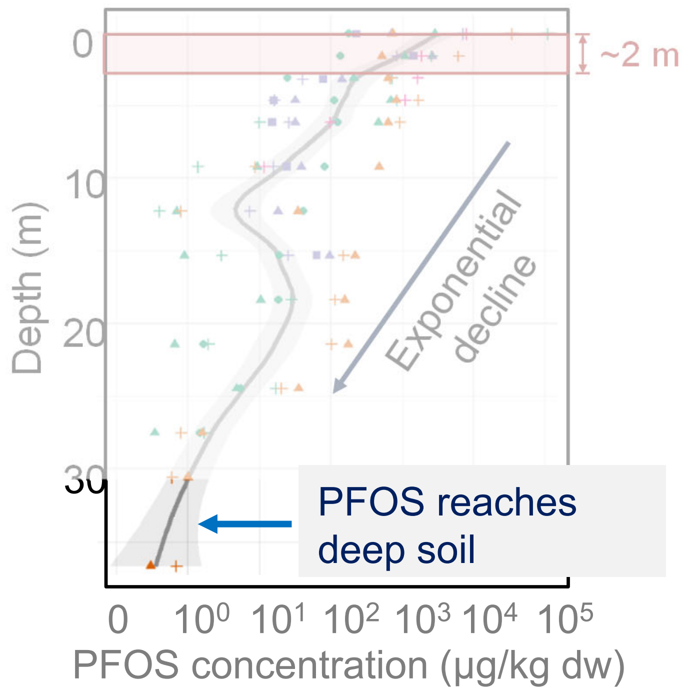


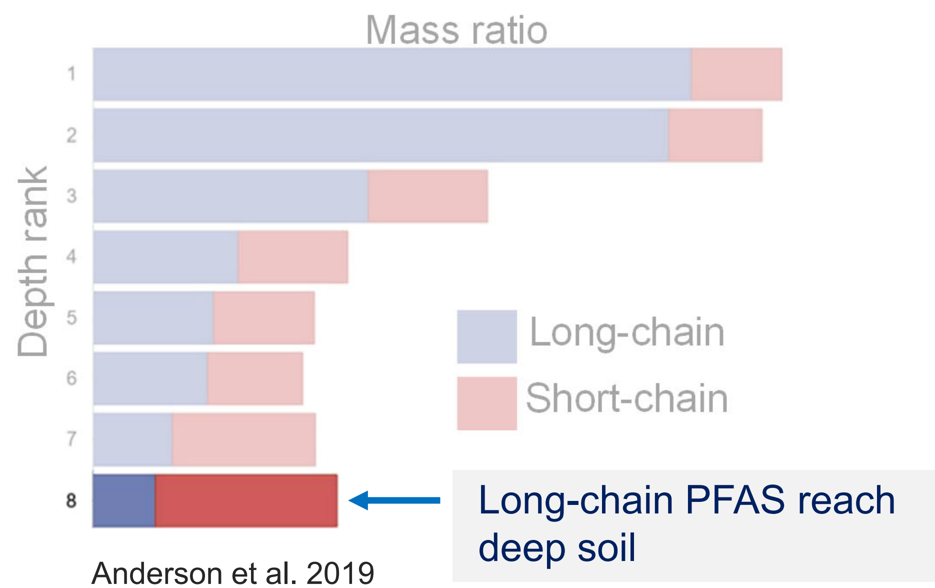
- PFBS, PFHxS, and PFOS reach groundwater table at t = 0.6 yrs, 7 yrs, and 45 yrs.
- PFOS is much more strongly retained in the soil than PFBS and PFHxS.
- Long-chain PFAS is retained in the shallow soil; while short-chain PFAS reach much deeper depth.

Zeng, Brusseau & Guo. 2021 JH

Field data: spatial variation of concentrations in soils

PFAS concentration profiles in the soil





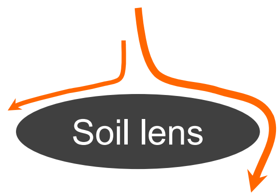
Anderson et al. 2019
Brusseau, Anderson, Guo. 2020.

- The simulations capture strong retention of long-chain PFAS in shallow soil
- But they fail to represent leaching to deep soil and early arrival to groundwater

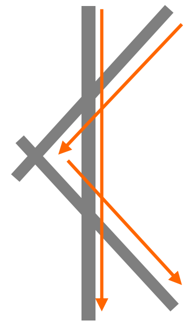
Hypothesis

Heterogeneity-generated preferential flow leads to long-chain PFAS leaching to deep soil.

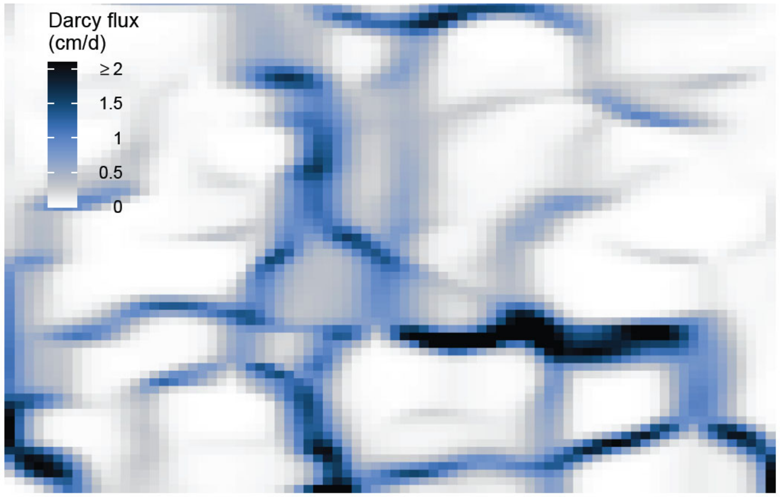
Preferential flow



- Funnel flow



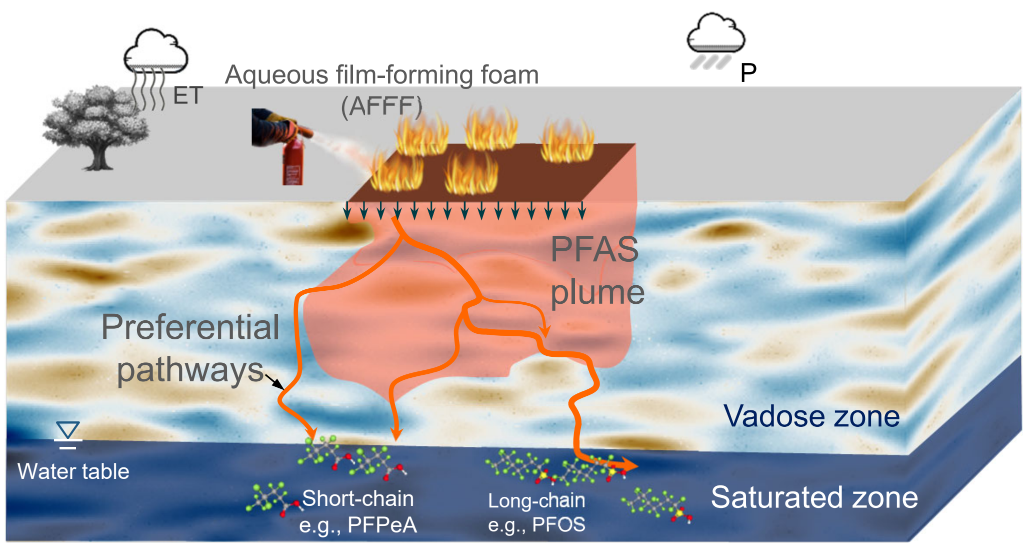
- Macropores/Fractures
- Other high-conductivity channels



Zeng & Guo. 2021 AWR
Zeng & Guo. 2023 GRL

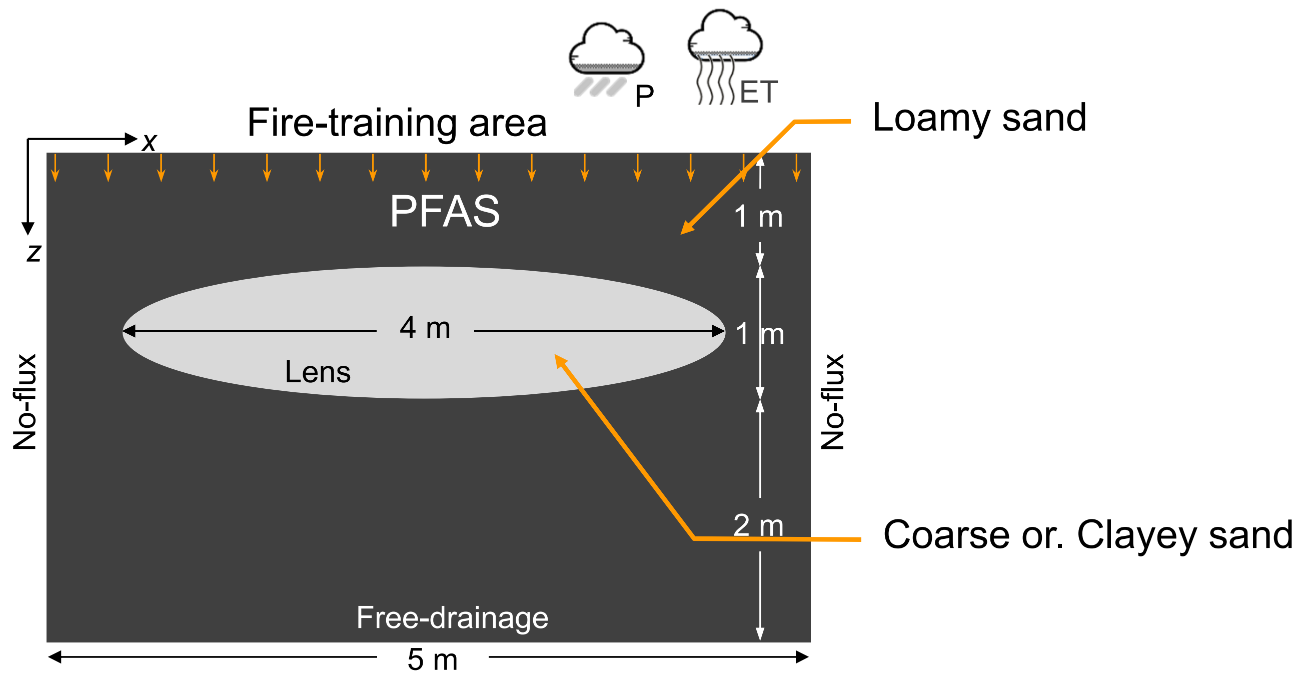
PFAS contamination at a fire-training area (FTA)

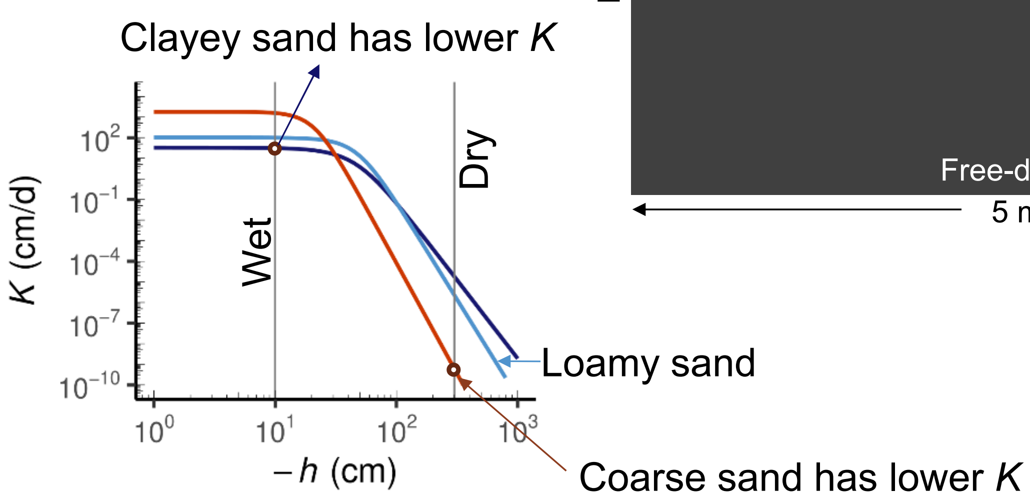
- Area: 30 m × 30 m.
- 1% diluted AFFF.
- Fire training: 30 min per 10 days for 30 yrs.
- Water table is deeper than 4 m.

