Starting Soon

Practical Approaches for PFAS Fate & Transport Evaluation Training

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CLU-IN Training Page (slides available):
https://www.clu-in.org/conf/itrc/PFAS-fate-transport/

Housekeeping

This event is being recorded; Event will be available On Demand after the event at the main training page

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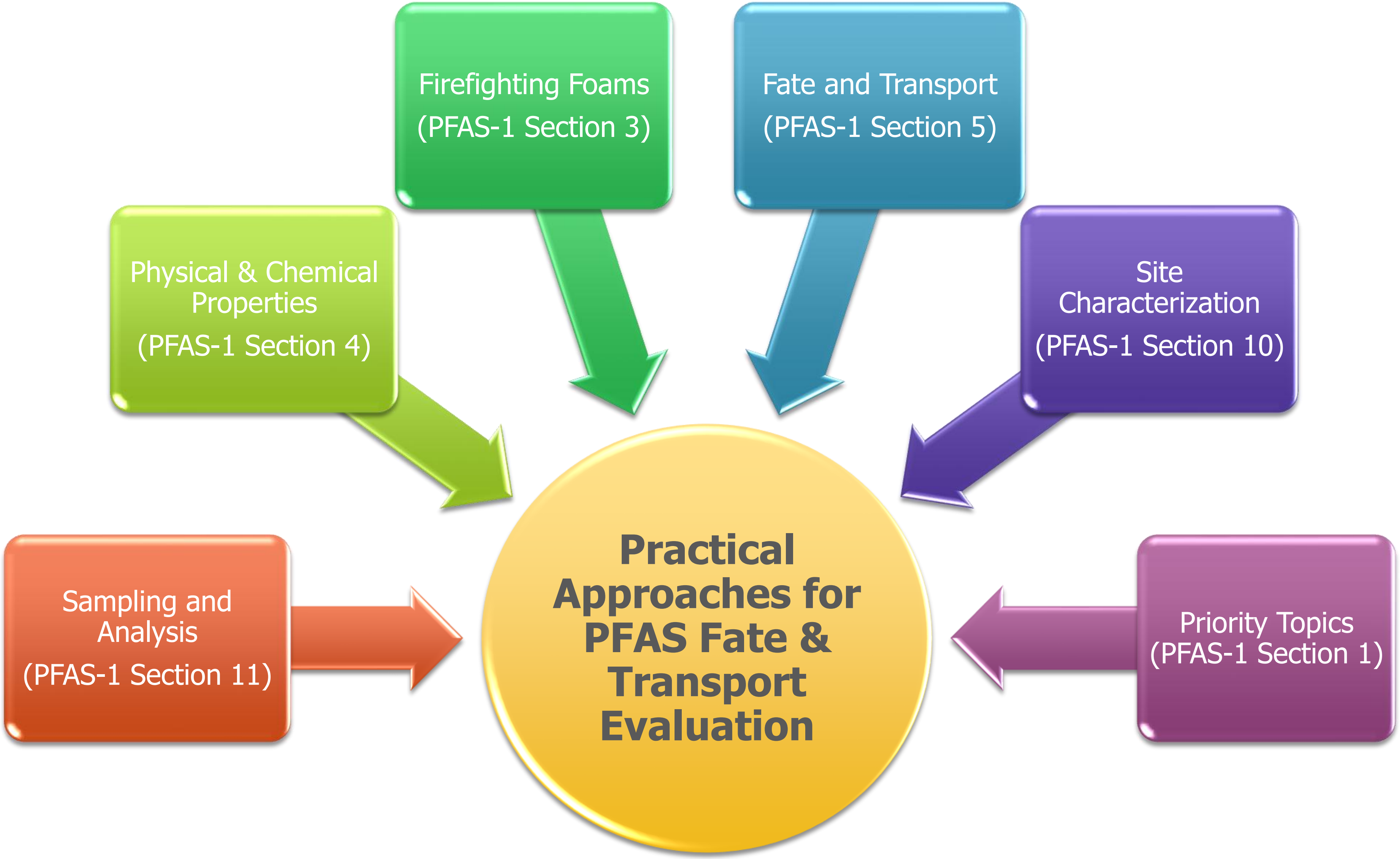
Practical Approaches for PFAS Fate & Transport Evaluation

