Practical Applications of Lysimeters within a Regulatory Framework and Lessons Learned

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Outline

- Porous Cup Suction Lysimeters – the Basics
- Practical Applications
- Lysimeters within a Regulatory Framework
- Construction & Installation
- Lessons Learned

An Introduction to Lysimetry

What is a lysimeter?

What is a lysimeter used for?

1. A **scientific instrument** used to measure and collect water that moves through unsaturated soil

2. Provides **quantifiable data** for components of the water cycle

3. Used in **agriculture** to optimize irrigation and nutrient management, in **environmental monitoring** to track pollutant movement, and in **hydrological studies** to improve water resource management

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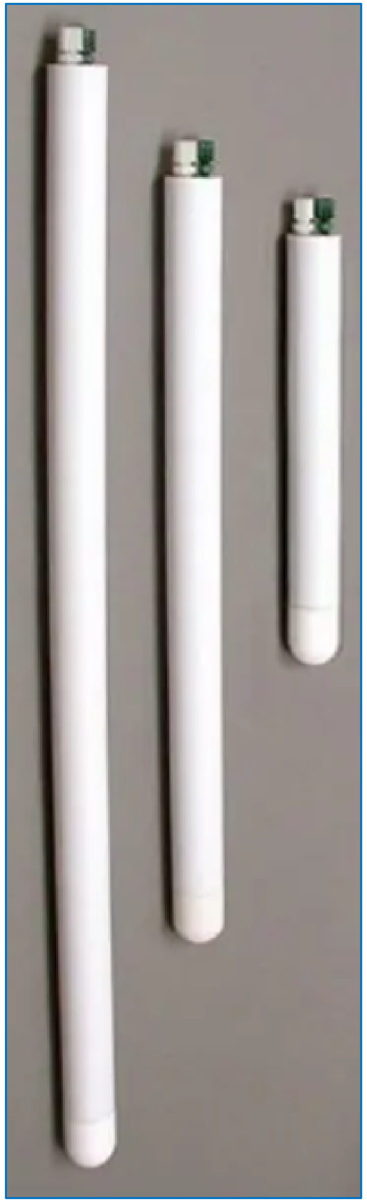
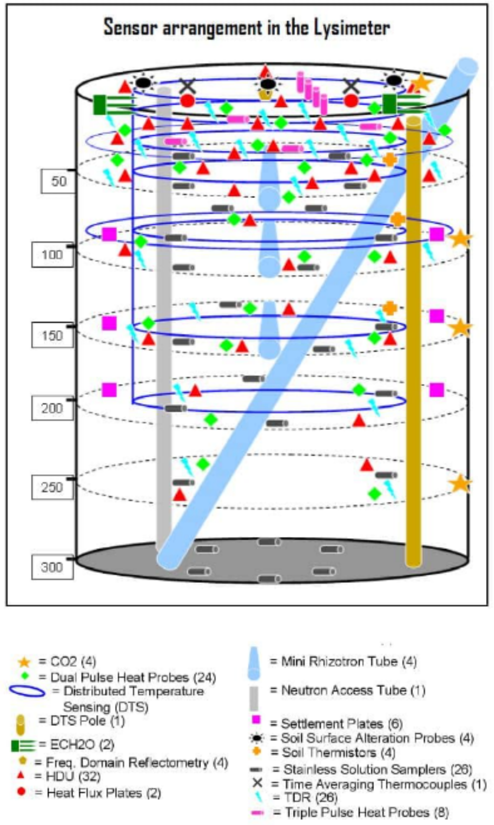
Types of Lysimeters



Top Left: Wick Lysimeter (fixed tension lysimeter), Edaphic Scientific, Edaphic.com.au

Bottom Left: Weighing Lysimeter (non-field variety), Edaphic Scientific, Edaphic.com.au

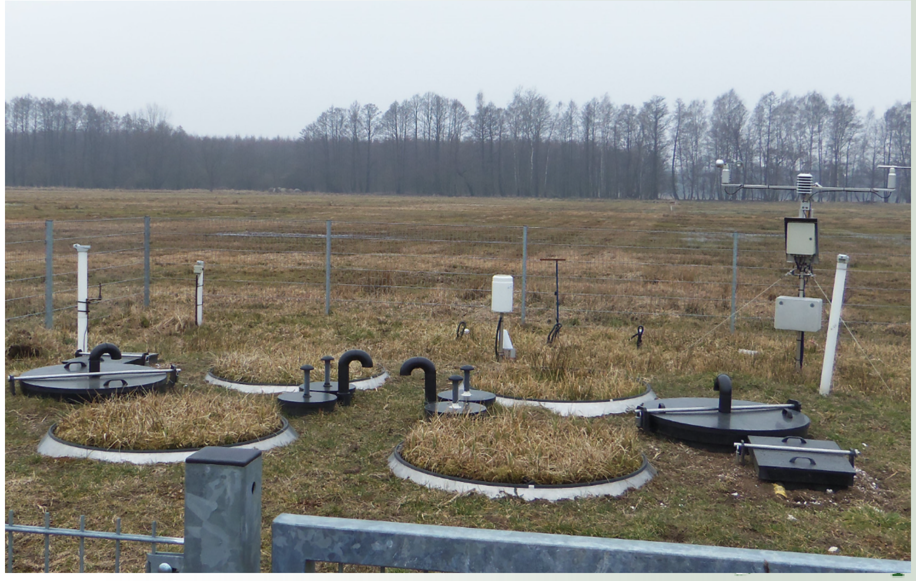
Right: Porous Cup Suction Lysimeters (porewater samplers), Soil Moisture Equipment Corp, Soilmoisture.com



Above: Internal sensors within SEPHAS field weighing lysimeters, SEPHAS Lysimeter Facility, Desert Research Institute, DRI.edu

Top Right: Field Weighing Lysimeters, SEPHAS Lysimeter Facility, Desert Research Institute, DRI.edu

Bottom Right: Lysimeter Station (field lysimeters), Hoskin Scientific, Hoskin.ca



Porous Cup Suction Lysimeters

Image: Soil Moisture Corporation

Used to:

- Collect water from the pore space of unsaturated soils
- Determine the soluble constituents removed in gravity drainage