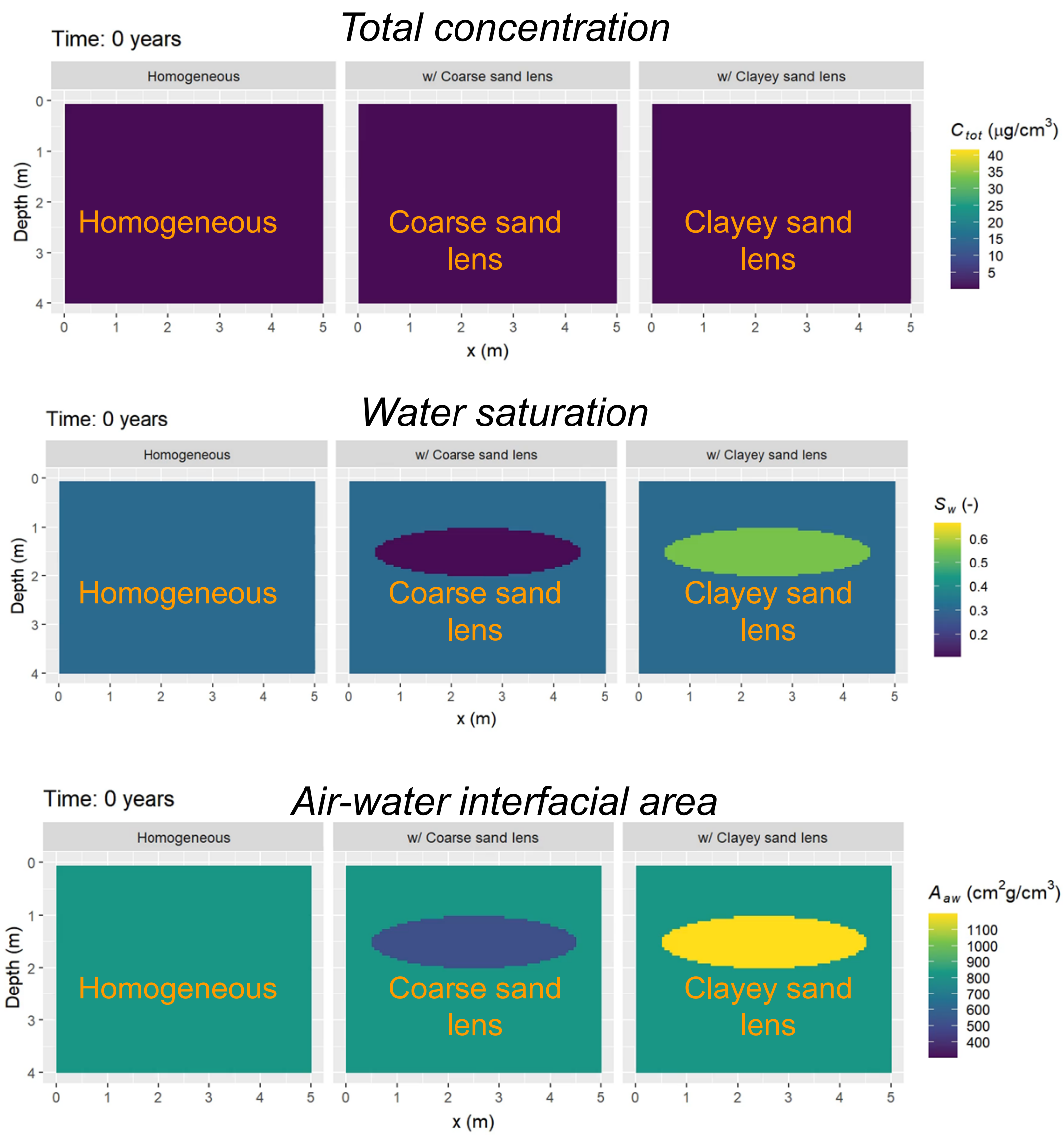


(Zeng, Guo, 2021; Guo, Zeng, Brusseau, 2020)

Soil lenses


P
ET
Fire-training area
x
z
PFAS
1 m
4 m
1 m
Lens
No-flux
No-flux
2 m
Free-drainage
5 m
Loamy sand
Coarse or. Clayey sand

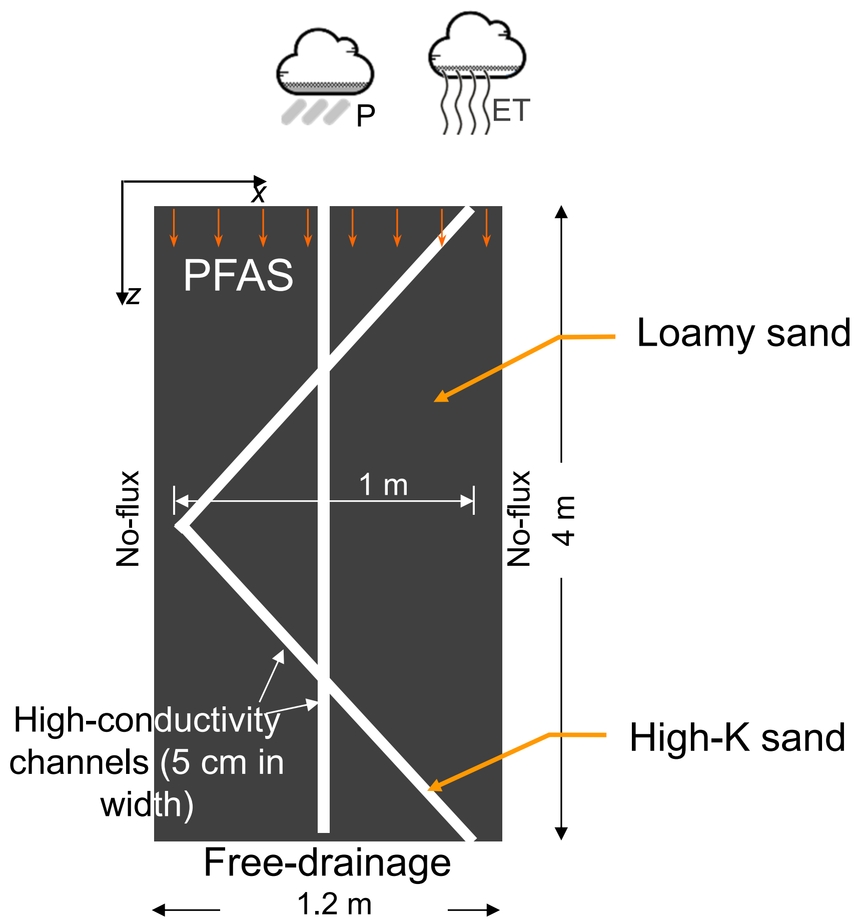

Clayey sand has lower K
K (cm/d)
Wet
Dry
Loamy sand
–h (cm)
Coarse sand has lower K



Accelerated leaching caused by soil lenses

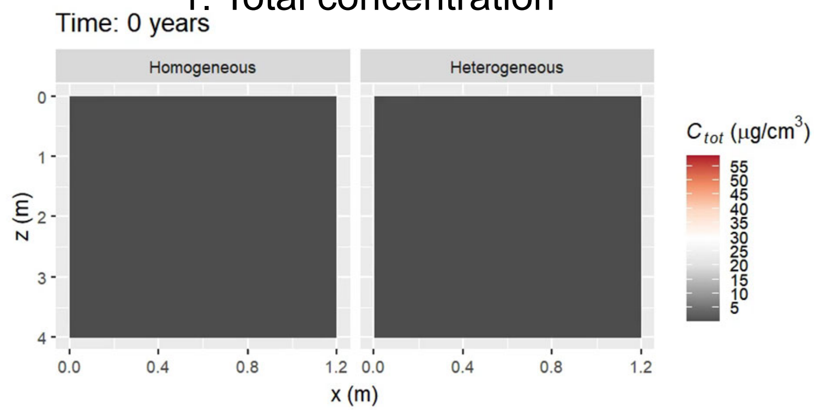
- PFAS leaching is accelerated in the presence of the preferential flow pathways.
- Along these flow pathways, air-water interfaces are destructed, which further accelerates PFAS migration.
- This is a phenomenon **unique** for PFAS, especially those long-chain compounds.

Macropores/Fractures

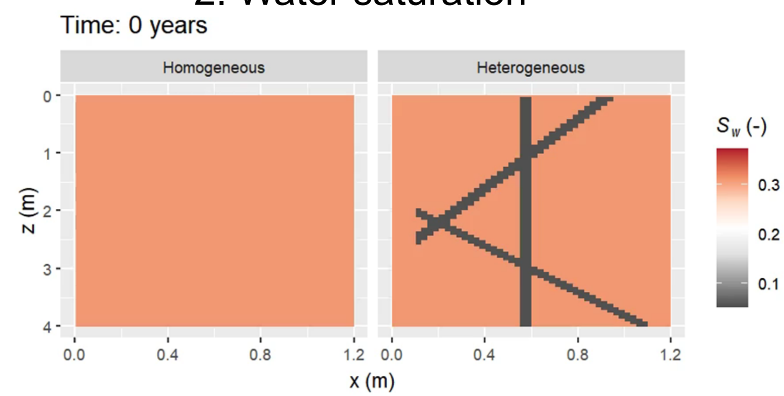


Early arrival and horizontal spreading caused by macropores/fractures

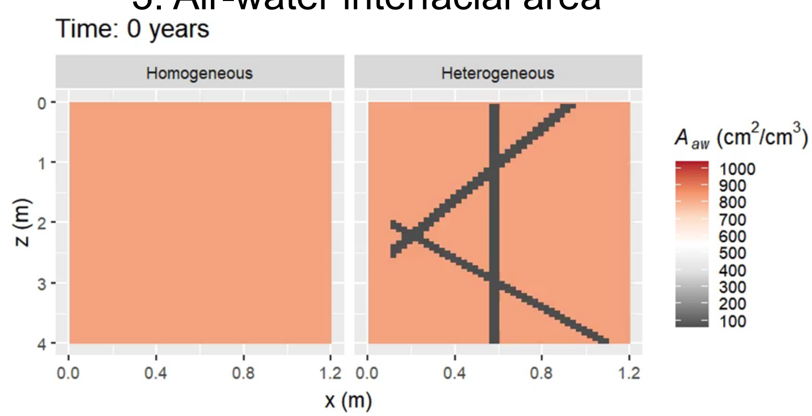
1. Total concentration



2. Water saturation

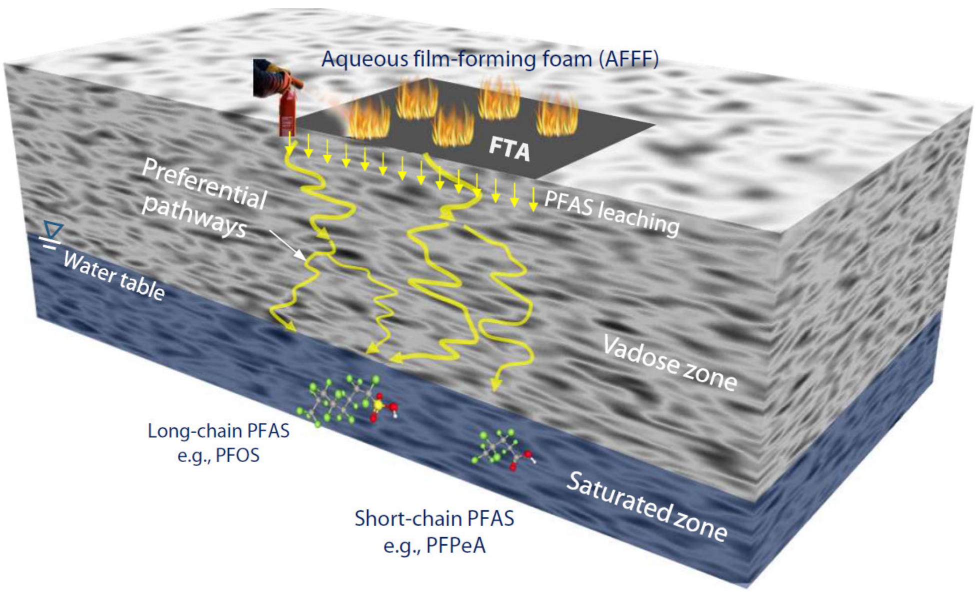


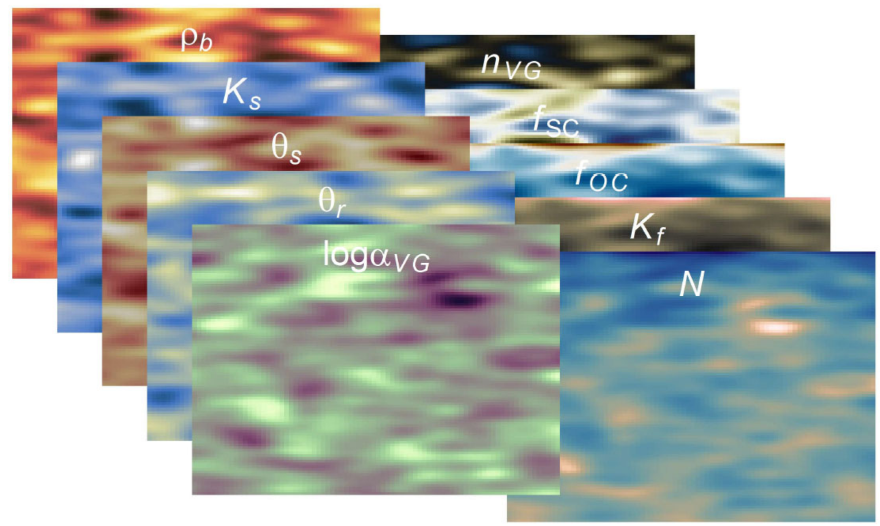
3. Air-water interfacial area



- During the early time, high-conductivity channels accelerate PFAS leaching;
- During the late time, the leaching efficiency is reduced due to "shortcut-circuiting" channels surrounding the soil matrix.

More complex heterogeneities



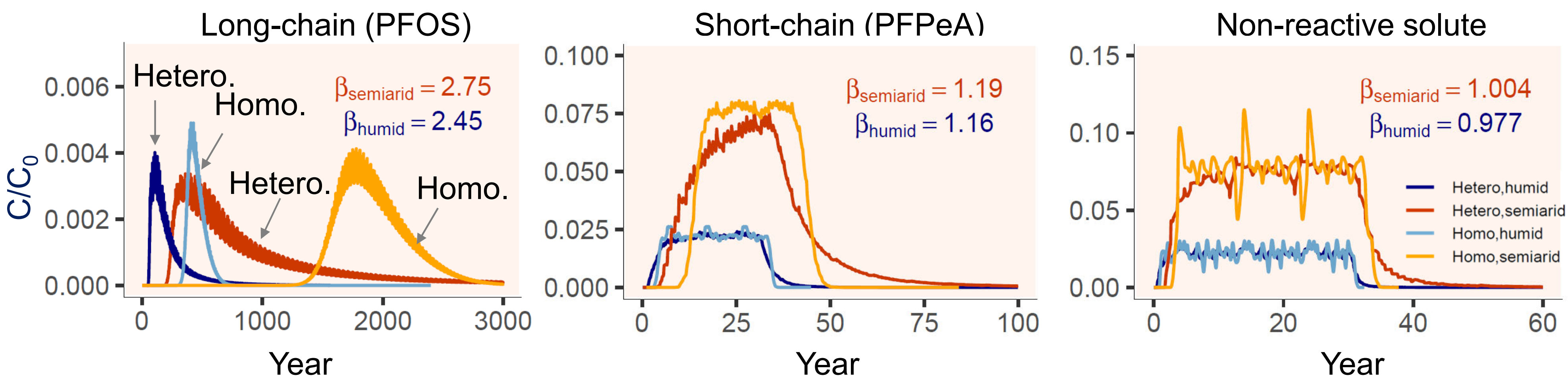


Zeng & Guo. 2023 GRL

- Stochastically generated heterogeneous parameter fields based on field measurements.
- Geochemical properties correlate with hydraulic parameters.