Materials Used Today



PFAS-1 https://pfas-1.itrcweb.org

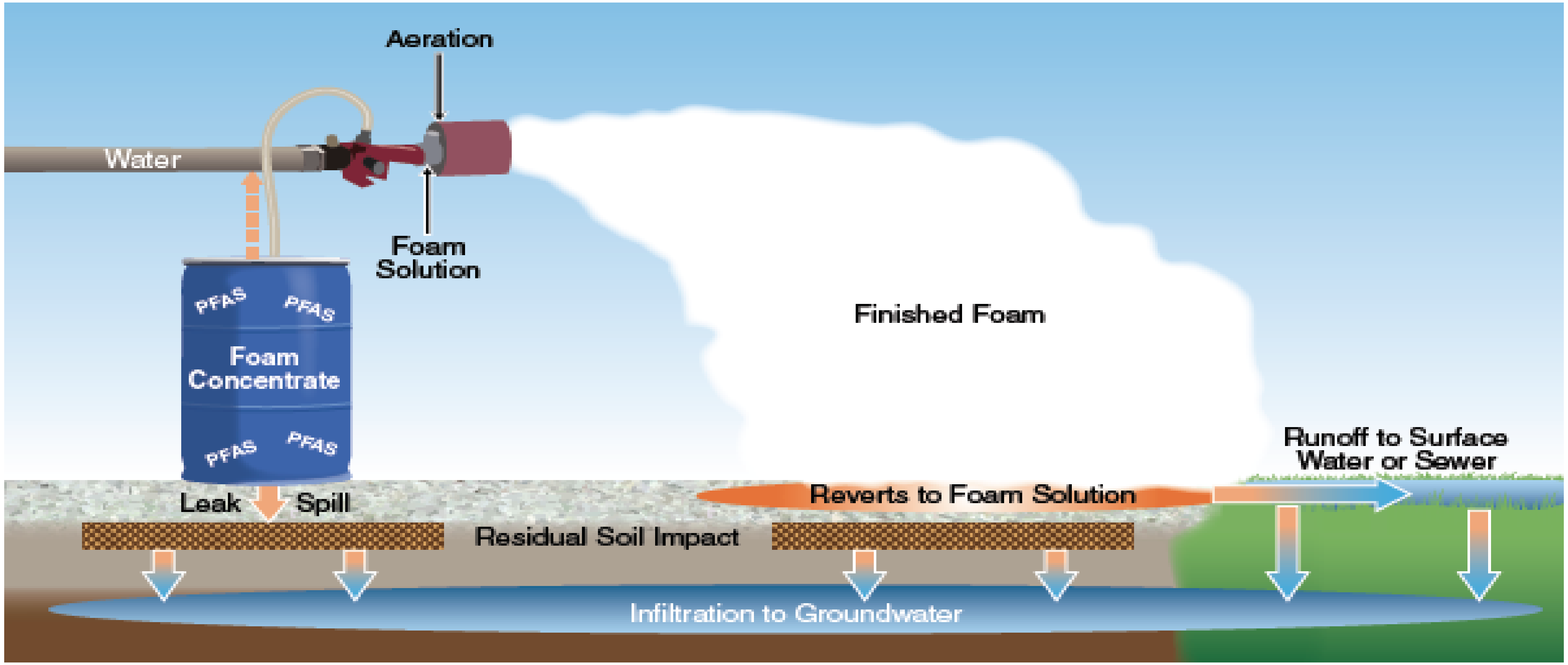
Training Scope

Practical Approaches for PFAS Fate & Transport Evaluation

Review of topics that apply to a hypothetical aqueous film-forming foam (AFFF) release scenario

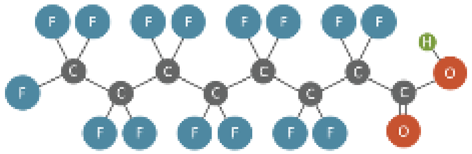
- Includes discussion of specific site characteristics and relevant environmental compartments
- Not a comprehensive look at the hypothetical scenario

Hypothetical Source: Class B AFFF

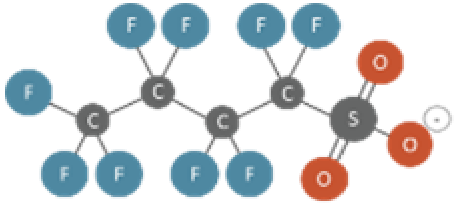


PFAS-1 Figure 3-4 Release of firefighting foam.
Source: Adapted from figure by J. Hale, Kleinfelder, used with permission.