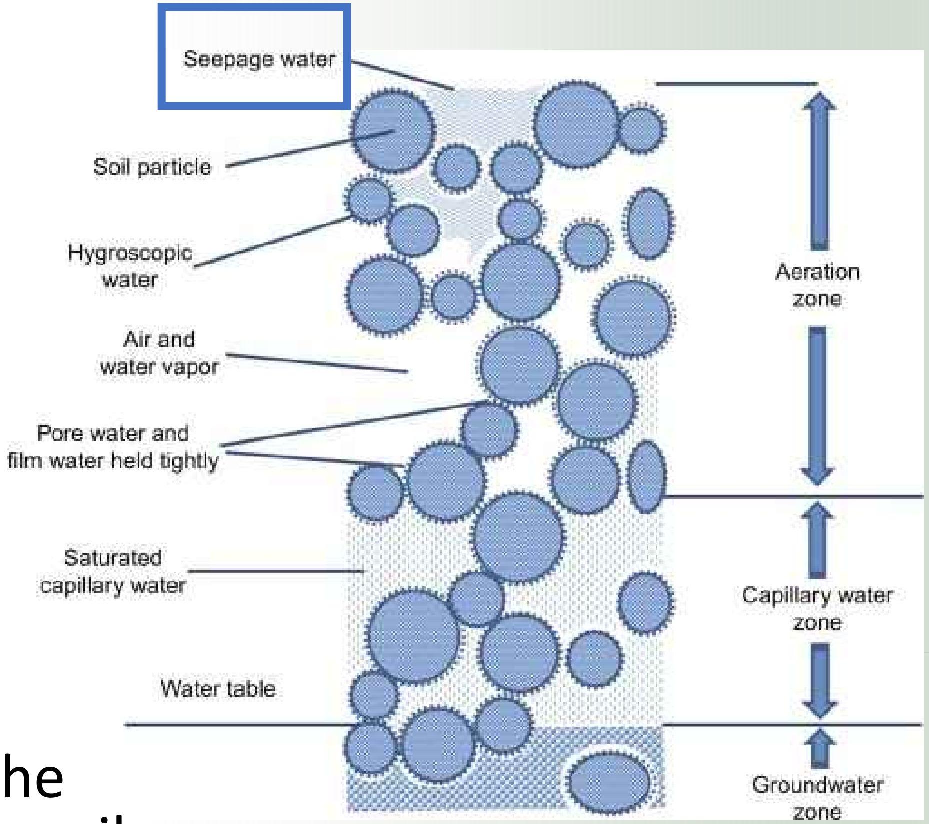
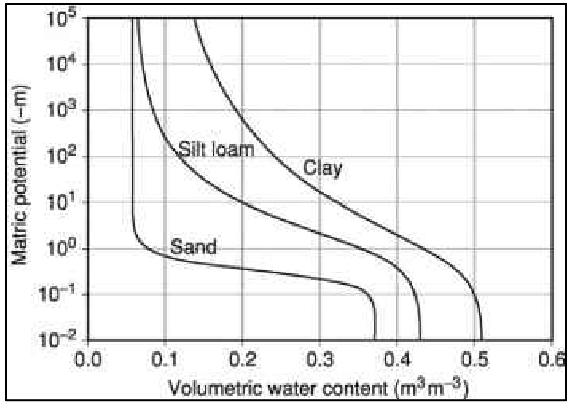


Image: Bonito et al. 2018 Environmental Geochemistry: Chapter 10 Site Characterization, Data Analysis and Case Histories



Graph: Tuller & Or 2005

A **suction lysimeter** allows for the application of a vacuum to draw soil moisture from pore space and into a reservoir for sample collection

Application of a vacuum is not vacuum enhanced sampling

Practical Applications

1. Direct measurement of porewater – assess wider range of interaction between contaminants and soil components

2. Source strength determination – continuing contributions to the groundwater plume

3. Mass flux / mass discharge evaluations for fate and transport understanding

4. Risk assessment and course of action determination

Source strength evaluation: Where is the risk?

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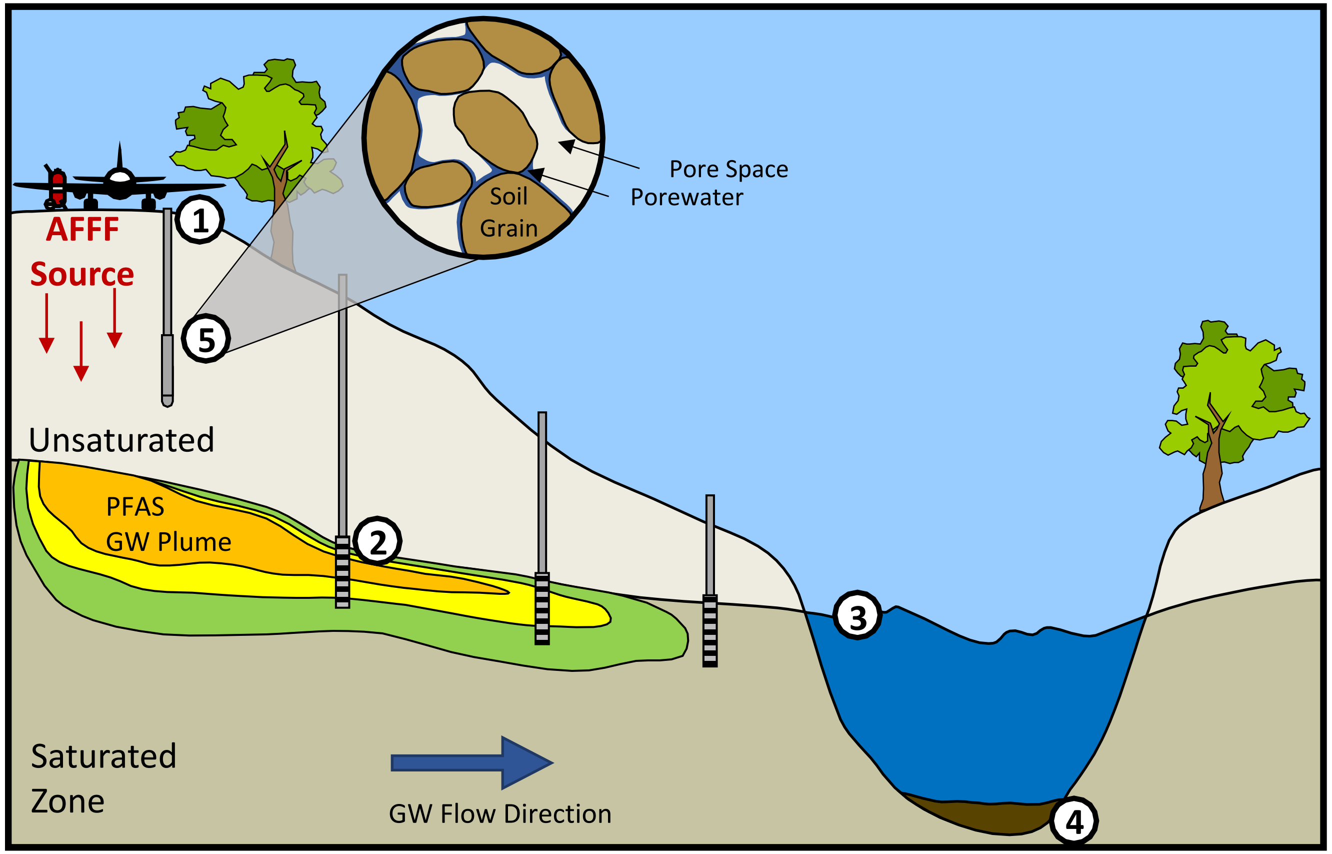
Practical Applications at AFFF-Impacted Sites



AFFF Source Impacted Soils

How do we bridge this gap?