Preferential flow uniquely accelerated PFAS leaching in the vadose zone

Breakthrough concentration (C/C_0)



Zeng & Guo. 2023 GRL

Can we develop simplified models for practical screening-type analysis?

PFAS transport in the vadose zone: simplified mathematical model

Steady-state unsaturated flow:

$$q = K$$

PFAS transport:

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{\theta}\frac{\partial C_s}{\partial t} + \frac{1}{\theta}\frac{\partial C_{aw}}{\partial t} + \frac{\partial}{\partial z}(vC) - \frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) = 0$$

Advection | Dispersion

Linear and rate-limited solid-phase adsorption (SPA)

$$C_{s,1} = F_s K_d C$$

Instantaneous

$$\frac{dC_{s,2}}{dt} = \alpha_s[(1-F_s)K_d C - C_{s,2}]$$

Kinetic

Linear and equilibrium air-water interfacial adsorption (AWIA)

$$C_{aw} = F_{aw} A_{aw} K_{aw} C$$

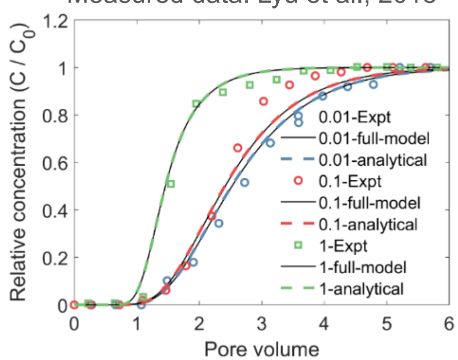
Instantaneous

Guo, Zeng, Brusseau, Zhang. AWR. 2022

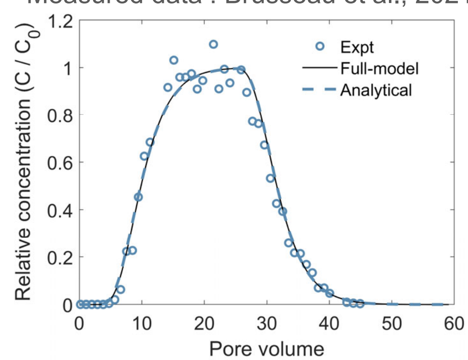
θ	Water content
h	Pressure head
K	Hydraulic conductivity
v	Pore-water velocity
D	Dispersion coefficient
C	Aqueous concentration
$C_{s,1}$	Instantaneous SPA
$C_{s,2}$	Kinetic SPA
C_{aw}	Instantaneous AWIA
K_d	Linear SPA coefficient
F_s	Fraction of instantaneous sites
A_{aw}	Air-water interfacial area
K_{aw}	AWIA coefficient
F_{aw}	Fraction of instantaneous sites

Model validation: vs. miscible-displacement experiments

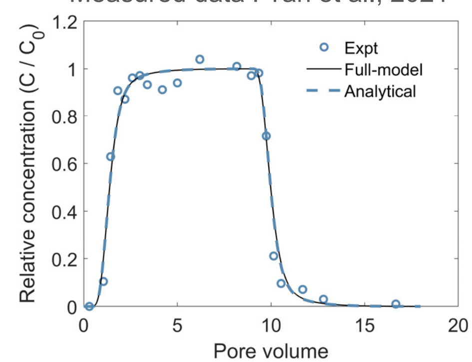
Experimental data set #1
PFOA (1 mg/L, 0.1 mg/L, 0.01 mg/L)
Measured data: Lyu et al., 2018



Experimental data set #2
PFOS (0.1 mg/L)
Measured data : Brusseau et al., 2021



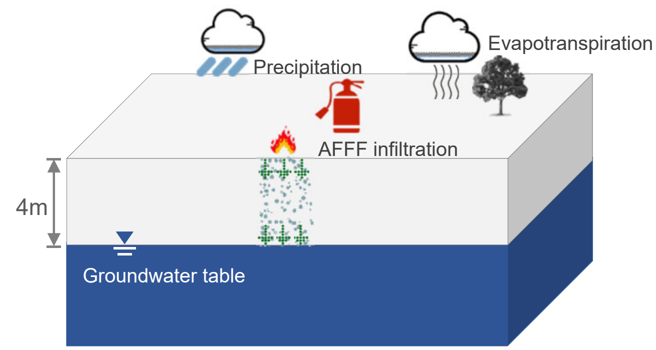
Experimental data set #3
GenX (10 mg/L)
Measured data : Yan et al., 2021



- Analytical solutions are identical to the numerical solutions of the full-process model.
- Independent model predictions match well with experimental data.

Model validation: vs. full-process model

- PFAS contamination scenario at an AFFF-impacted fire training area site

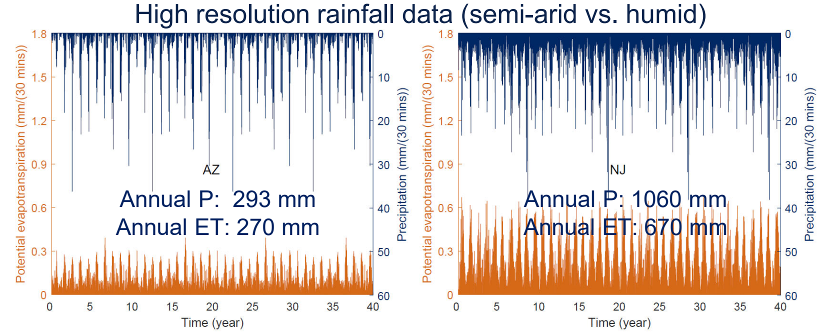


✓ Fire training: one session every 10 days lasting for 30 years

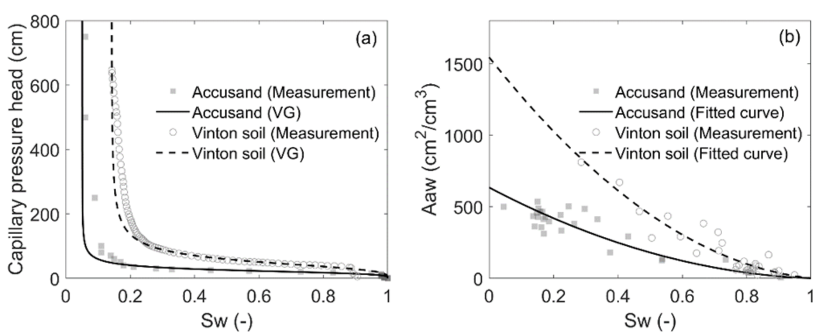
✓ Representative PFAS mixture in 1% diluted AFFF solution

PFPeA: 0.23 mg/L, PFOA: 0.9 mg/L, PFHxS: 7.1 mg/L, PFOS: 100 mg/L

High resolution rainfall data (semi-arid vs. humid)



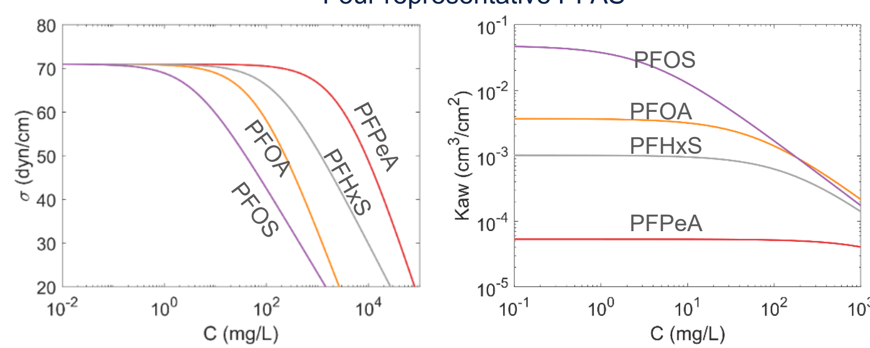
Two soil types (Accusand vs. Vinton)



Soil water characteristics

Air-water interfacial area

Four representative PFAS

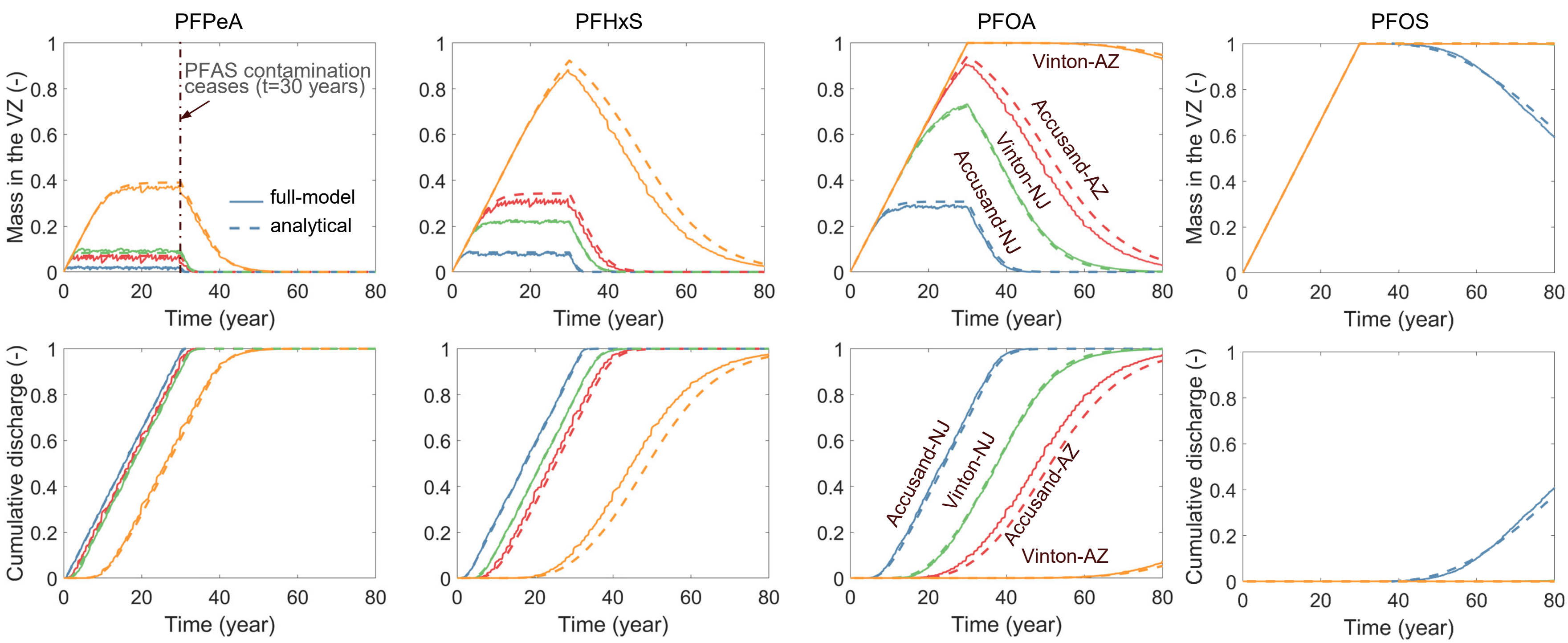


Surface tension data

Air-water interfacial adsorption coeff.

Simulated long-term PFAS leaching in the vadose zone

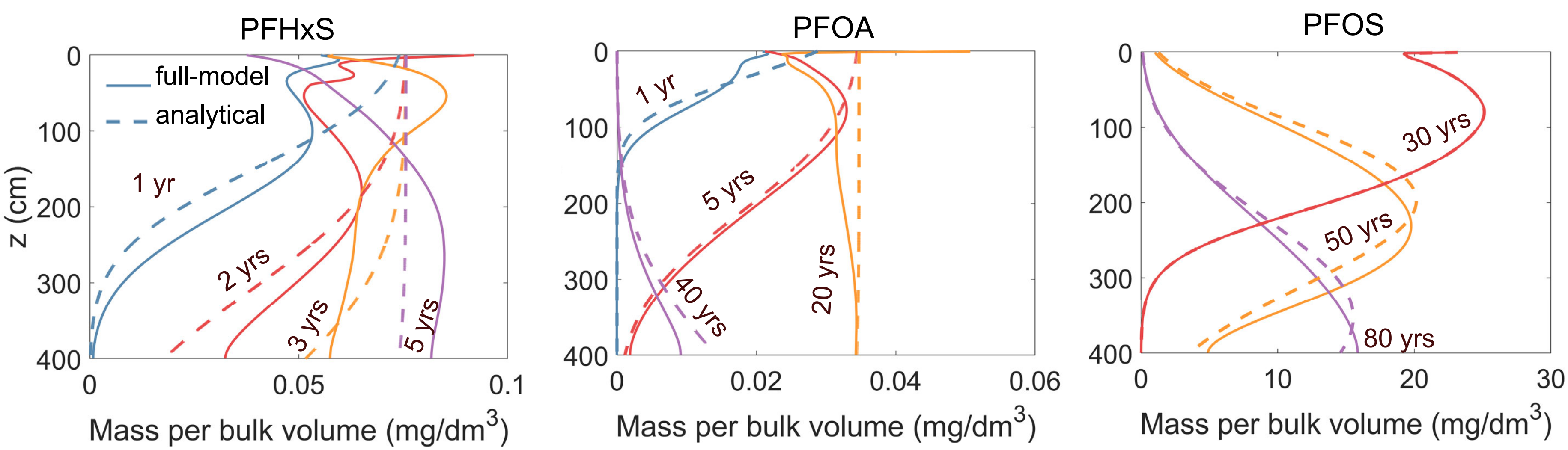
- PFAS retention in the vadose zone and mass discharge to groundwater



➢ Analytical model matches remarkably well with the full-process model for all four PFAS.