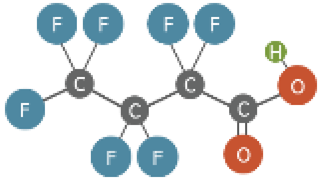
PFAS Chemistry is Unique



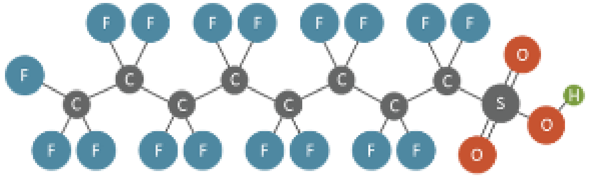
PFOA (perfluorooctanoic acid)



PFBS (Perfluorobutane sulfonic acid)



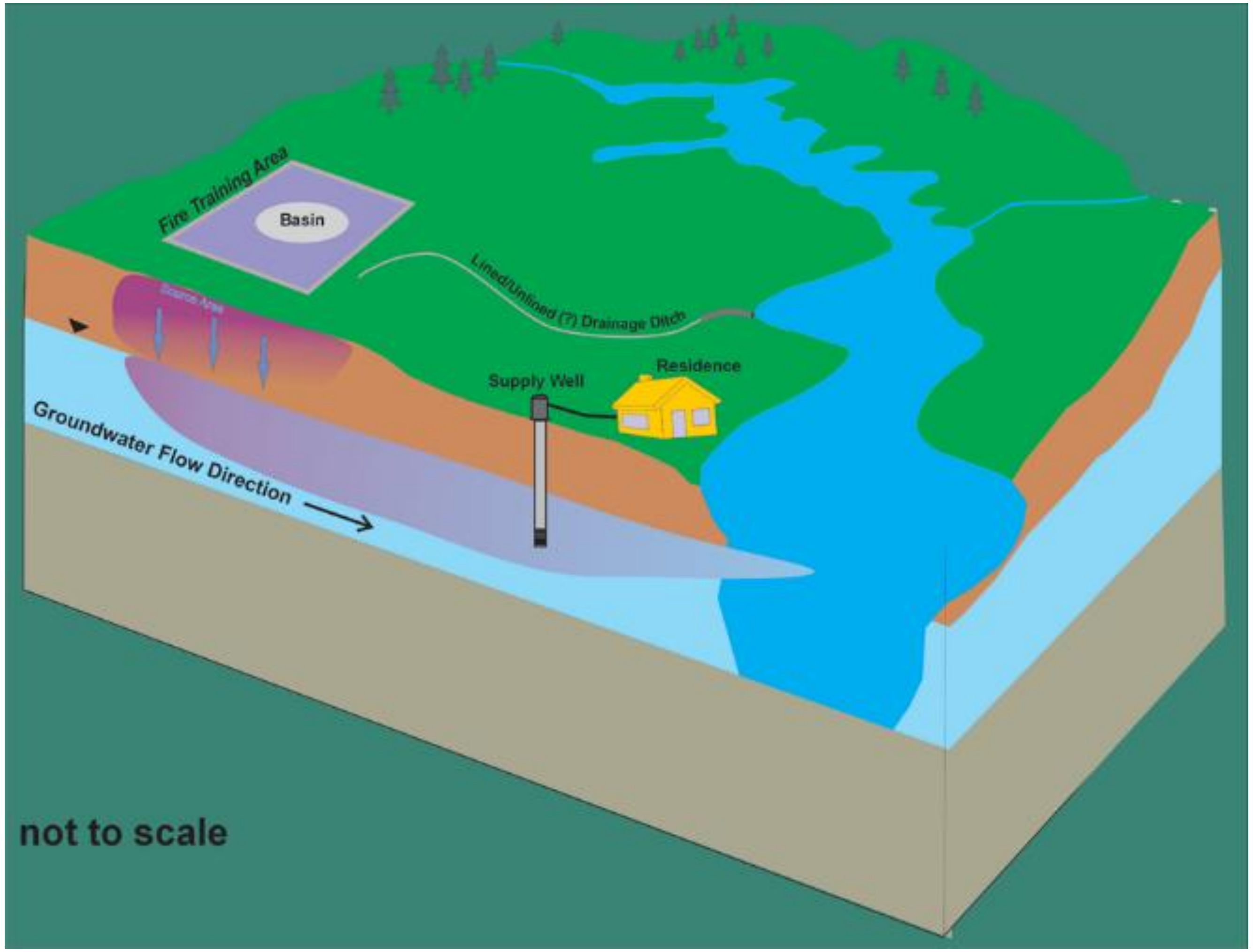
PFBA (Perfluorobutanoic acid)



Perfluorooctane sulfonic acid (PFOS)

How does that Translate to Site Dynamics?