?

Where should remediation efforts be focused?

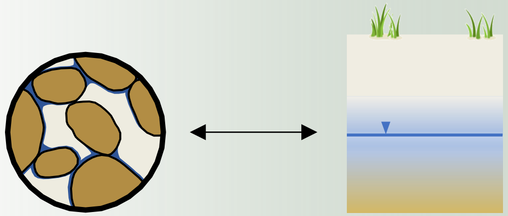
Impacted Groundwater above PSLs

Practical Applications

What is the soil concentration needed to produce an exceedance in groundwater above project screening levels?

Intermediate Steps:

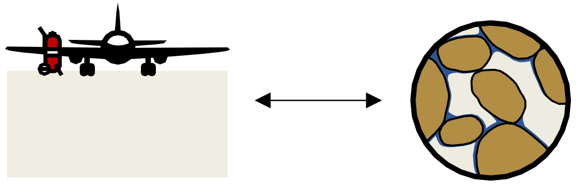
1. What porewater concentration will result in groundwater concentrations above PSLs?



Use a Dilution Attenuation Factor (DAF) to compare porewater concentrations to groundwater concentrations

- Empirical estimate or derived from CSM information (calculations)

2. What soil concentration will result in porewater concentrations above that threshold?



DAF & Porewater_{PAL}

Bringing together Porewater & Groundwater

$\text{Porewater}_{PAL} = \text{Groundwater}_{PAL} \times \text{DAF}$

$$DAF = 1 + \left[\frac{K \cdot i \cdot d}{I \cdot L}\right] \quad d = (0.0112 \cdot L^2)^{0.5} + d_a\left(1 - e^{-L \cdot I / K \cdot i \cdot d_a}\right)$$

PAL	Project Action Level
K	Hydraulic Conductivity
i	Hydraulic Gradient
d	Mixing Zone Depth
I	Recharge Rate
L	Groundwater Plume Length
d_a	Saturated Plume Thickness

High quality conceptual site models and supplemental sampling support the determination of site-specific dilution attenuation factors

Anderson, R. H., Environ. Sci. Technol. 2021, 55, 6580-6583

Threshold Soil Concentrations

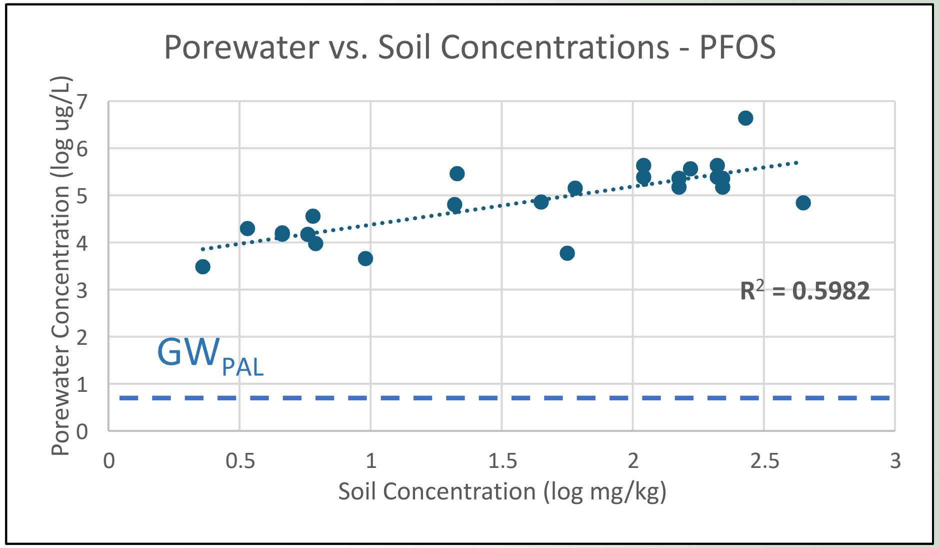
Bringing together soil & porewater

What soil concentration will result in porewater concentrations above the Porewater_{PAL}?

- Empirical estimate from log/log relationships between porewater and co-located soil samples

$\log(PW_{PAL}) = 0.81\mathbf{x} + 3.6$ $\quad\quad x = \log(C_{soil\ mg/kg})$

- Or calculate based on soil-water partition coefficient (K_d) and air water interfacial component



$$SSL^{Rev} = C_{soil} = C_{gw} \times DAF \times [K_d + (K_{aw}a_{aw} + \theta_w + \theta_a H)\frac{1}{\rho_b}]$$

traditional

Compare site soil concentrations to threshold value for source strength evaluation

EPA Superfund

Soil Screening Guidance: Technical Background Document

soil sample porewater

$$C_T = C_p\left(K_d + \frac{\theta_w}{\rho} + \frac{k_{ia}a_i}{\rho}\right)$$ for PFAS

Equation: Brusseau & Guo, 2023
Supporting PFAS-LEACH, ESTCP ER21-5041

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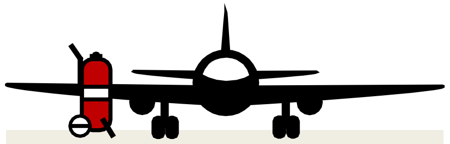
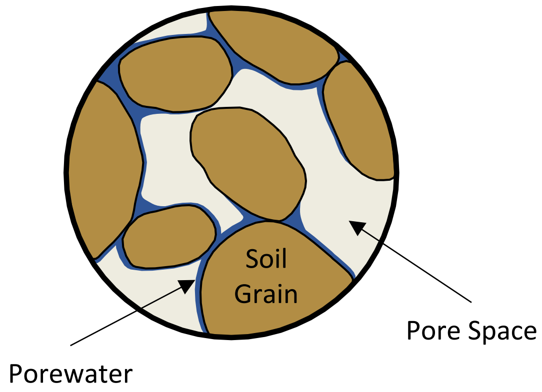
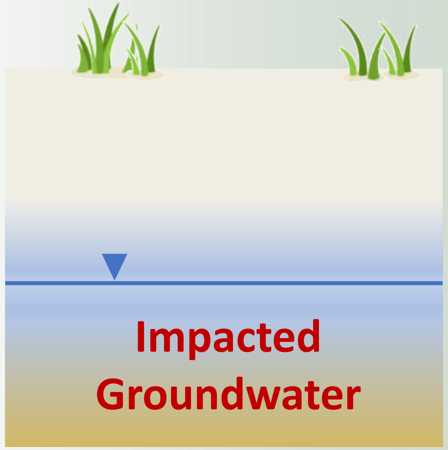
Source Strength Evaluation