Simulated long-term PFAS leaching in the vadose zone

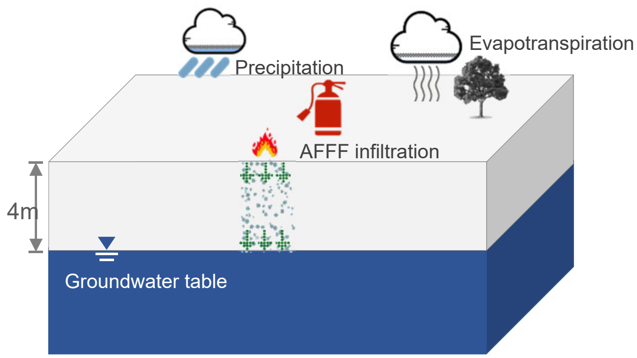
- Spatial total concentration profiles (NJ, Accusand)



➢ The concentration profiles simulated by the analytical model agrees well with those by the full-process model.

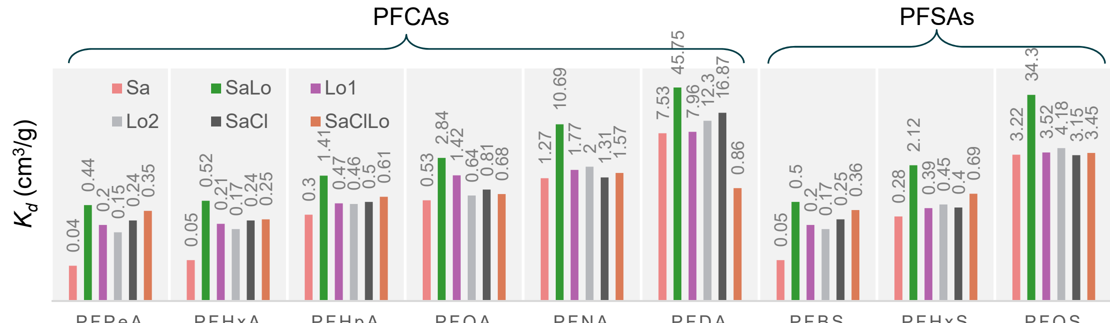
Applying the analytical model as a screening-type tool

- PFAS contamination scenario at an AFFF-impacted fire training area site



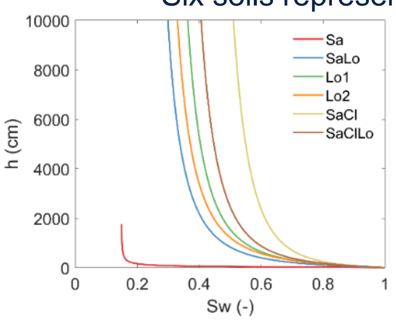
✓ Fire training: one session every 10 days lasting for 30 years

✓ Six soils and nine PFAS in 1% diluted AFFF solution

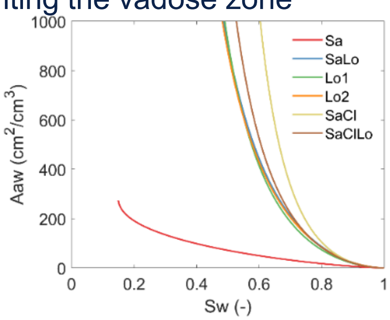


Nguyen et al. 2020

Six soils representing the vadose zone

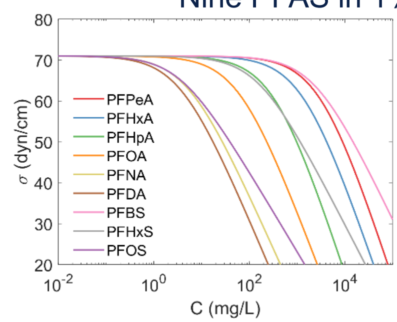


Soil water characteristics

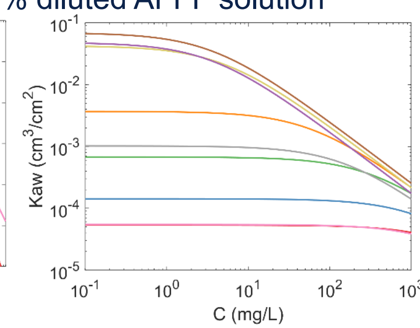


Air-water interfacial area

Nine PFAS in 1% diluted AFFF solution



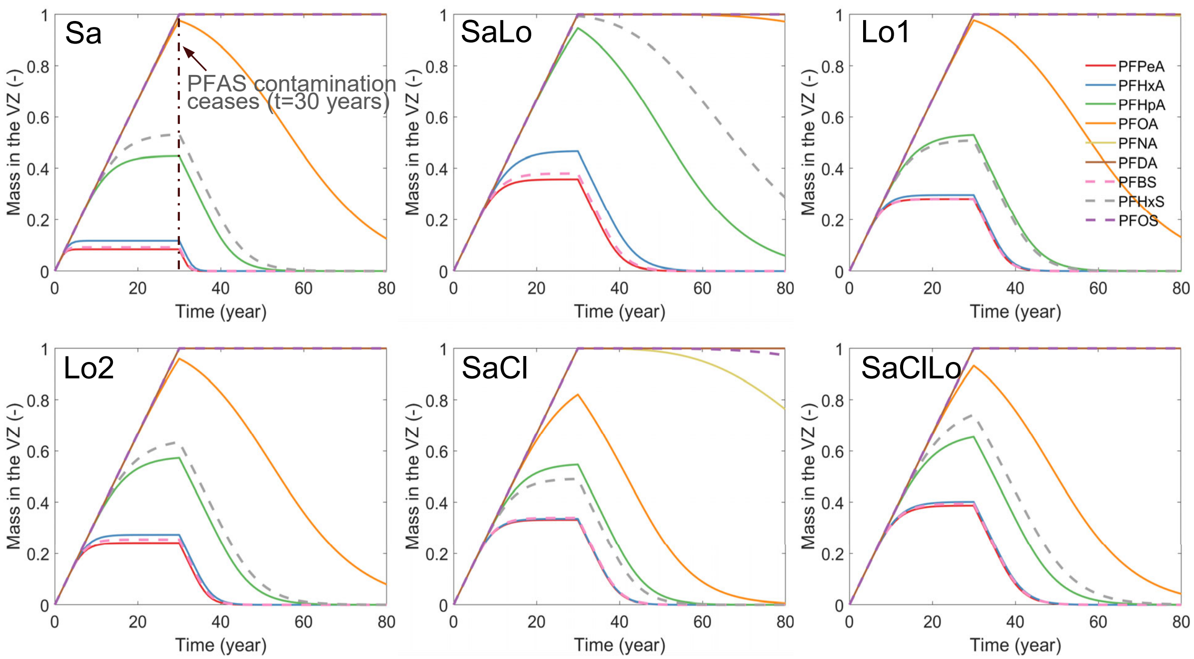
Surface tension data



Air-water interfacial adsorption coeff.

Simulated long-term PFAS leaching in the vadose zone

- PFAS retention in the vadose zone

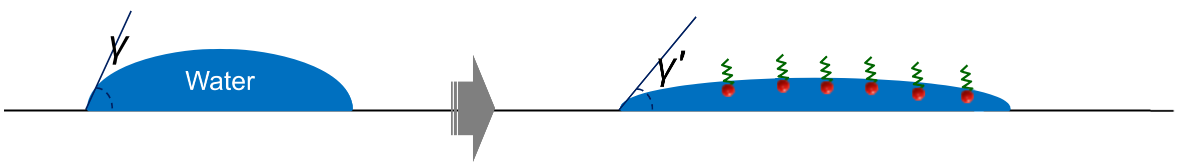


- PFAS retention increases with chain length and varies among different soils.
- Finer-grain soils may have weaker retention than coarser-grain soils due to reduced AWIA resulting from greater Sw and reduced air-water interfacial area.

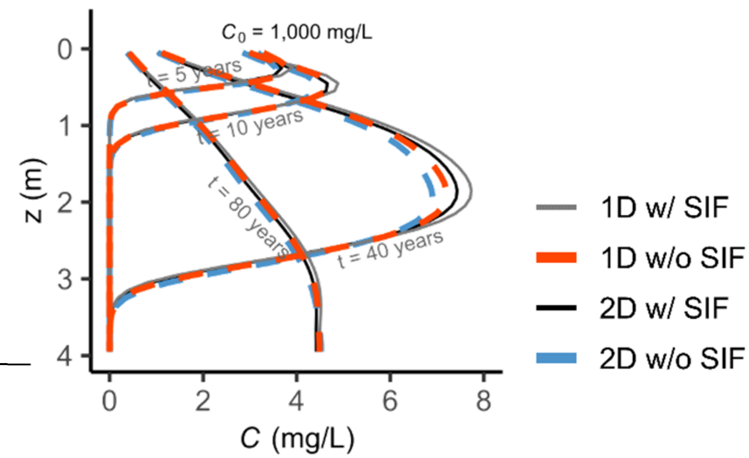
Additional processes

- ❑ Surfactant-induced flow (SIF)

Reduction in surface tension & contact angle
can induce drainage



PFOS concentration profiles



- Zeng, J. and Guo, B., 2021. Multidimensional simulation of PFAS transport and leaching in the vadose zone: Impact of surfactant-induced flow and subsurface heterogeneities. *Advances in Water Resources*, *155*, p.104015.

- ❑ The presence of multicomponent PFAS and hydrocarbon surfactants retention in the vadose zone

- Guo, B., Saleem, H. and Brusseau, M.L., 2023. Predicting Interfacial Tension and Adsorption at Fluid−Fluid Interfaces for Mixtures of PFAS and/or Hydrocarbon Surfactants. *Environmental Science & Technology.*

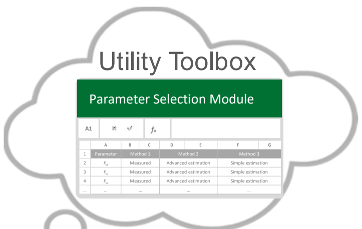
- ❑ The impact of thin water films in controlling PFAS transport in water-unsaturated soils

- Chen, S. and Guo, B., 2023. Pore-scale modeling of PFAS transport in water-unsaturated porous media: Air–water interfacial adsorption and mass-transfer processes in thin water films. *Water Resources Research*, p.e2023WR034664.

PFAS-LEACH: Predicting PFAS Leaching in Source Zones

PFAS-LEACH – A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones

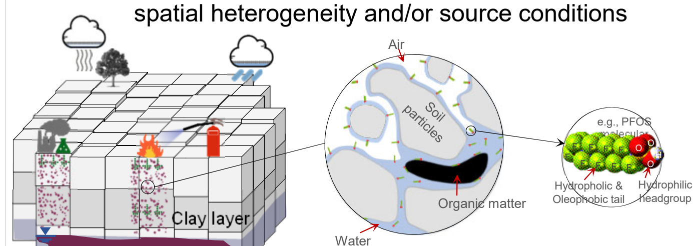
i. Three simulators spanning wide range of complexity
ii. Comprehensive parameter selection module
iii. Documentation and user manual



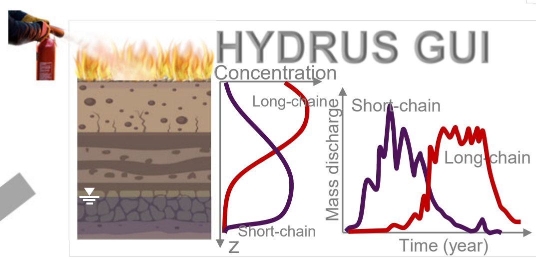
(Brusseau et al., 2019)

Tier 1 – PFAS-LEACH-COMP

Feature: Full-process model in 3D
Anticipated application: Sites w/ sufficient data; complex spatial heterogeneity and/or source conditions



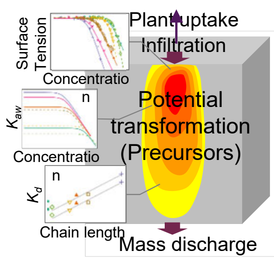
(Guo et al., 2020; Zeng et al., 2021; Zeng & Guo, 2021)



Tier 2 – PFAS-LEACH-HYDRUS

Feature: Implemented in HYDRUS-1D GUI
Anticipated application: Insignificant lateral heterogeneity; efficient uncertainty quantification

(Zeng et al., 2021)



Tier 3 – PFAS-LEACH-Screening

Feature: Implemented in Excel
Anticipated application: Limited data; early stage of site management; order-of-magnitude estimate with uncertainty range

(Guo et al., 2022)

Computational Cost/Input Parameters

Model Complexity

ESTCP Project ER21-5041
"Development and demonstration of PFAS-LEACH"

Take-home message

- We develop mathematical models with varying complexity representing PFAS-specific transport processes.
- Air-water interfacial adsorption leads to strong retention of (long-chain) PFAS.
- Surfactant-induced flow appears to have a minor impact on long-term PFAS leaching.
- Preferential flow destructs air-water interfaces and accelerates PFAS leaching to deep vadose zone.
- The simplified model provides an efficient and accurate screening-type tool for quantifying vadose-zone PFAS leaching.