The Site – AFFF Firefighting Training Facility



Source: Alex MacDonald. Used with Permission.

Case Study – AFFF Firefighting Training Facility

Facility Attributes

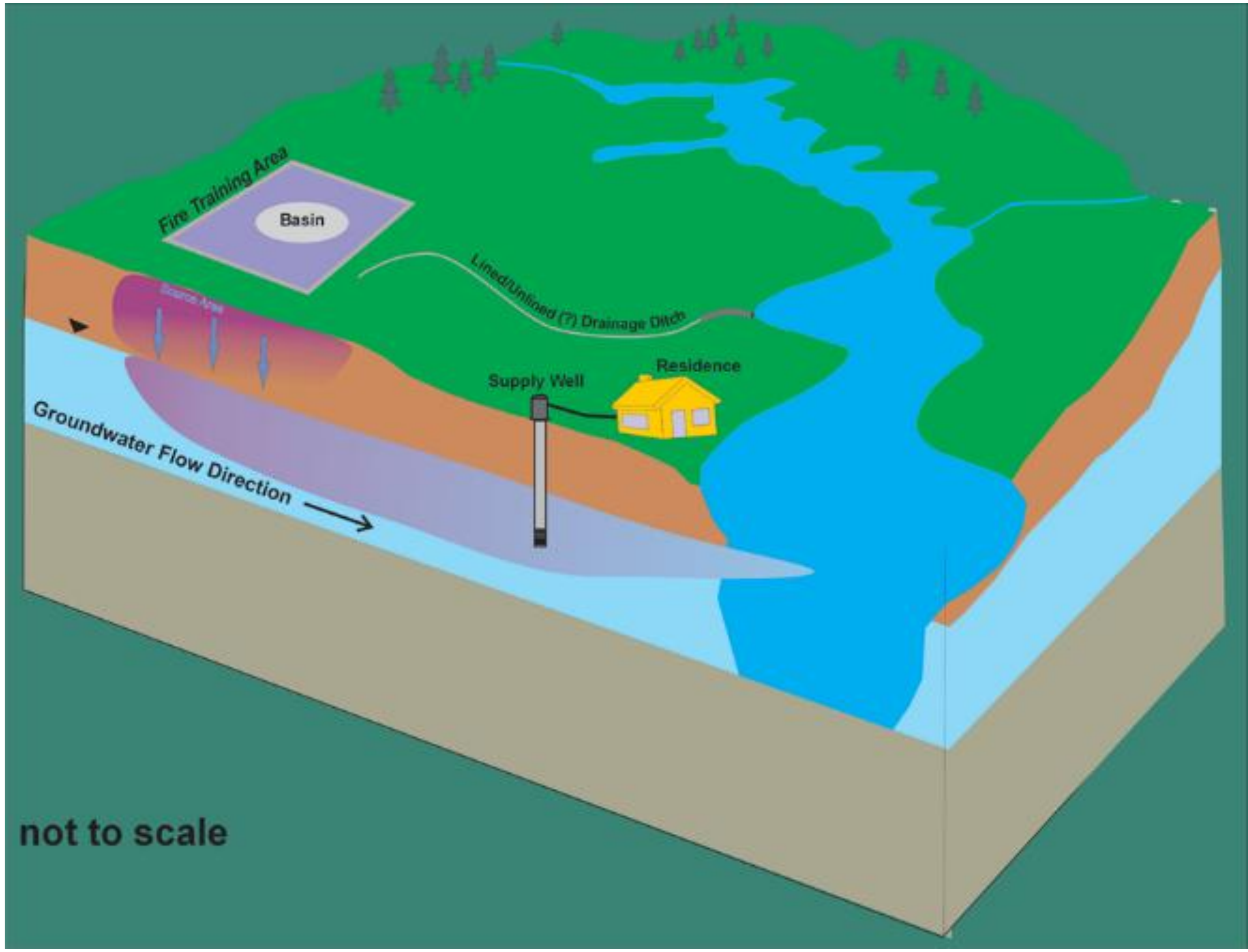
- Hypothetical unlined 8-acre facility operated from around 1970 to 1999
- Used to train local firefighters in using AFFF
- Main feature - a concrete basin to float burning fuel
- Residential community downgradient uses groundwater for domestic and agricultural supply
- Groundwater discharges to surface water

Source: Alex MacDonald. Used with Permission.