AFFF Source Impacted Soils





Soil Threshold Value

Quantitative Model (ex: PFAS-LEACH) for Site-Specific Screening Level

DAF

GW_{PAL}

Site soils > soil threshold value contribute to the GW plume above GW_{PAL} and should be prioritized for remediation

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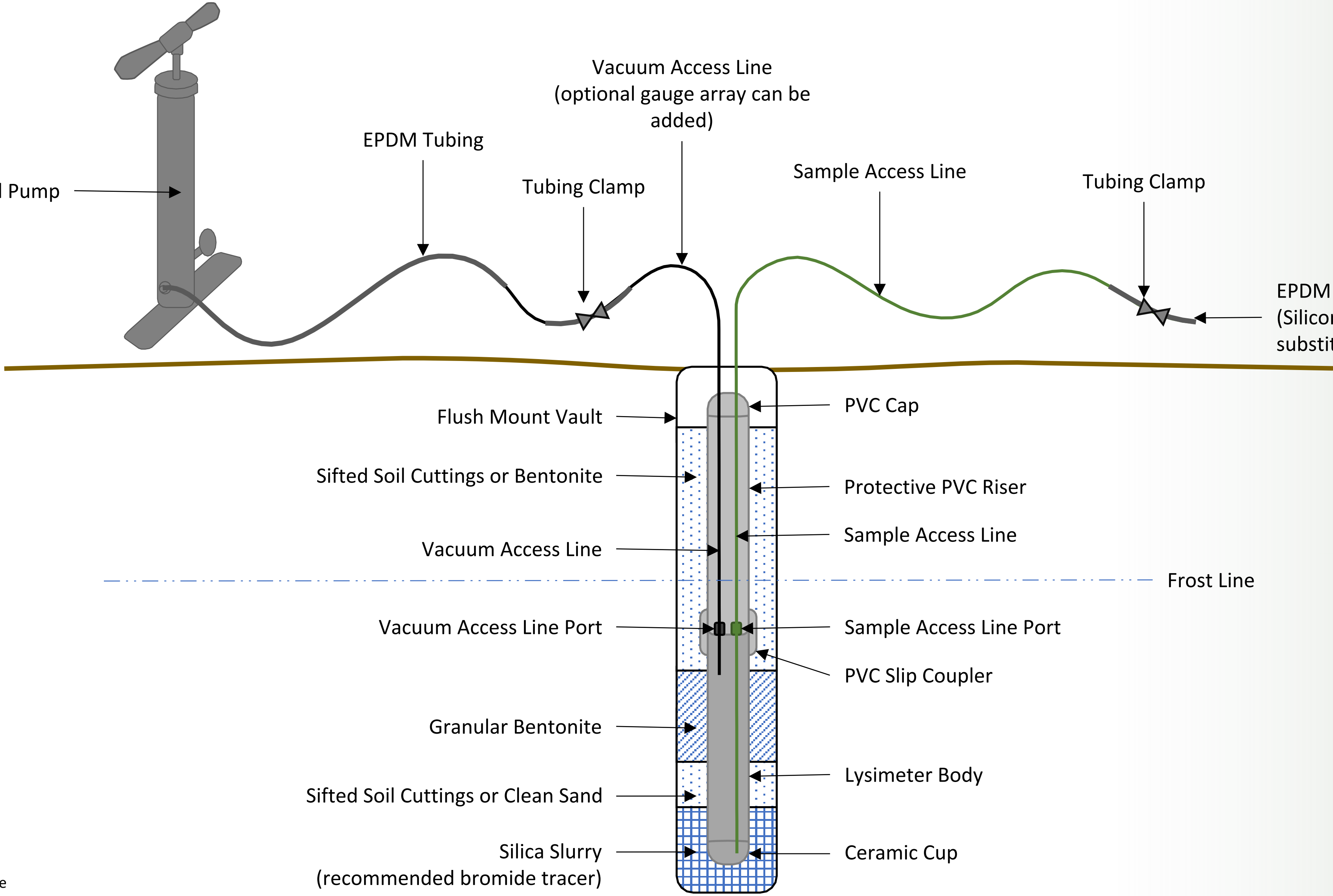
Regulatory Framework

- Fate and transport contaminant pathway evaluation
- Risk evaluation: where is the PFAS?
- Determination of data-driven and site-specific clean up objectives
- Prioritize impacted media for remediation based on source strength
- Determine volume of soil for cleanup to reduce flux to no longer sustain the groundwater plume