NSF
EAR 2023351
EAR 2054575
CAREER 2237015

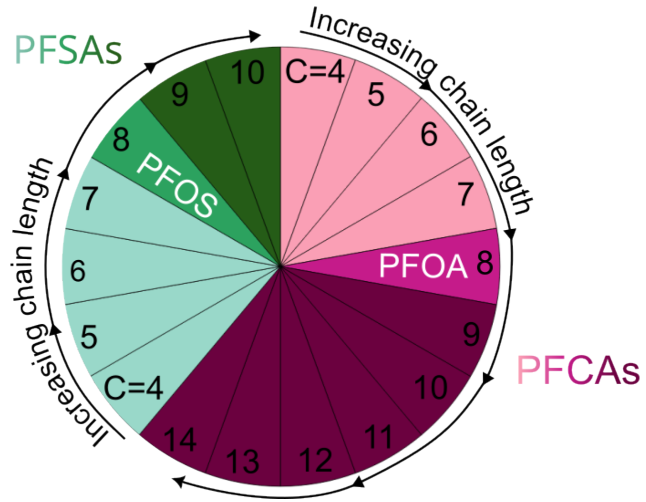
ESTCP
Project ER21-5041

Relevant publications

- Guo, B., Saleem, H. and Brusseau, M.L., 2023. Predicting Interfacial Tension and Adsorption at Fluid–Fluid Interfaces for Mixtures of PFAS and/or Hydrocarbon Surfactants. *Environmental Science & Technology*. 2023, 57, 21, 8044–8052
- Zeng, J. and Guo, B., 2023. Reduced accessible air–water interfacial area accelerates PFAS leaching in heterogeneous vadose zones. *Geophysical Research Letters*, 50(8), p.e2022GL102655.
- Brusseau, M.L. and Guo, B., 2023. Revising the EPA dilution-attenuation soil screening model for PFAS. *Journal of Hazardous Materials Letters*, 4, p.100077.
- Chen, S. and Guo, B., 2023. Pore-scale modeling of PFAS transport in water-unsaturated porous media: Air–water interfacial adsorption and mass-transfer processes in thin water films. *Water Resources Research*, p.e2023WR034664.
- Guo, B., Zeng, J., Brusseau, M.L. and Zhang, Y., 2022. A screening model for quantifying PFAS leaching in the vadose zone and mass discharge to groundwater. *Advances in Water Resources*, 160, p.104102.
- Zeng, J., Brusseau, M.L. and Guo, B., 2021. Model validation and analyses of parameter sensitivity and uncertainty for modeling long-term retention and leaching of PFAS in the vadose zone. *Journal of Hydrology*, *603*, p.127172.
- Zeng, J. and Guo, B., 2021. Multidimensional simulation of PFAS transport and leaching in the vadose zone: Impact of surfactant-induced flow and subsurface heterogeneities. *Advances in Water Resources*, *155*, p.104015
- Guo, B., Zeng, J. and Brusseau, M.L., 2020. A mathematical model for the release, transport, and retention of pfas in the vadose zone. *Water Resources Research*, *56*(2), p.e2019WR026667.

Approaching PFAS Data – Integrating an Array of Visualizations into the Conceptual Site Model

Dr. Ryan David Swanson
Dr. Jim Montague
Jeffrey Temple



HGL

Restoring the Environment.
Protecting Our Future.

PFAS Response

REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 3-5, 2023

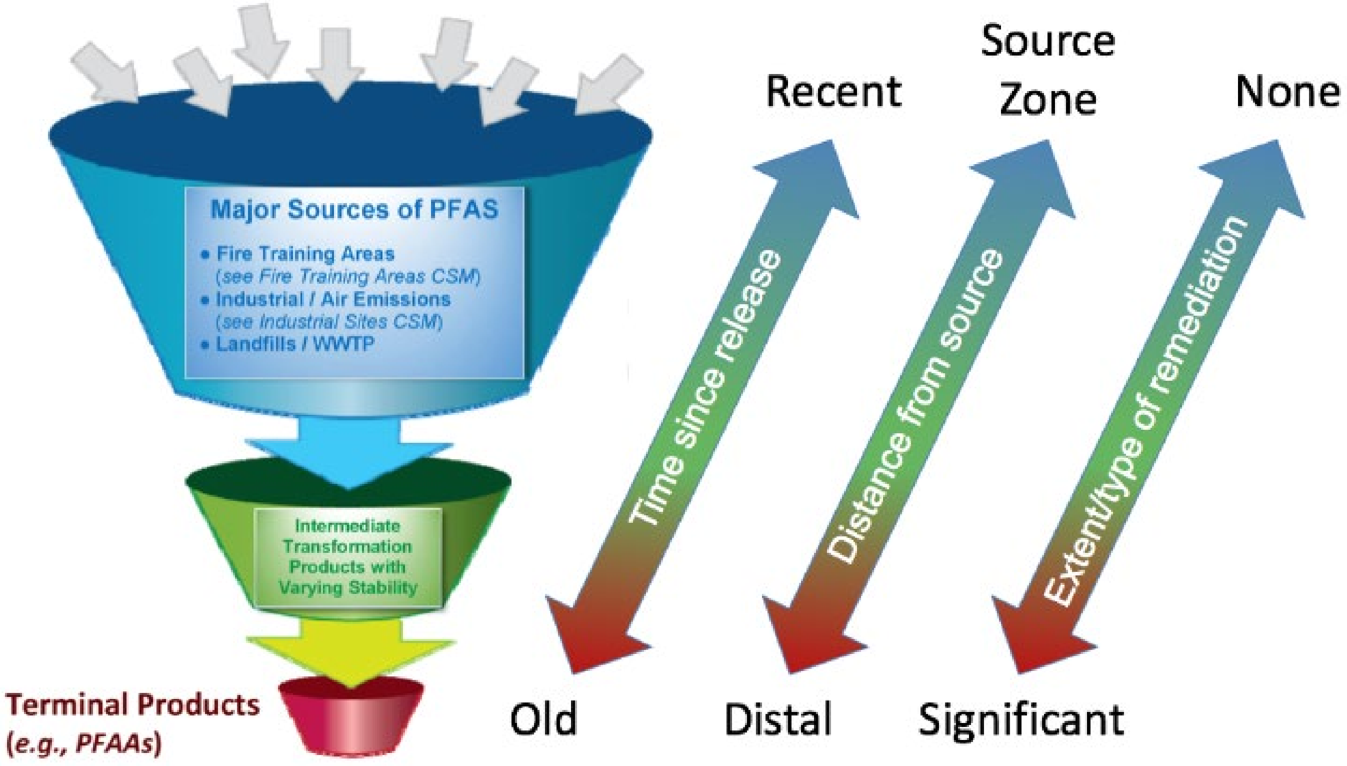
Culprits & Challenges

- Low health advisory levels
- 8 PFAS with RSLs
- Relative concentrations can be critical in
  - Identifying sources (e.g., wastewater effluent, AFFF, landfill leachate)
  - Locating source areas,
  - Delineating unique plumes
  - Quantifying PFAS

Note: Many of our sites are sensitive, so their locations have been masked.

Our Focus & Goal

- CERCLA sites in the Remedial Investigation phase
- Comingled plumes including from AFFF and non-AFFF sources
- Conceptual Site Model development that support better informed environmental restoration decisions

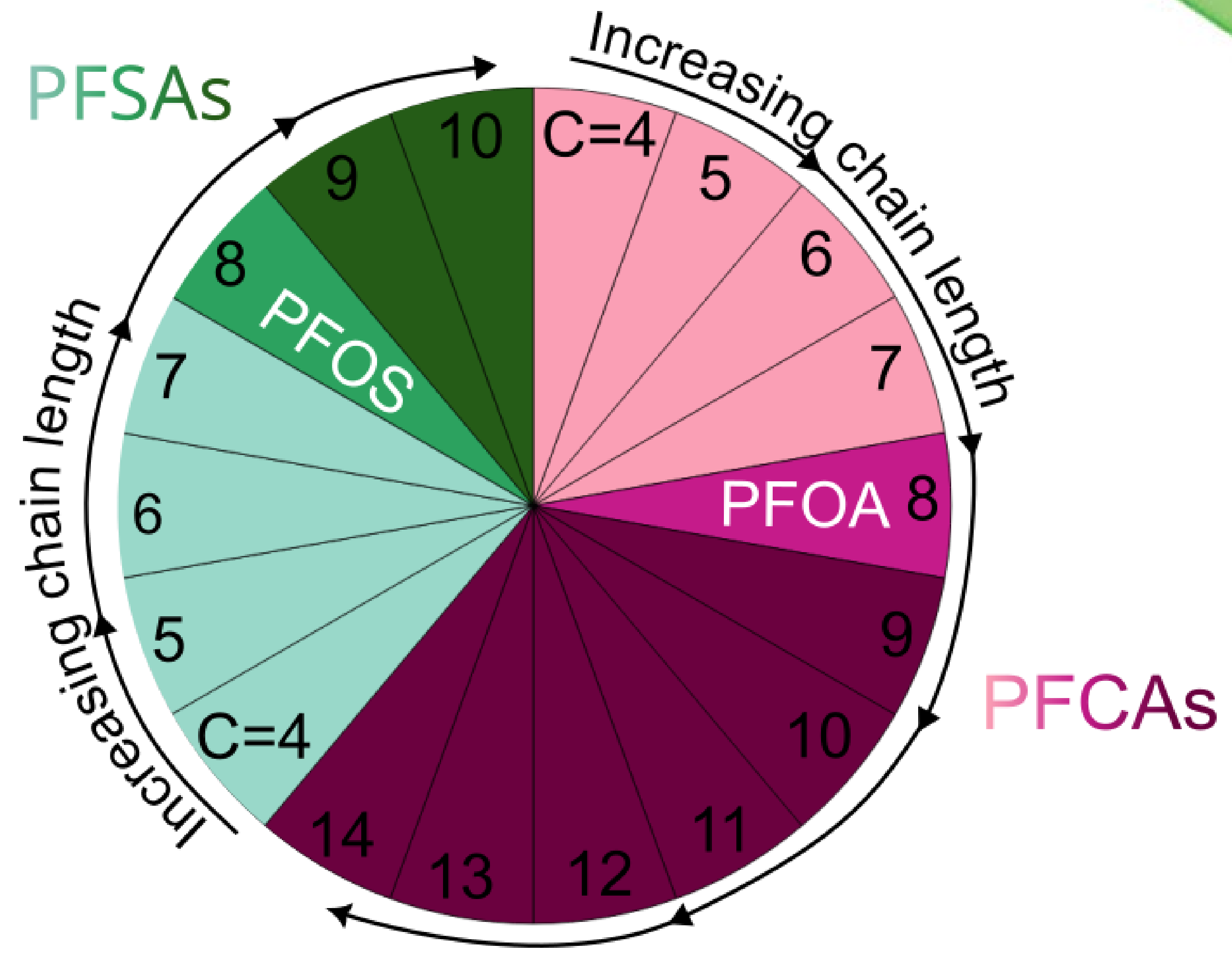


Source: L. Trozzolo, TRC, and C. Higgins, Colorado School of Mines.

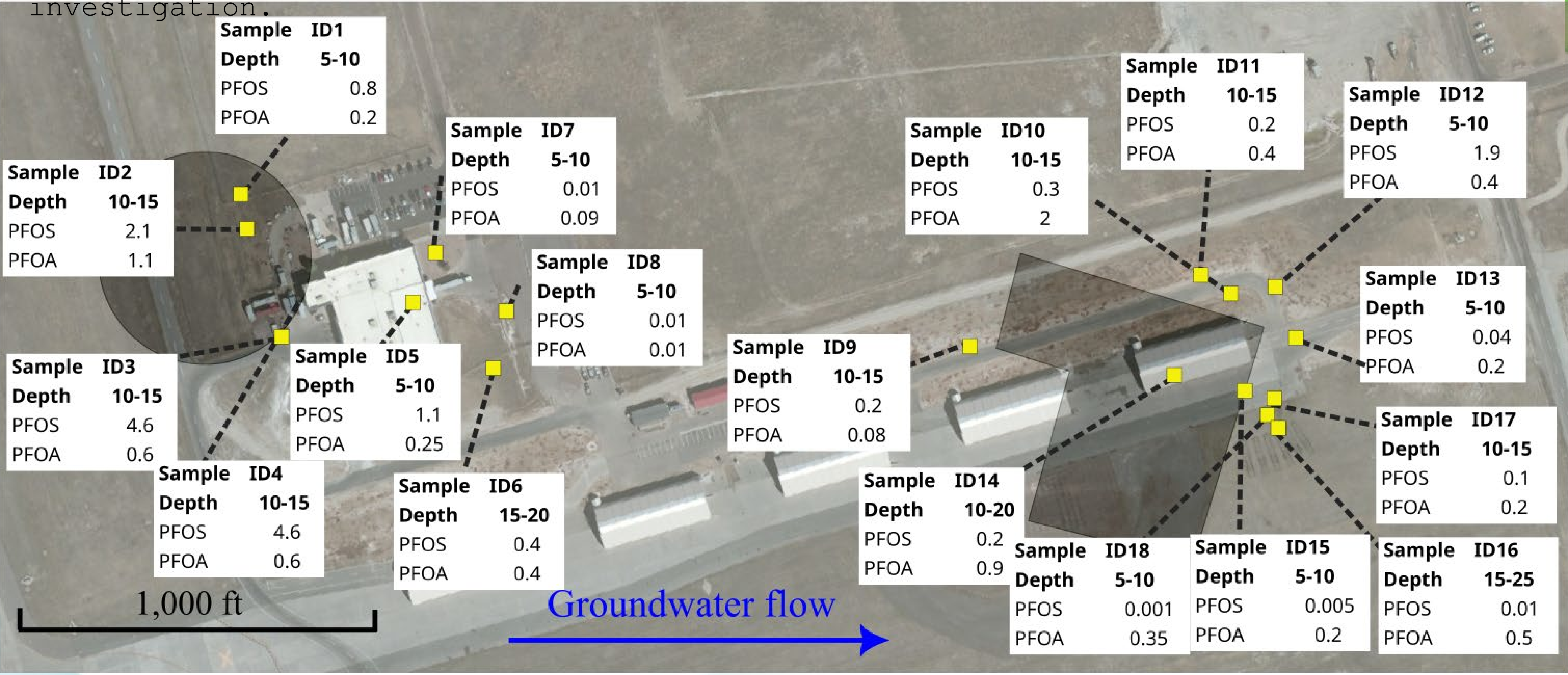
Today's Topics

- Multiple flavors of pie (charts)
- Stacking blocks
- Stacking rings

No one approach is sufficient, but these are some of our favorite methods.