Case Study – AFFF Firefighting Training Facility

Facility and Surrounding Area 3-D View

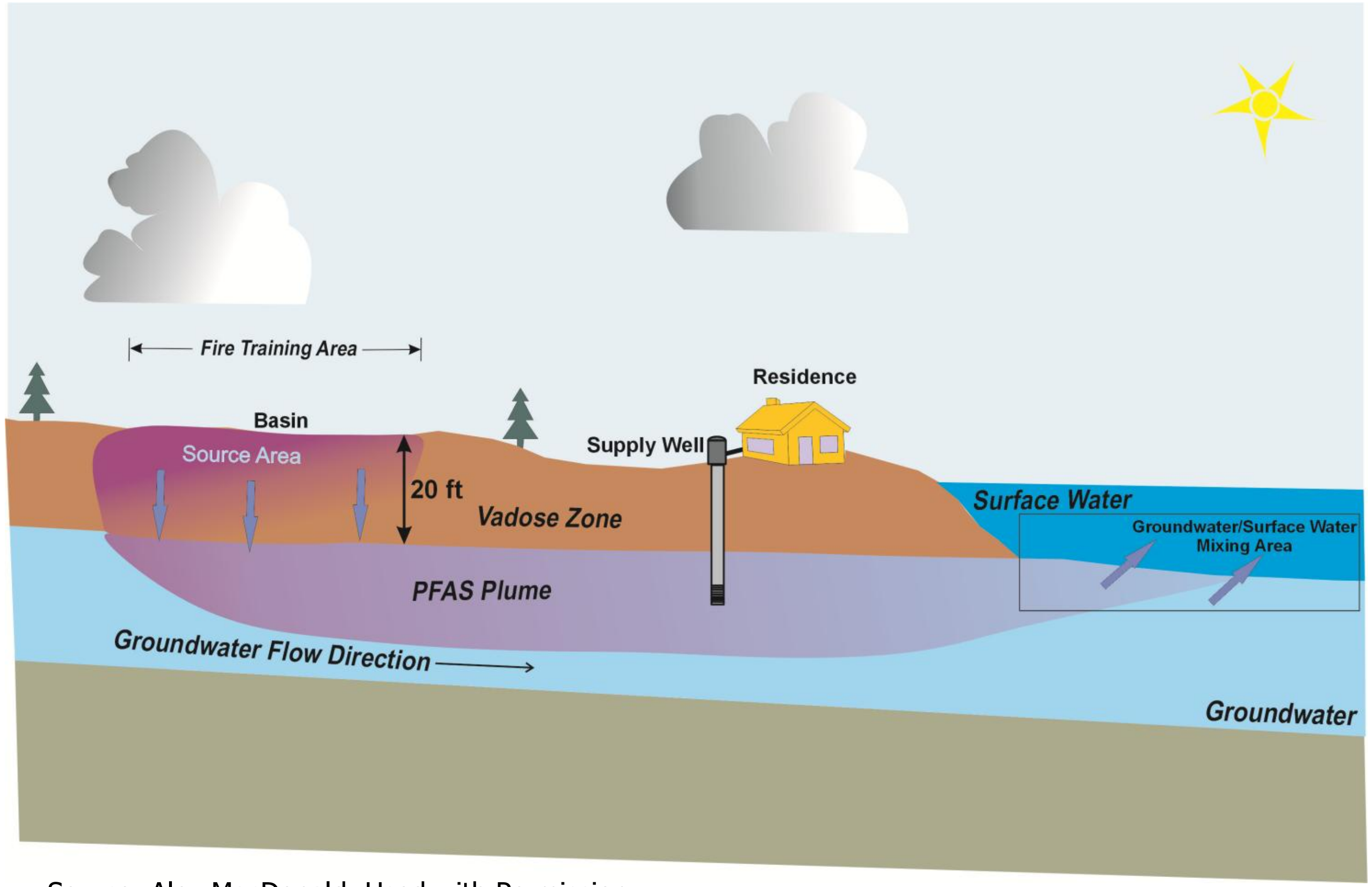
- Light purple area – former training facility with concrete apron
- Community is represented by the single house with supply well
- Interim treatment has been installed on water supply wells while the investigation is implemented
- Potential PFAS discharge to surface water during storm events
- Potential human exposures to PFAS