Construction

Image: Soil Moisture Corporation



Lysimeter surface completion

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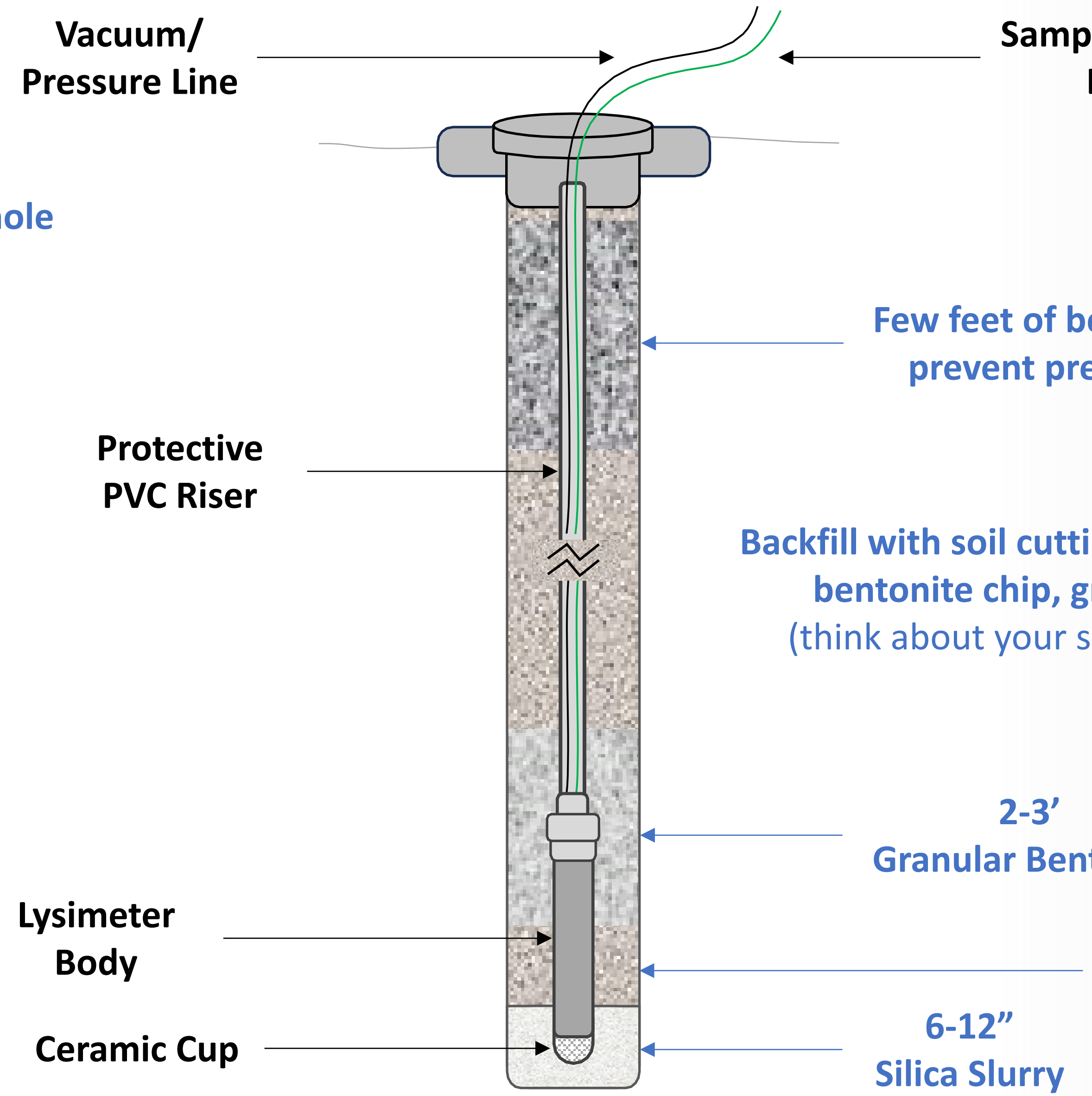
Construction

For 2” lysimeter, optimal borehole diameter is about 4”



Few feet of bentonite at the top to prevent preferential pathways

Backfill with soil cuttings, hydrated bentonite chip, grout, etc.
(think about your site setting)

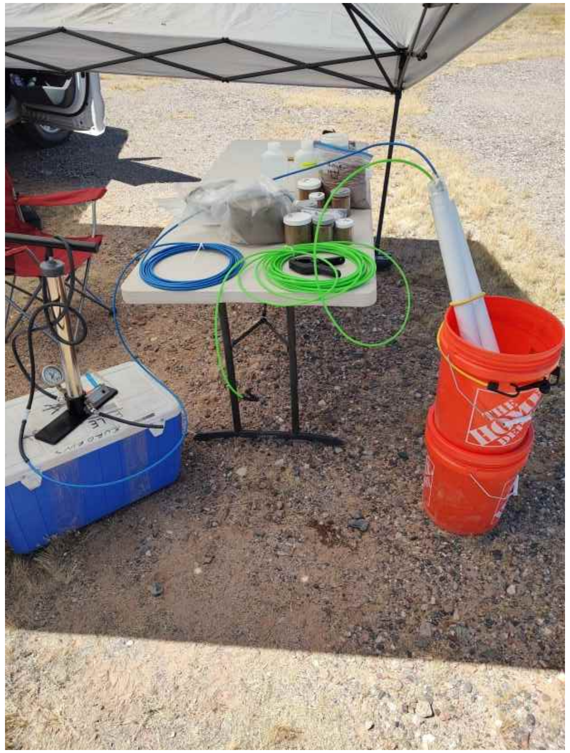
2-3’
Granular Bentonite

Up to 6”
Sand Pack

6-12”
Silica Slurry

What is the path forward for standardization?

Field Installation - Preparation



- Inspect lysimeters for damage and complete vacuum/pressure testing prior to installation

- Proper assembly is key
- Document your installation details

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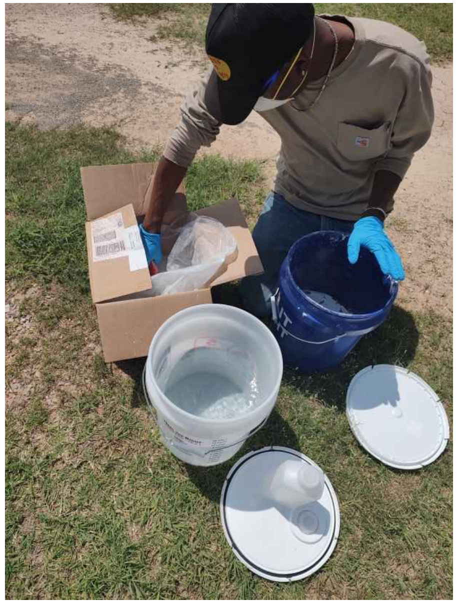
Field Installation – Silica Slurry




- When working around the silica flour (200 mesh), an N95 mask (or more protective) is necessary due to silica hazard.
- Keep the silica flour away from and downwind of your work zone. Stay upwind of the open bag/box as much as possible.
- Thick slurry – like a thick pancake batter, see the “V” running off the gloves.
- Do not mix it until you are ready to use it, it will immediately start to settle. Give it a final stir before you send it down the borehole.
- Recommend using a bromide tracer: (NaBr) about 5 grams in 2 gallons of PFAS-free water; collect a sample for analysis.
- Make sure to let the slurry set up around the ceramic cup, give it at least 45 minutes, then vacuum test before continuing installation