This figure transmits *data*, not *knowledge*: *Okay* for the site investigation.



HOW CAN WE BEST TRANSMIT KNOWLEDGE?

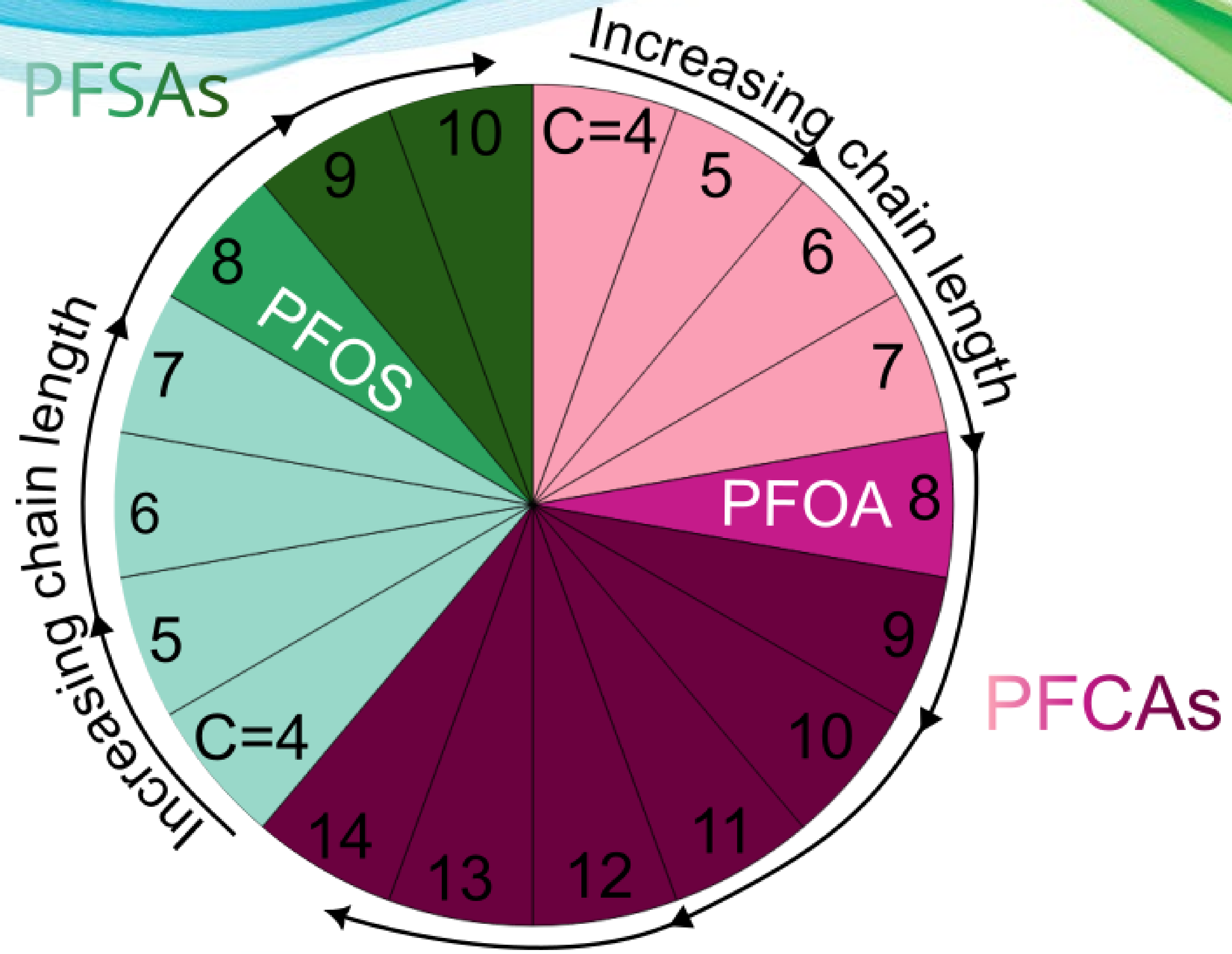
PFAS Analyte Name	Abbreviation	Type	No. of Carbons
Perfluorobutanoic Acid	PFBA	Perfluoroalkyl carboxylic acids	4
Perfluoropentanoic Acid	PFPeA	Perfluoroalkyl carboxylic acids	5
Perfluorohexanoic Acid	PFHxA	Perfluoroalkyl carboxylic acids	6
Perfluoroheptanoic Acid	PFHpA	Perfluoroalkyl carboxylic acids	7
Perfluorooctanoic Acid	PFOA	Perfluoroalkyl carboxylic acids	8
Perfluorononanoic Acid	PFNA	Perfluoroalkyl carboxylic acids	9
Perfluorodecanoic Acid	PFDA	Perfluoroalkyl carboxylic acids	10
Perfluoroundecanoic Acid	PFUnA	Perfluoroalkyl carboxylic acids	11
Perfluorododecanoic Acid	PFDoA	Perfluoroalkyl carboxylic acids	12
Perfluorotridecanoic Acid	PFTrDA	Perfluoroalkyl carboxylic acids	13
Perfluorotetradecanoic Acid	PFTeDA	Perfluoroalkyl carboxylic acids	14
Perfluorobutane Sulfonic Acid	PFBS	Perfluoroalkane sulfonic acids	4
Perfluoropentane Sulfonic Acid	PFPeS	Perfluoroalkane sulfonic acids	5
Perfluorohexane Sulfonic Acid	PFHxS	Perfluoroalkane sulfonic acids	6
Perfluoroheptane Sulfonic Acid	PFHpS	Perfluoroalkane sulfonic acids	7
Perfluorooctane Sulfonic Acid	PFOS	Perfluoroalkane sulfonic acids	8
Perfluorononane Sulfonic Acid	PFNS	Perfluoroalkane sulfonic acids	9
Perfluorodecane Sulfonic Acid	PFDS	Perfluoroalkane sulfonic acids	10

~2 Hues (red & green) with 3 Different Saturations

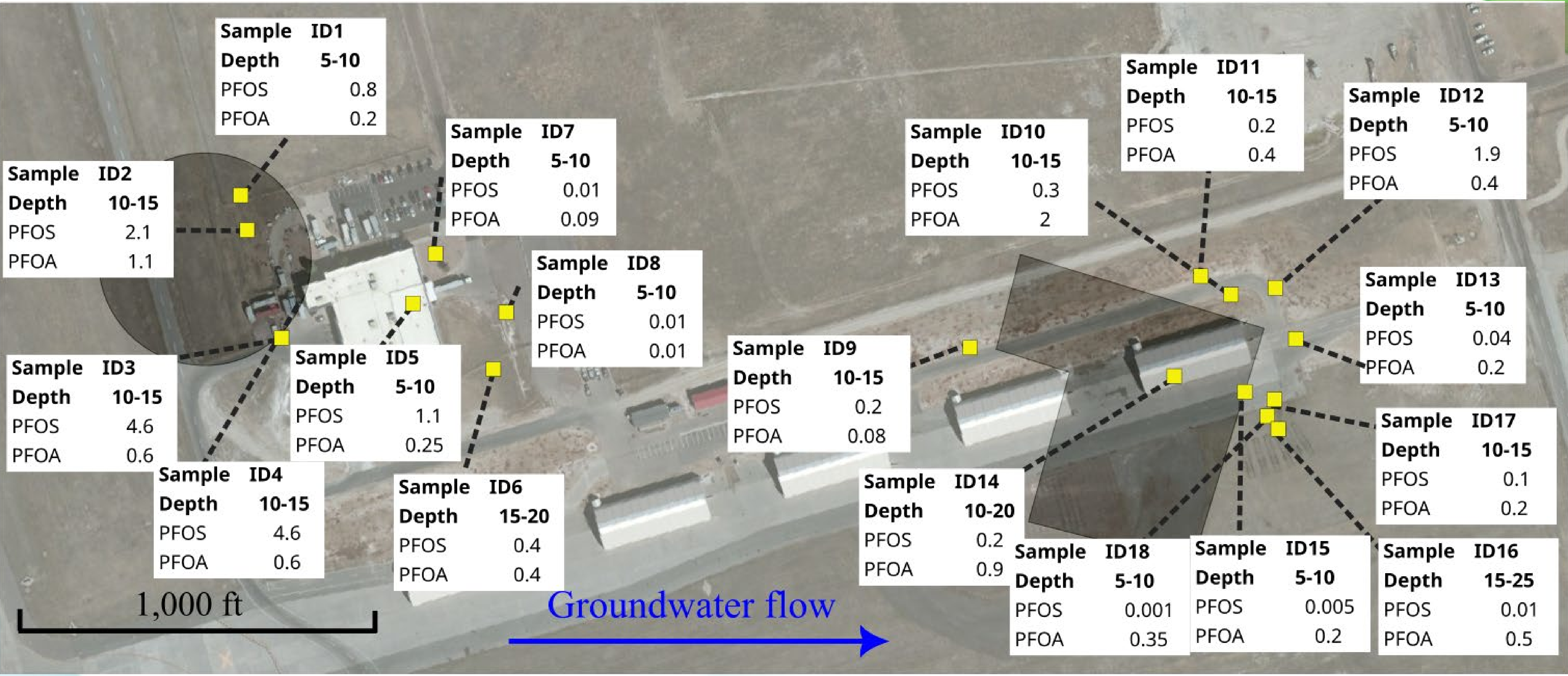
Terminal Perfluoroalkyl carboxylic acids (PFCAs)
Decreasing Mobility

Terminal Perfluoroalkane sulfonic acids (PFSAs)
Decreasing Mobility

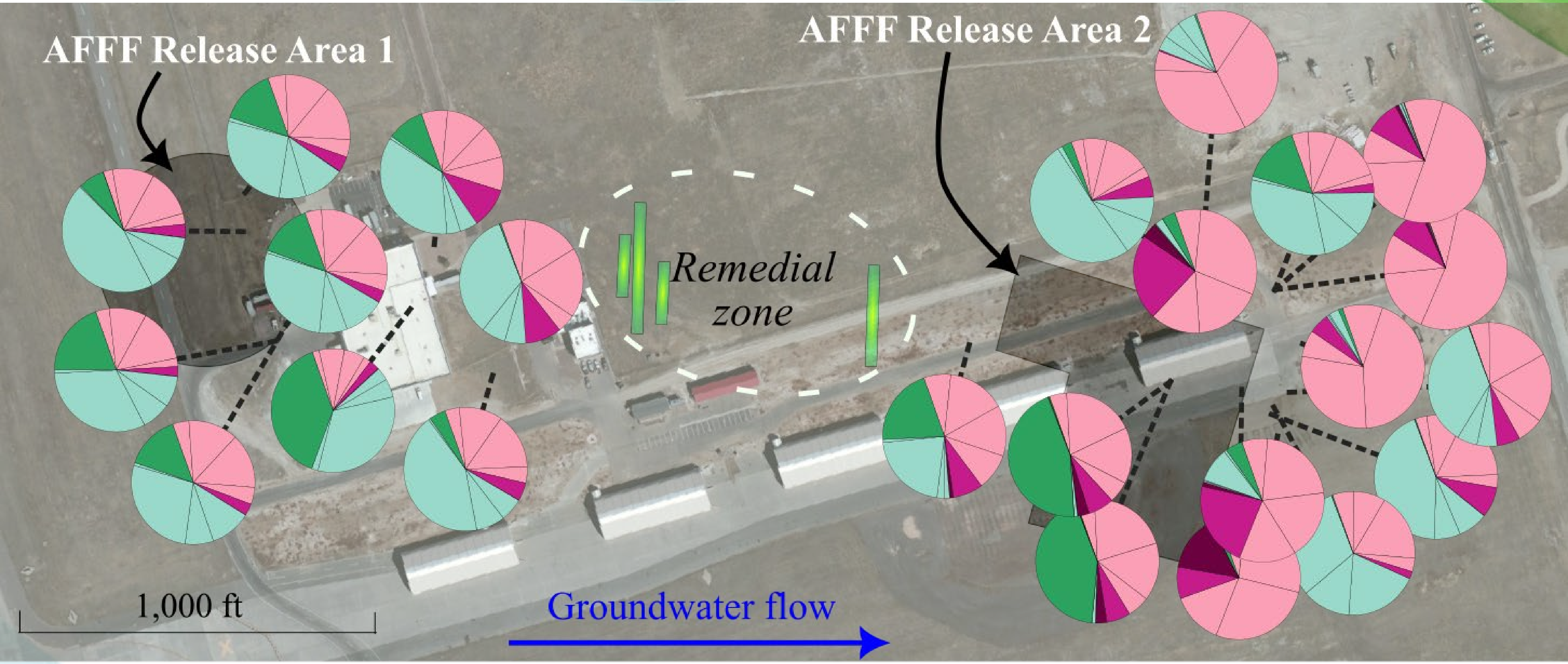
Flavor #1


PFSAs
Increasing chain length
C=4
5
6
7
PFOA 8
9
10
11
12
13
14
PFCAs
Increasing chain length
C=4
5
6
7
8
PFOS
9
10

This figure transmits *data*, not *knowledge*.



HOW CAN WE BEST TRANSMIT KNOWLEDGE?