Case Study – AFFF Firefighting Training Facility

Cross-Sectional View

- 20-foot vadose zone
- Fluctuating water table – 5ft
- Subsurface consists of heterogeneous unconsolidated sediments
- Saturated zone approximately 30 ft thick, underlain by impermeable confining layer
- PFAS in groundwater discharges to surface water
- Average annual recharge 15 inches/year
- Nearest well 300 feet downgradient

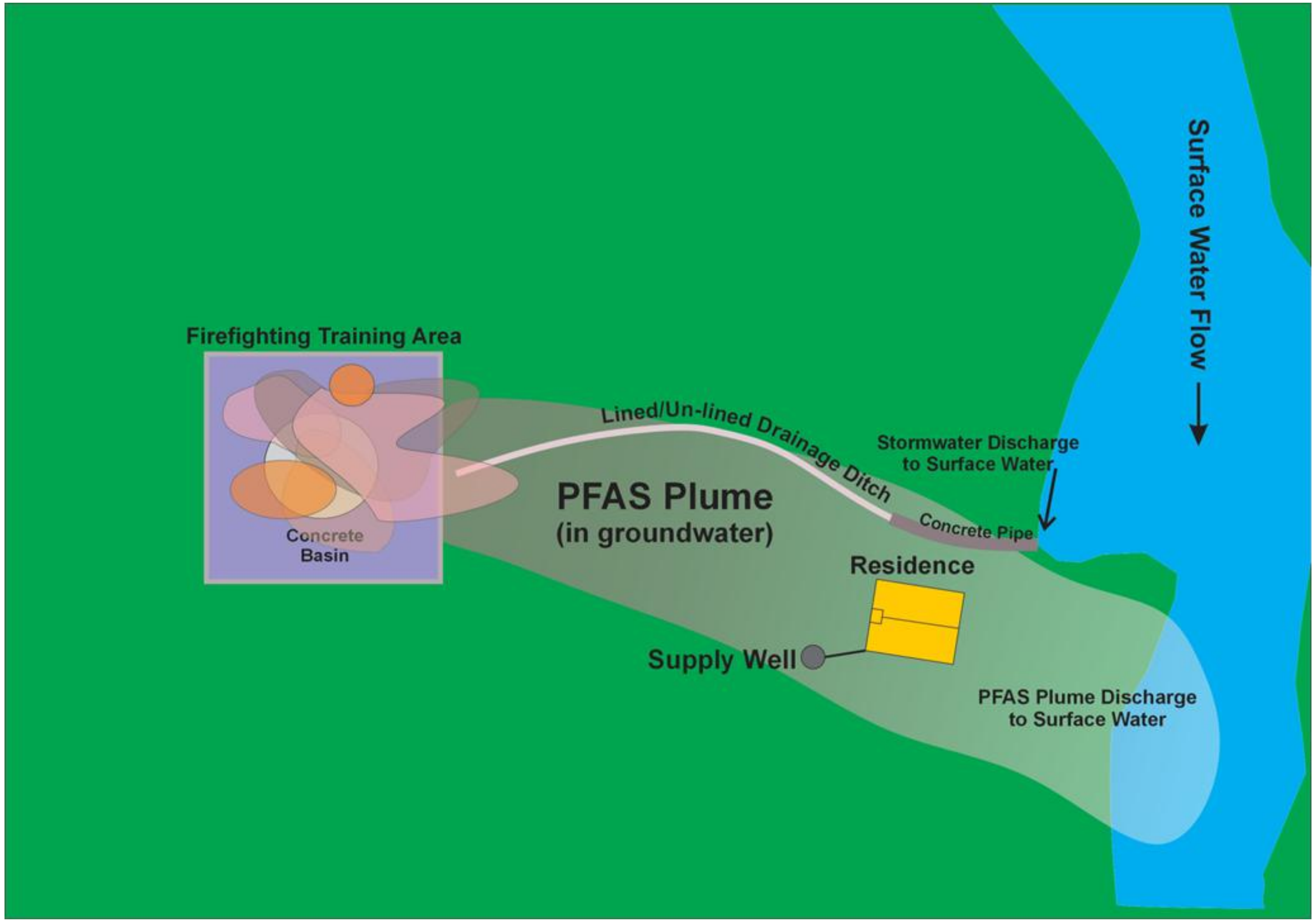


Source: Alex MacDonald. Used with Permission.