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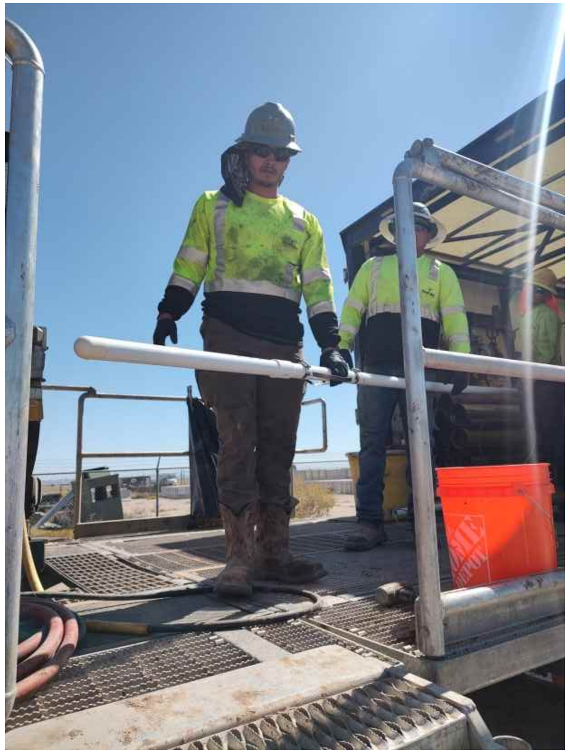
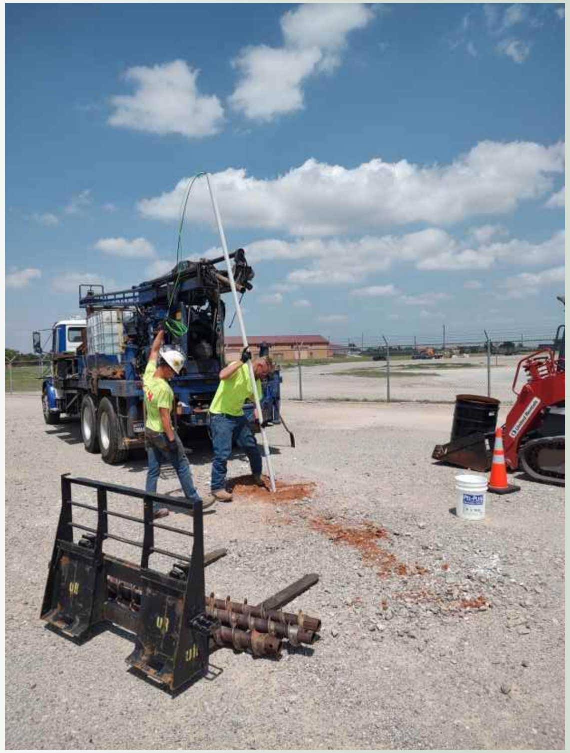
Field Installation



- Supervise and direct subcontractor installation and tasks



- Check the lysimeter holds a vacuum at different installation steps along the way

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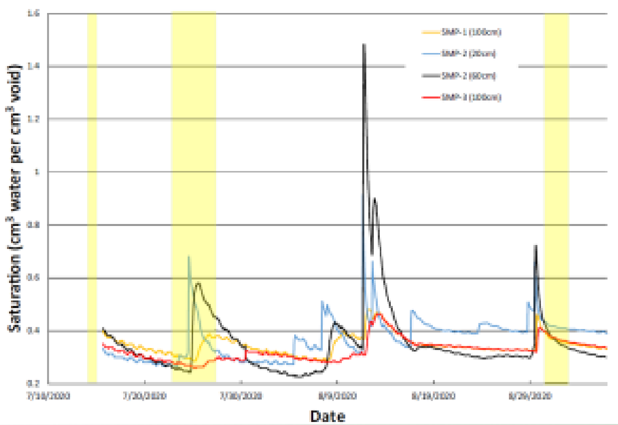
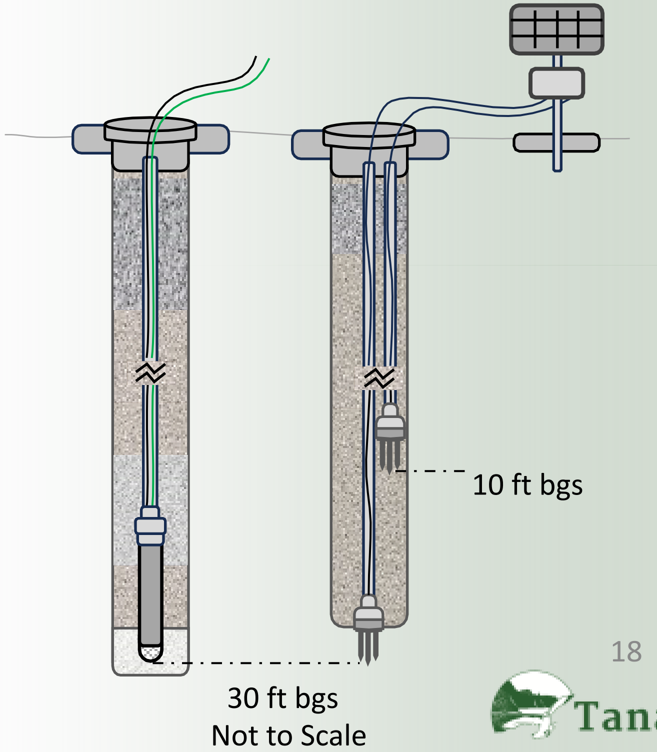
Sampling

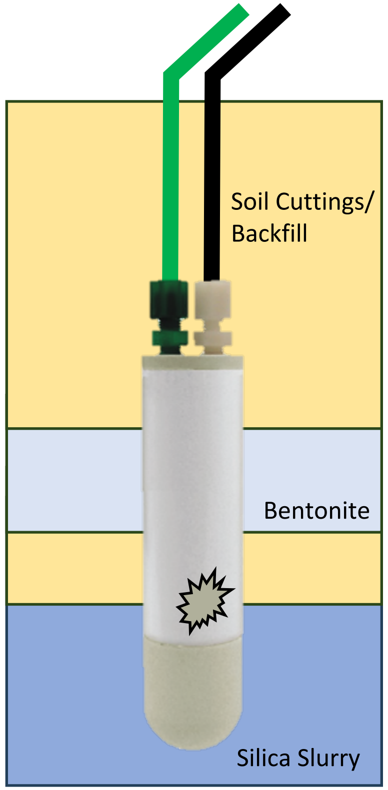
- Sampling events may take days depending on soil moisture content and recent precipitation events
- Low volume samples can be typical – communicate with lab
- Consider paired lysimeters and soil moisture meters
  - Guide sample activities decision making
  - Supports troubleshooting
  - Additional line of evidence for fate and transport evaluation
- Determine location specific vacuum settings based on soil type and/or grain size analysis



Schaefer et al., *JCH*, 2022



Lessons Learned – Common Mistakes



- No vacuum/pressure testing completed prior to installation
- Installed too shallow – connection ports above the frost line
- No protective casing over access tubing – physical damage to tubing
- Ceramic cup not fully set in the silica slurry
- Tubing not completely connected to the ports
- Cracked ceramic cup or other damage