AFFF Release Area 1
AFFF Release Area 2
Remedial zone
1,000 ft
Groundwater flow

PFAS Analyte Name	Abbreviation	Type	No. of Carbons
4:2 Fluorotelomer Sulfonic Acid	4:2 FTS	Fluorotelomer sulfonic acids	6
6:2 Fluorotelomer Sulfonic Acid	6:2 FTS	Fluorotelomer sulfonic acids	8
8:2 Fluorotelomer Sulfonic Acid	8:2 FTS	Fluorotelomer sulfonic acids	10
Perfluorobutanoic Acid	PFBA	Perfluoroalkyl carboxylic acids	4
Perfluoropentanoic Acid	PFPeA	Perfluoroalkyl carboxylic acids	5
Perfluorohexanoic Acid	PFHxA	Perfluoroalkyl carboxylic acids	6
Perfluoroheptanoic Acid	PFHpA	Perfluoroalkyl carboxylic acids	7
Perfluorooctanoic Acid	PFOA	Perfluoroalkyl carboxylic acids	8
Perfluorononanoic Acid	PFNA	Perfluoroalkyl carboxylic acids	9
Perfluorodecanoic Acid	PFDA	Perfluoroalkyl carboxylic acids	10
Perfluoroundecanoic Acid	PFUnA	Perfluoroalkyl carboxylic acids	11
Perfluorododecanoic Acid	PFDoA	Perfluoroalkyl carboxylic acids	12
Perfluorotridecanoic Acid	PFTrDA	Perfluoroalkyl carboxylic acids	13
Perfluorotetradecanoic Acid	PFTeDA	Perfluoroalkyl carboxylic acids	14
Perfluorobutane Sulfonic Acid	PFBS	Perfluoroalkane sulfonic acids	4
Perfluoropentane Sulfonic Acid	PFPeS	Perfluoroalkane sulfonic acids	5
Perfluorohexane Sulfonic Acid	PFHxS	Perfluoroalkane sulfonic acids	6
Perfluoroheptane Sulfonic Acid	PFHpS	Perfluoroalkane sulfonic acids	7
Perfluorooctane Sulfonic Acid	PFOS	Perfluoroalkane sulfonic acids	8
Perfluorononane Sulfonic Acid	PFNS	Perfluoroalkane sulfonic acids	9
Perfluorodecane Sulfonic Acid	PFDS	Perfluoroalkane sulfonic acids	10
N-Methyl Perfluorooctanesulfonamidoacetic Acid	NMeFOSAA	Perfluorooctane sulfonamidoacetic acids	11
N-Ethyl Perfluorooctanesulfonamidoacetic Acid	NEtFOSAA	Perfluorooctane sulfonamidoacetic acids	12
Perfluorooctane Sulfonamide	PFOSA	Perfluoroalkane sulfonamides	8
Perfluoroalkyl ether carboxylic acid	GenX	Per- and Polyfluoroether carboxylic acids	6

Precursors

Terminal Perfluoroalkyl carboxylic acids (PFCAs)
Decreasing Mobility

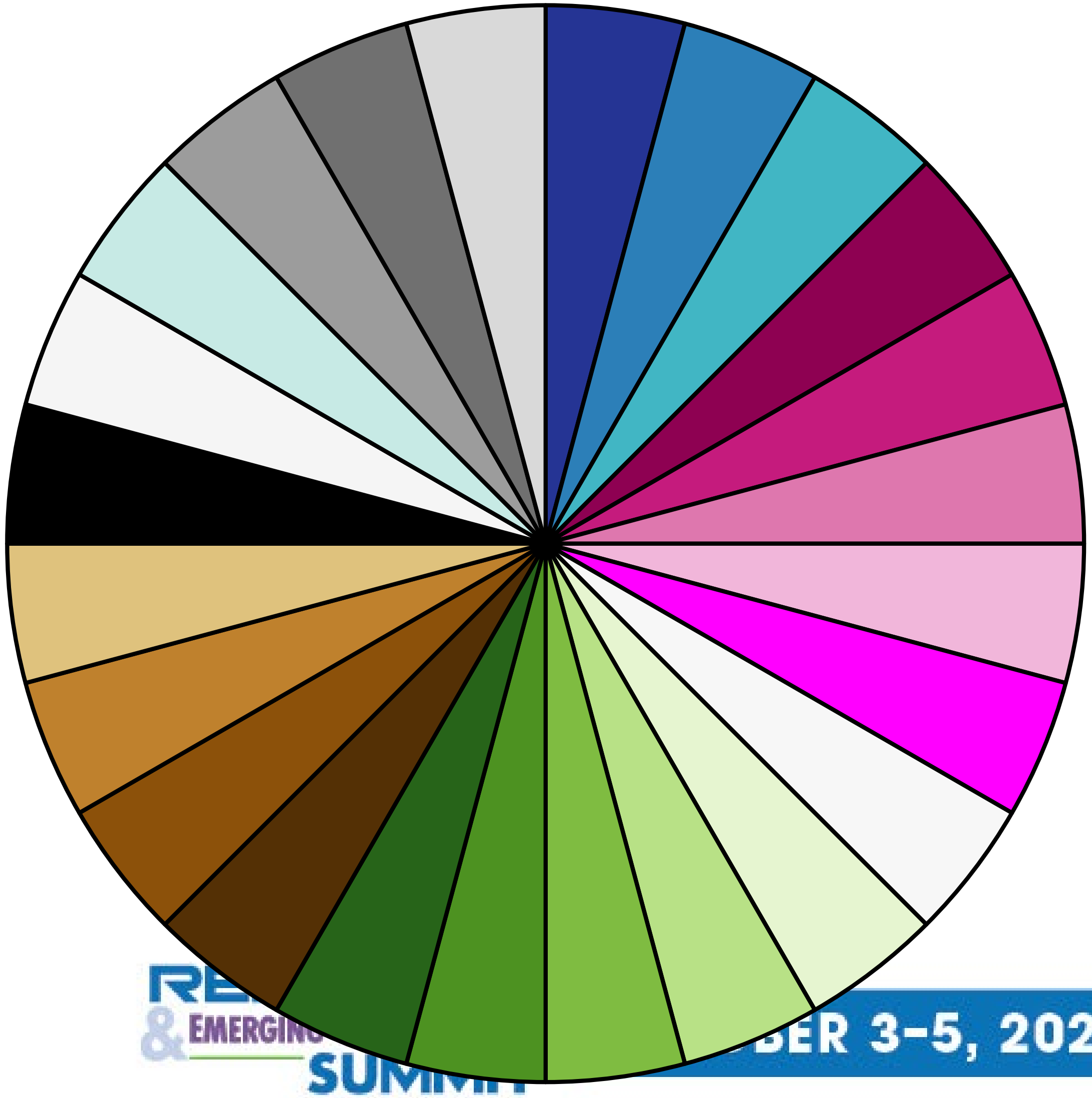
Terminal Perfluoroalkane sulfonic acids (PFSAs)
Decreasing Mobility