Case Study – AFFF Firefighting Training Facility

Overhead View

- Note – different shapes in the training area
- Fuels used for generating fire are another pollutant for investigation
- Stormwater from the training area travels a lined/unlined drainage ditch to surface water



Case Study – Goals of the Investigation

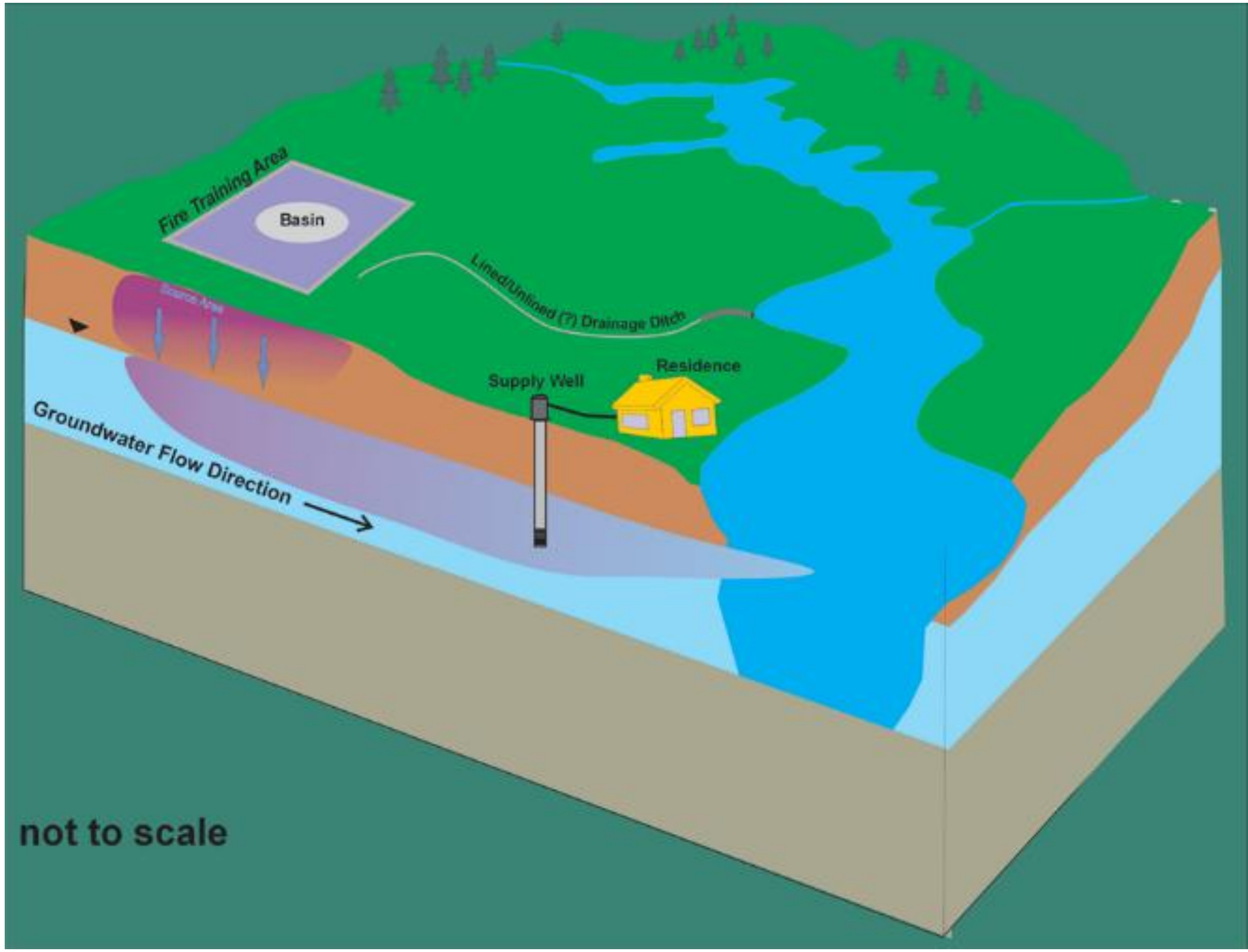
Gather available information