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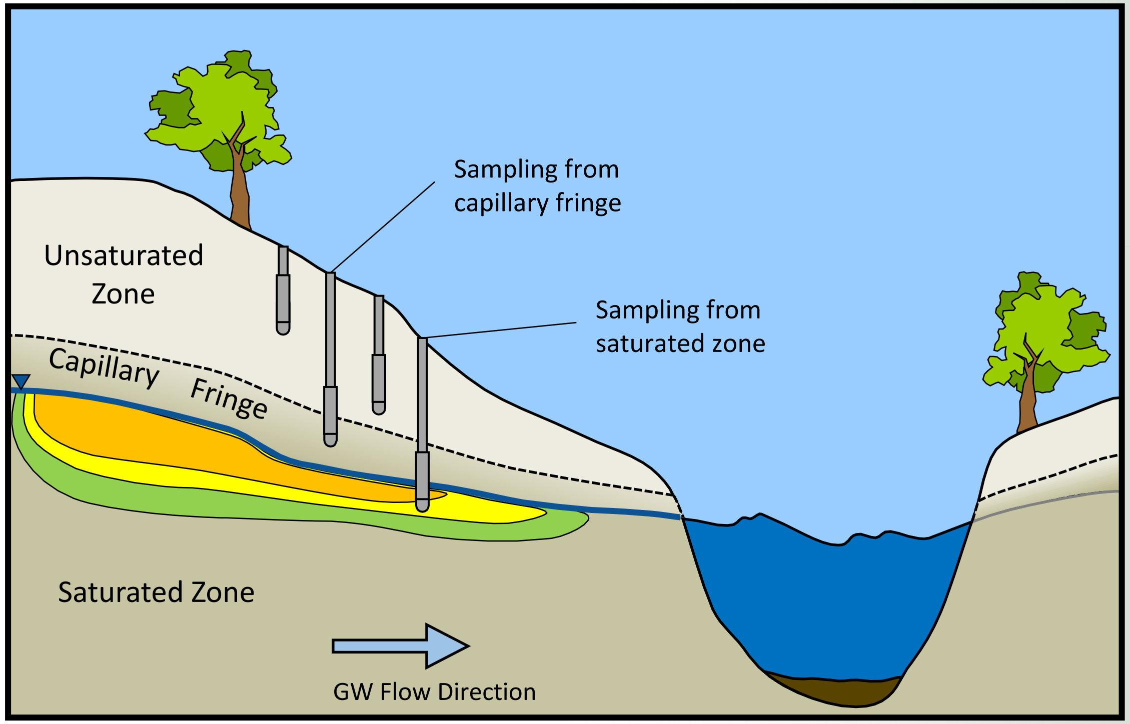
Lessons Learned - Installation

- Handle with care
- Test, test, and test again – if it doesn’t hold a vacuum now, it never will
  - Pre-installation vacuum & pressure testing
  - Vacuum testing after installation in silica slurry
  - Vacuum testing after finished installation
  - Complete vacuum testing at multiple vacuum settings
- Allow the silica slurry to set up around the ceramic cup before vacuum testing and continuing with installation (>45 minutes)
- Use centralizers for deeper installations (>25 ft bgs)

Lessons Learned

- Understand site conditions and project objectives prior to installation
  - How do subsurface structures impact lysimeter placement?
  - What evidence of the capillary fringe has been observed?
- Stick to a "standard," but allow room for professional judgement; think about gravity drainage
- Supplemental sampling is important
  - Soil: % moisture, grain size, pH, TOC, AEC/CEC
  - Porewater: bromide, anions, pH, TOC(DOC)



Lessons Learned – Training Matters

Proper training is important.

If you don't know, ask!

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ELSEVIER

Review

Evapotranspiration information reporting: I. Factors governing measurement accuracy

Richard G. Allen[a,*], Luis S. Pereira[b], Terry A. Howell[c], Marvin E. Jensen[d]

Table 2
Error, expressed as one standard deviation from the true mean value, expected for various types of ET measurement or retrieval systems.

Method	Typical error, %	Error for an experienced expert, trained and steeped in the physics of the process, %	Error for a novice or a person working outside their specialty area, %	Additional error caused by physical or equipment malfunction, %
Lysimeter	5–15	5	20–40	5–40
Soil water balance	10–30	10	20–70	10–40
Bowen ratio	10–20	10	20–50	5–40
Eddy covariance	15–30	10–15	30–50	10–40
Remote sensing energy balance	10–20	5–15	30–40	5–10
Remote sensing using vegetation indices	15–40	10–30	20–40	5–10
Sap flow	15–50	10–40	40–200	20–100
Scintillometers[a]	10–35	10–15	20–50	5–30

[a] Scintillometers measure sensible heat flux, only, and require estimating ET as a residual of the energy balance ($\lambda E = R_n - G - H$).

Stay engaged with subcontractors and field staff

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Key Points

- Use porous cup suction lysimeters for source strength evaluation and to answer: "where is the PFAS?"
- Thorough site characterization is key to utilizing porewater data. Understand where the lysimeters are being installed, what is being sampled, and why.
- Increased standardization is needed for lysimeter installation and operation; professional judgement is still necessary.
- Proper field techniques are crucial to accurate installation and operation.
- Think through project objectives when determining lysimeter details:
  - Installation depth, sampling frequency, sample analyses, dynamic hydraulics, soil horizons, etc.

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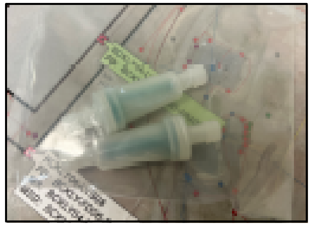
Patrick Curry, Erika Carter, and Jay Erikson

Questions?