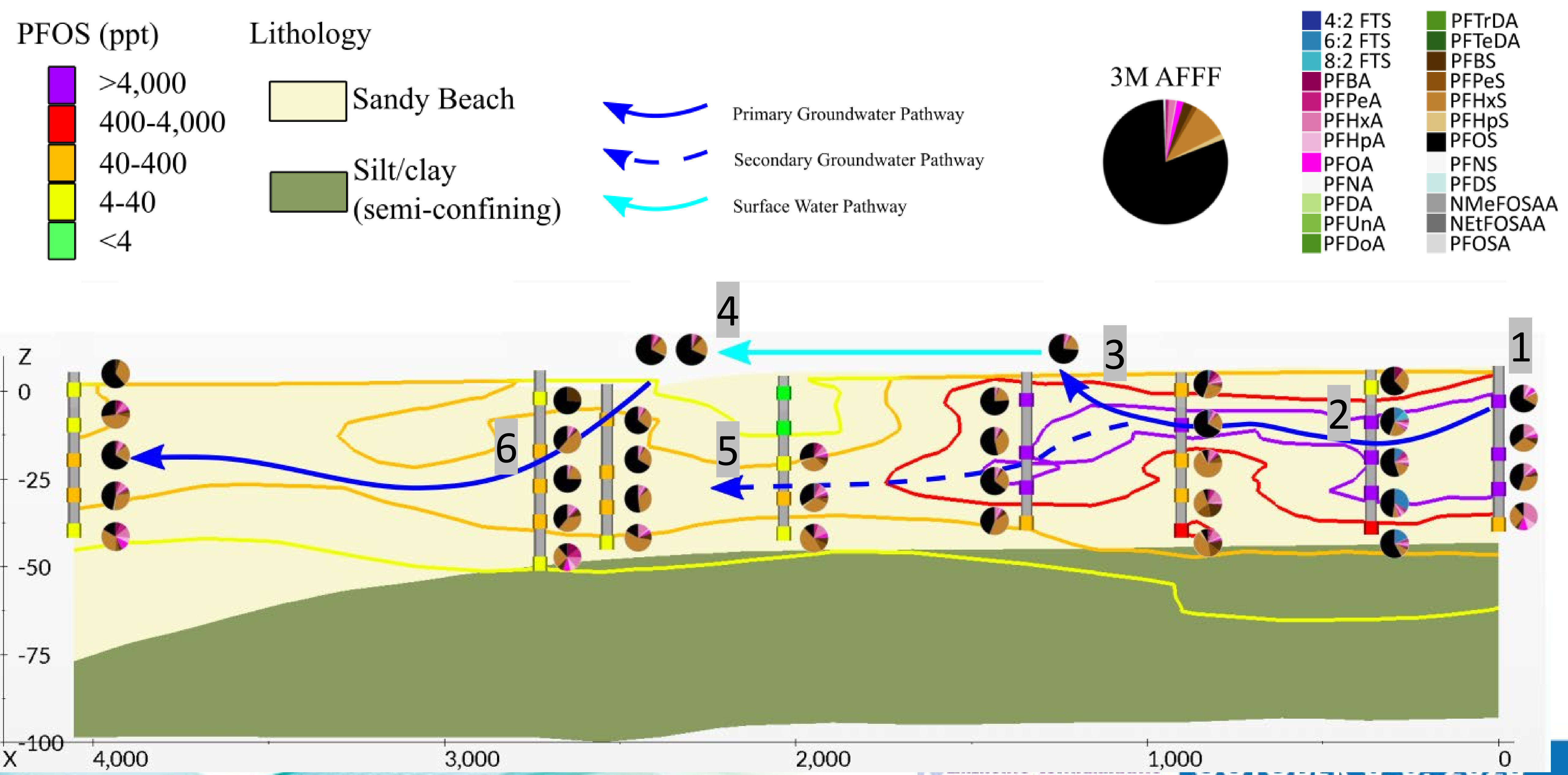
Precursors

Altered to Highlight PFOS/PFOA

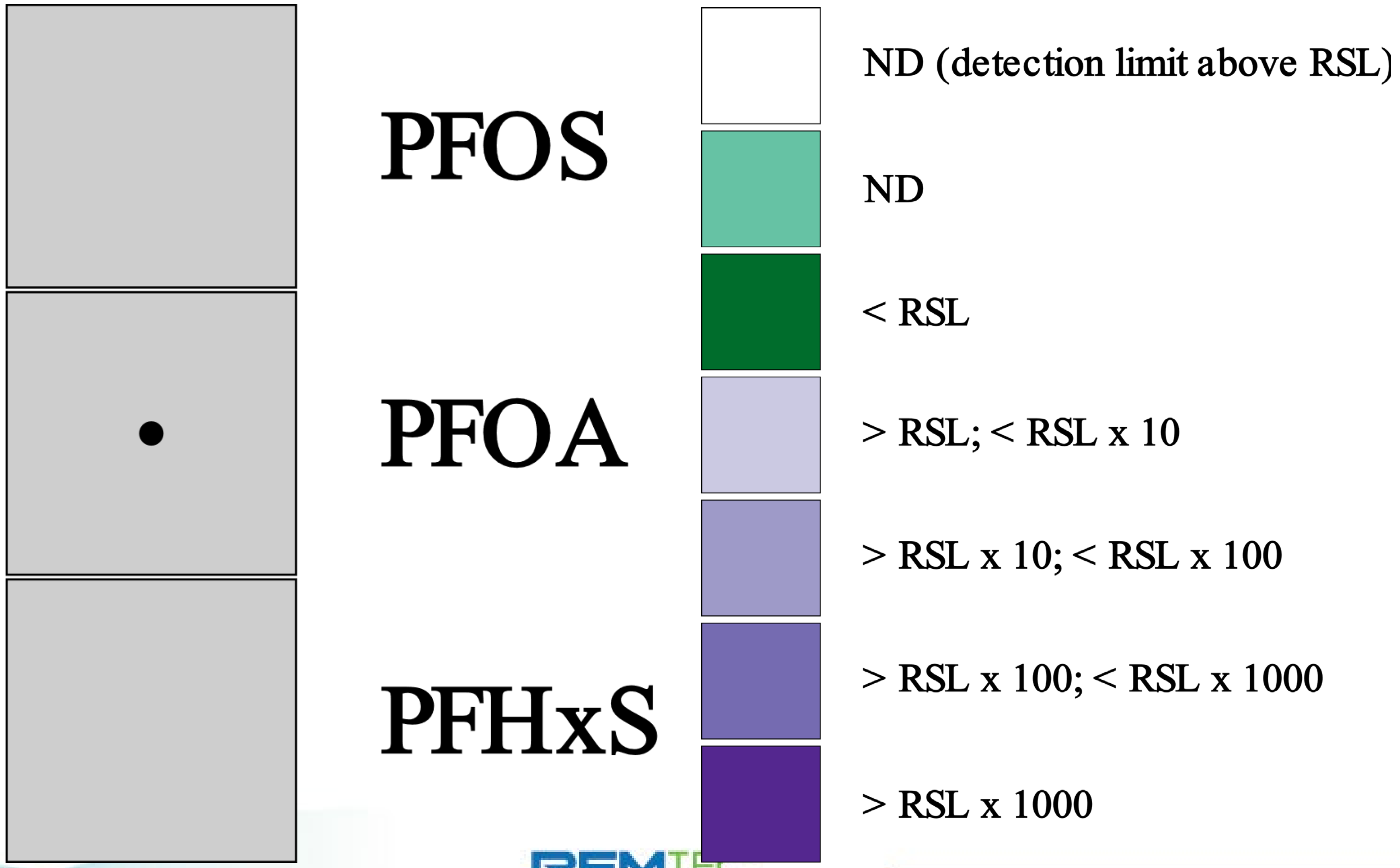
FLAVOR #2

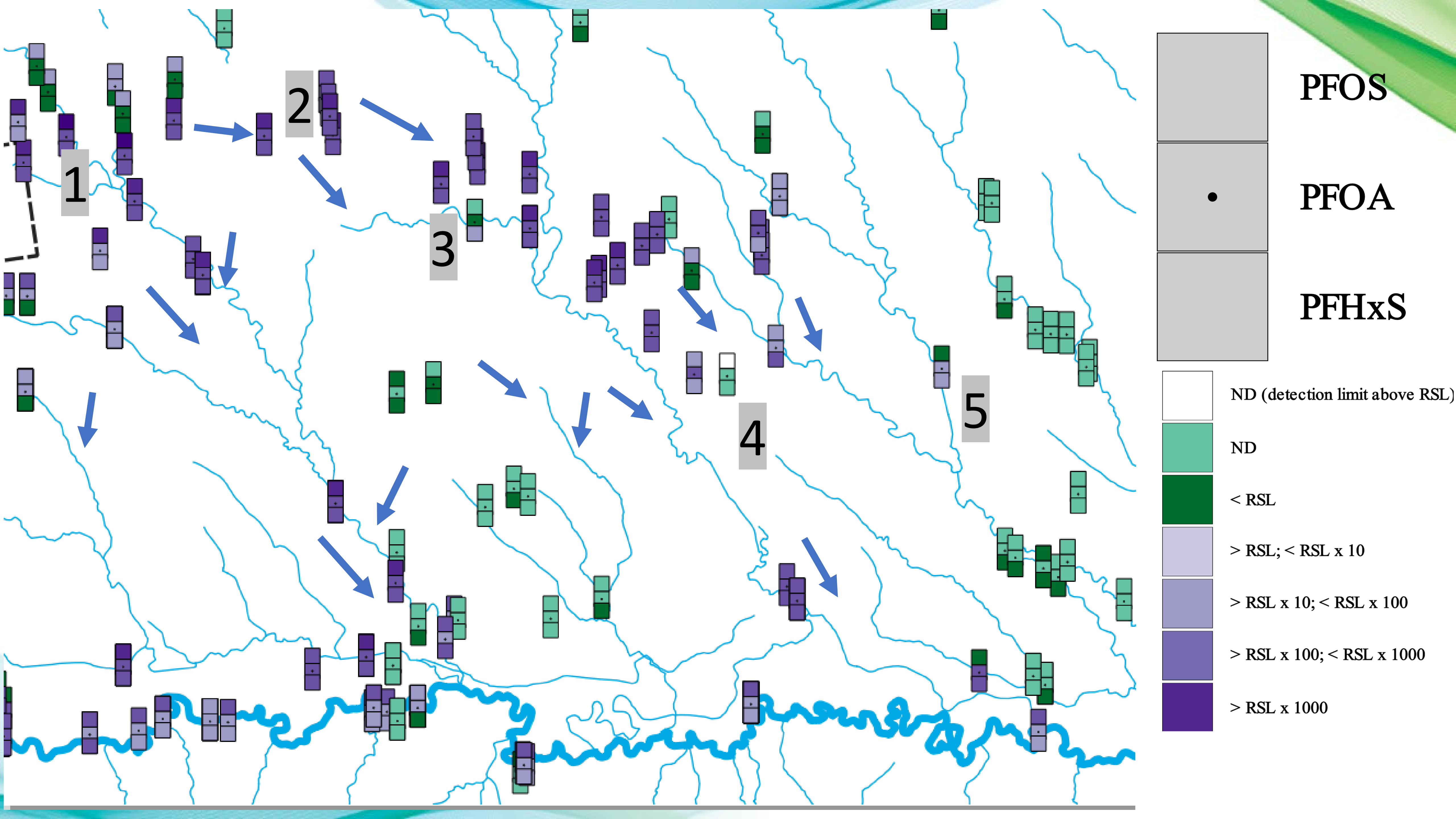
4:2 FTS	
6:2 FTS	
8:2 FTS	
PFBA	PFBS
PFPeA	PFPeS
PFHxA	PFHxS
PFHpA	PFHpS
PFOA	PFOS
PFNA	PFNS
PFDA	PFDS
PFUnA	NMeFOSAA
PFDoA	NEtFOSAA
PFTrDA	PFOSA
PFTeDA	GenX




PFOS (ppt)
>4,000
400-4,000
40-400
4-40
<4
Lithology
Sandy Beach
Silt/clay (semi-confining)
Primary Groundwater Pathway
Secondary Groundwater Pathway
Surface Water Pathway
3M AFFF
4:2 FTS
6:2 FTS
8:2 FTS
PFBA
PFPeA
PFHxA
PFHpA
PFOA
PFNA
PFDA
PFUnA
PFDoA
PFTrDA
PFTeDA
PFBS
PFPeS
PFHxS
PFHpS
PFOS
PFNS
PFDS
NMeFOSAA
NEtFOSAA
PFOSA
1
2
3
4
5
6
Z
0
-25
-50
-75
-100
X
4,000
3,000
2,000
1,000
0

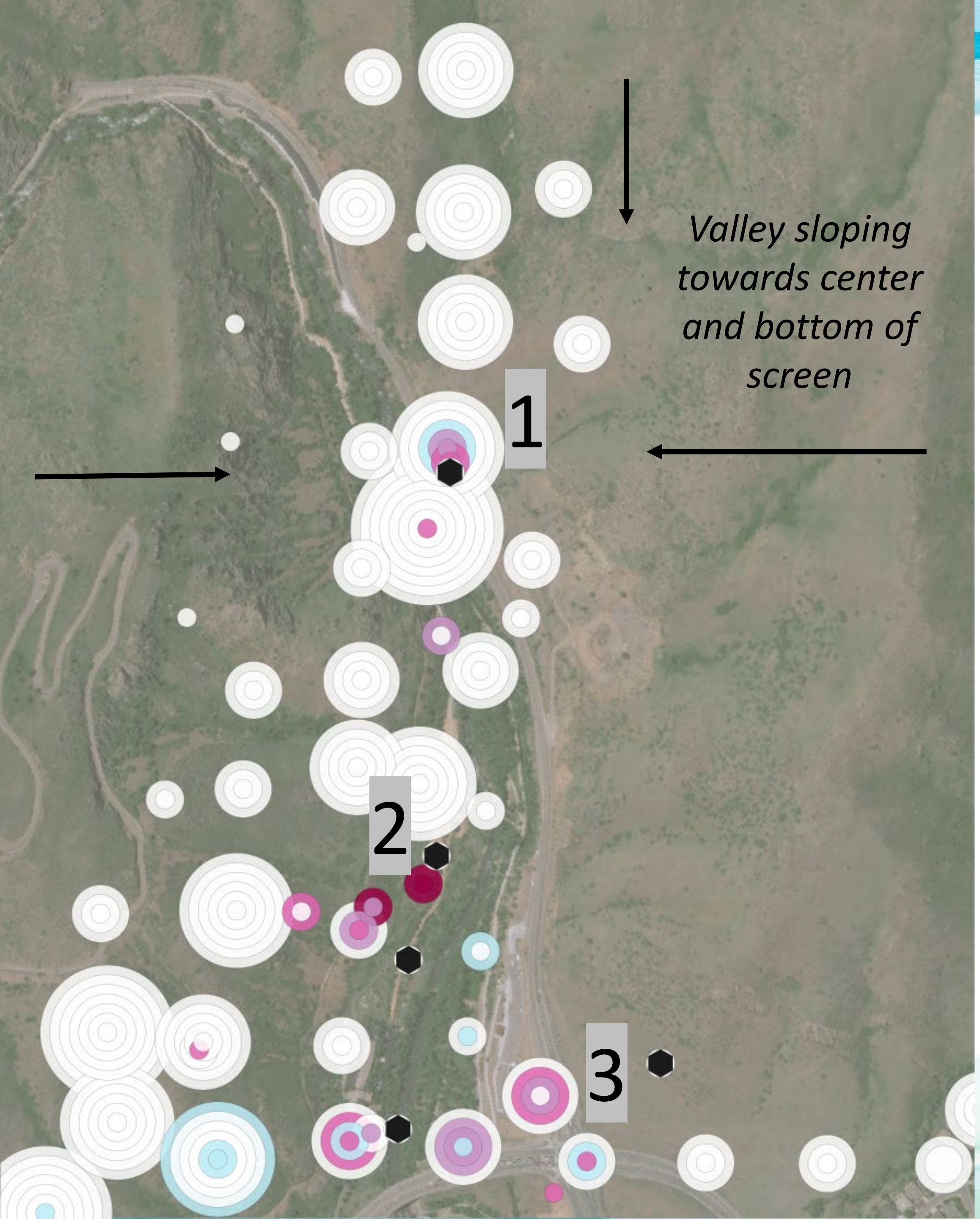
Position | Color




1
2
3
4
5
PFOS
PFOA
PFHxS
ND (detection limit above RSL)
ND
< RSL
> RSL; < RSL x 10
> RSL x 10; < RSL x 100
> RSL x 100; < RSL x 1000
> RSL x 1000

Concentric circles - PFAS at depth at approximately 5-ft intervals - innermost is shallowest; outermost is deepest - White areas - cleaner; redder areas - more impacted

<1/2 RSL	2x RSL - 5x RSL
1/2 RSL - RSL	5x RSL - 10x RSL
RSL - 2x RSL	>10x RSL



AFFF Release Area

Concentric circles - PFAS at depth at approximately 5-ft intervals - innermost is shallowest; outermost is deepest - White areas - cleaner; redder areas - more impacted

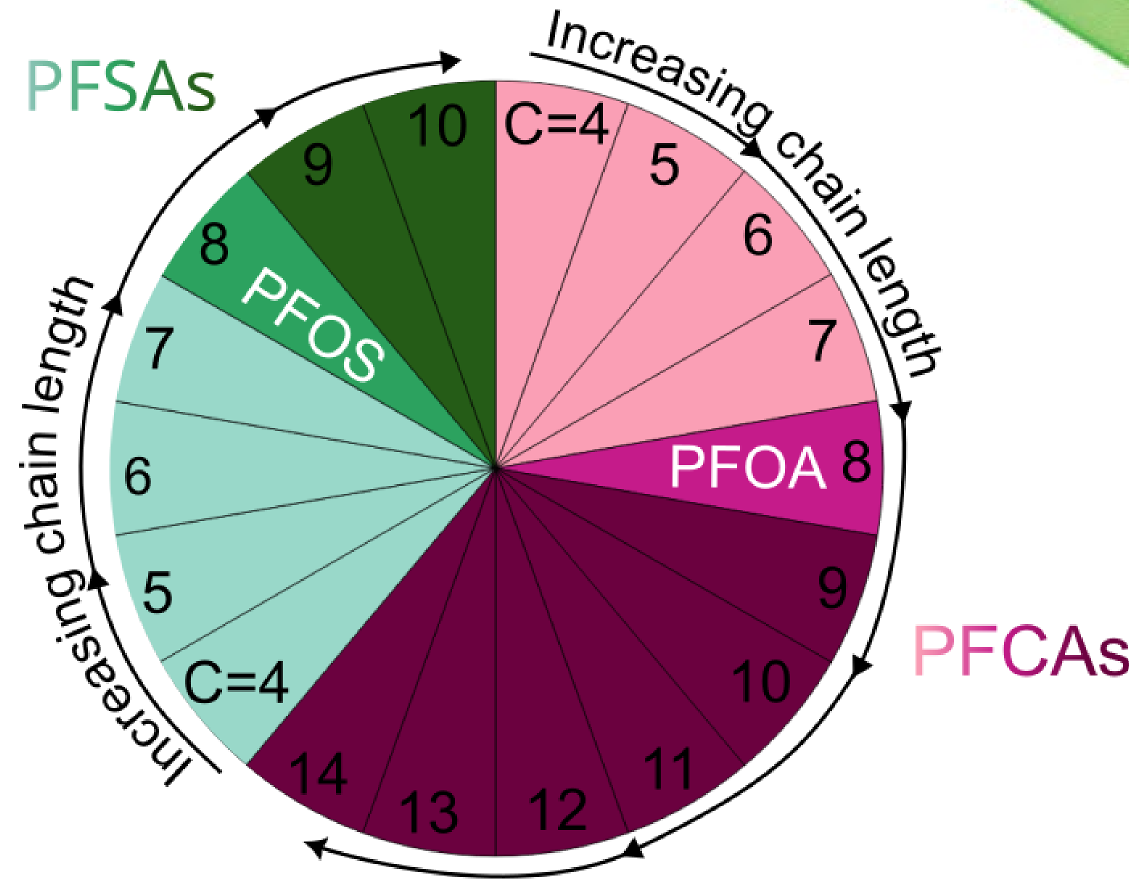
<1/2 RSL
1/2 RSL - RSL
RSL - 2x RSL
2x RSL - 5x RSL
5x RSL - 10x RSL
>10x RSL

WHY THIS WORKS:

PFOS in soil is the highest PFAS relative to the respective RSL at all locations, so we focus exclusively on a single analyte.

Conclusions

- Characterizing PFAS contamination is complex, with constantly changing targets.
- We highlighted ways to look at the whole suite of data, a trio of analytes, and just PFOS.
- Our figures should consider transmitting knowledge—not just data.
- No one approach will be sufficient, but many complementary approaches can be extremely valuable.



Questions?

Dr. Ryan David Swanson
rswanson@hgl.com

PFAS Response

HGL

Restoring the Environment.
Protecting Our Future.