Additional Information

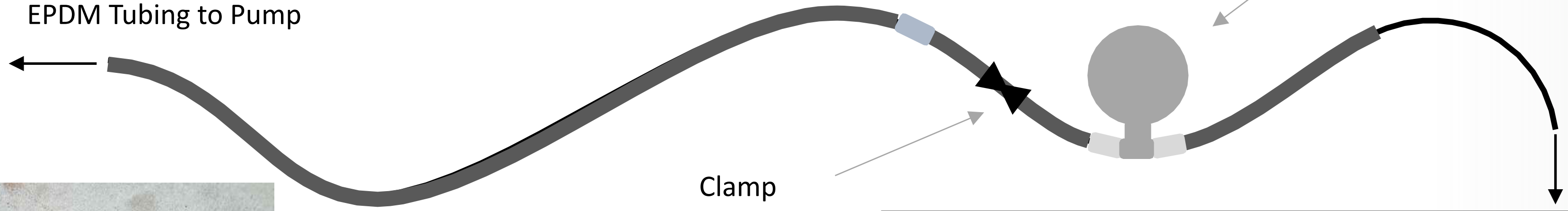
Sampling Tips

One-way filter prevents damage to pump from any soils in tubing

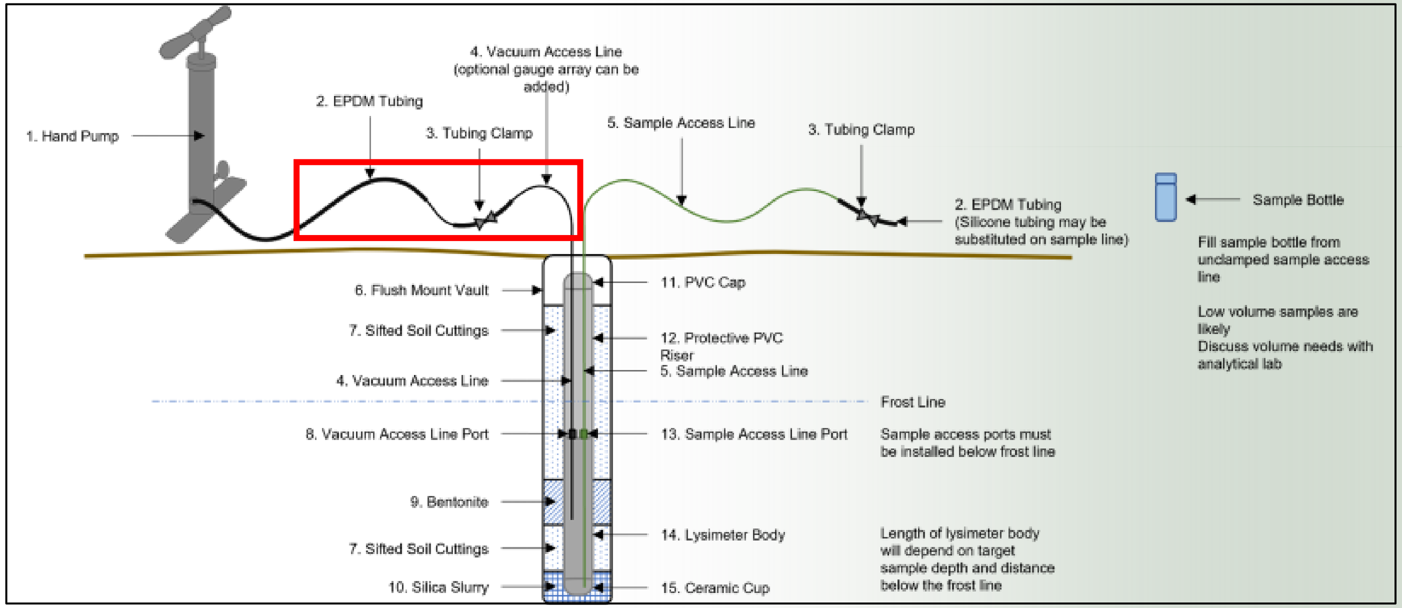


One-Way Filter

In-Line Gauge



In-line gauge provides visual guidance for when to sample or reset vacuum; aid for lysimeter evaluation if necessary



DAF & $Porewater_{PAL}$

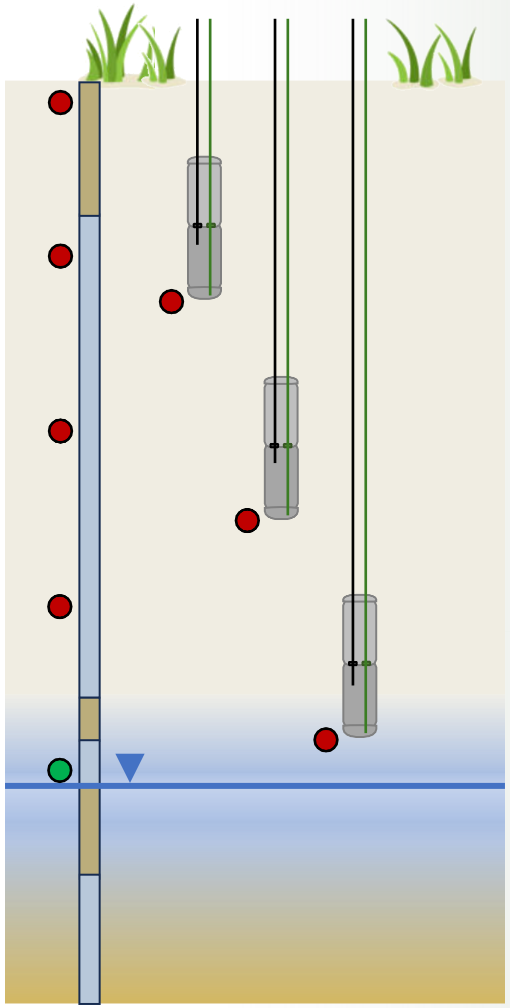
$Porewater_{PAL}$ = $Groundwater_{PAL}$ x DAF

$$DAF = 1 + \left[\frac{K \cdot i \cdot d}{I \cdot L}\right] \quad d = (0.0112 \cdot L^2)^{0.5} + d_a\left(1 - e^{-L \cdot I / K \cdot i \cdot d_a}\right)$$

CSM Derived Site-Specific DAF - PFOS		
GW_{PAL}	GW Project Action Level	4 ng/L
K	Hydraulic Conductivity	0.9 m/day
i	Hydraulic Gradient	0.005
d	Mixing Zone Depth	116 m
I	Recharge Rate	0.0004 m/day
L	Groundwater Plume Length	1000 m
d_a	Saturated Plume Thickness	10 m

DAF = 2.3

$Porewater_{PAL}$ = 9.2



SB03002 PFOS Soil Results	
Surface	1,100 mg/kg
4 ft	4,800 mg/kg
8 ft	1,600 mg/kg
12 ft	290 mg/kg
16 ft	4.6 mg/kg

LS03001 PFOS Results – 5 ft bgs		
Soil Sample		3,500 mg/kg
Porewater	Jan 2024	230,000 ng/L
	Apr 2024	210,000 ng/L

LS03002 PFOS Results – 10 ft bgs		
Soil Sample		320 mg/kg
Porewater	Jan 2024	27,000 ng/L
	Apr 2024	24,000 ng/L

LS03003 PFOS Results – 15 ft bgs		
Soil Sample		92 mg/kg
Porewater	Jan 2024	16,000 ng/L
	Apr 2024	15,000 ng/L

Anderson, R. H., Environ. Sci. Technol. 2021, 55, 6580-6583

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