Develop conceptual site model

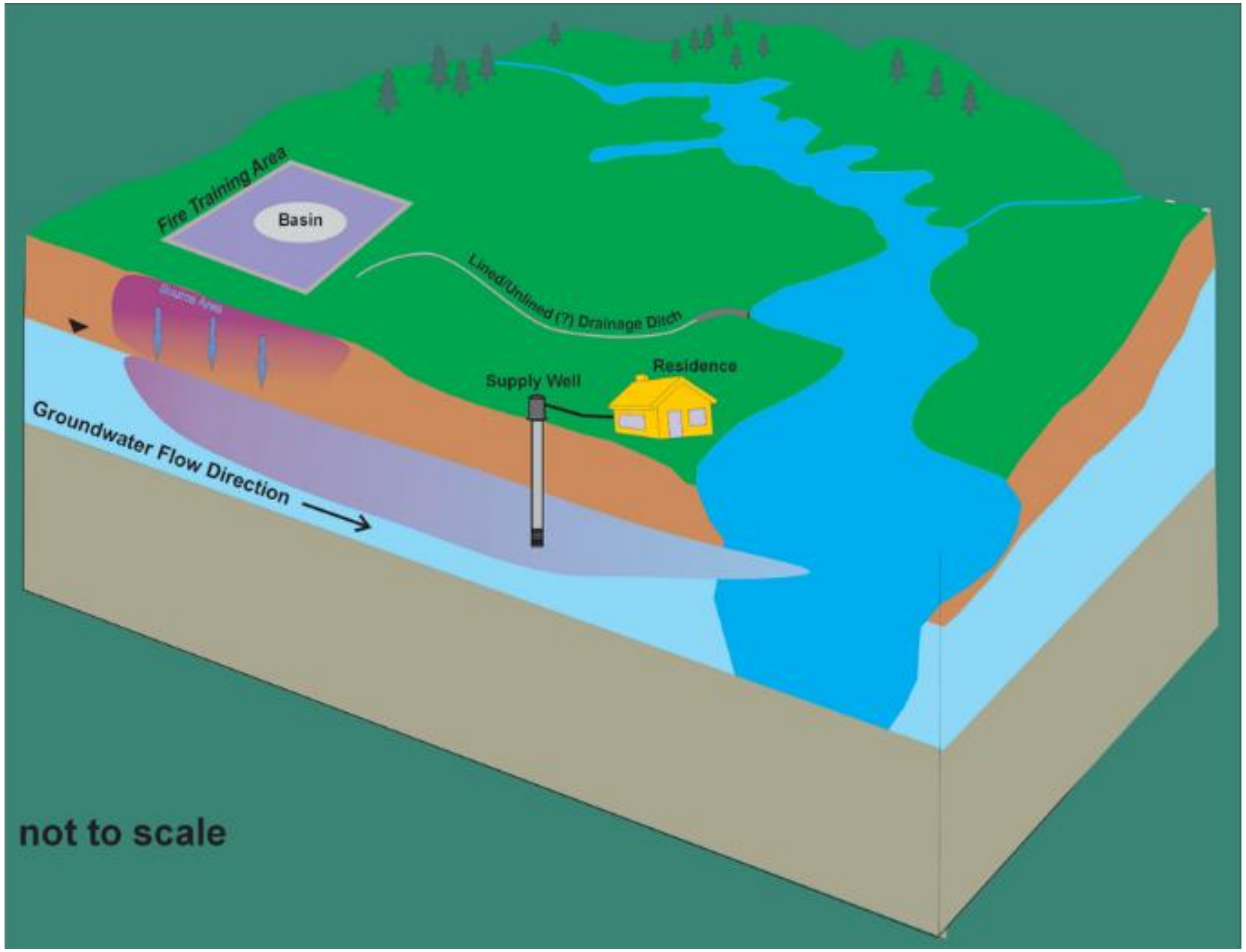
Identify human and ecological receptors

Produce a Sampling and Analysis Plan to:

- Determine extent of COCs
- Evaluate impacts to groundwater and surface water
- Locate and measure residual COC concentrations/mass
- Determine if sources are controlled
- Evaluate if regulatory values are exceeded
- Assess human and ecological risks



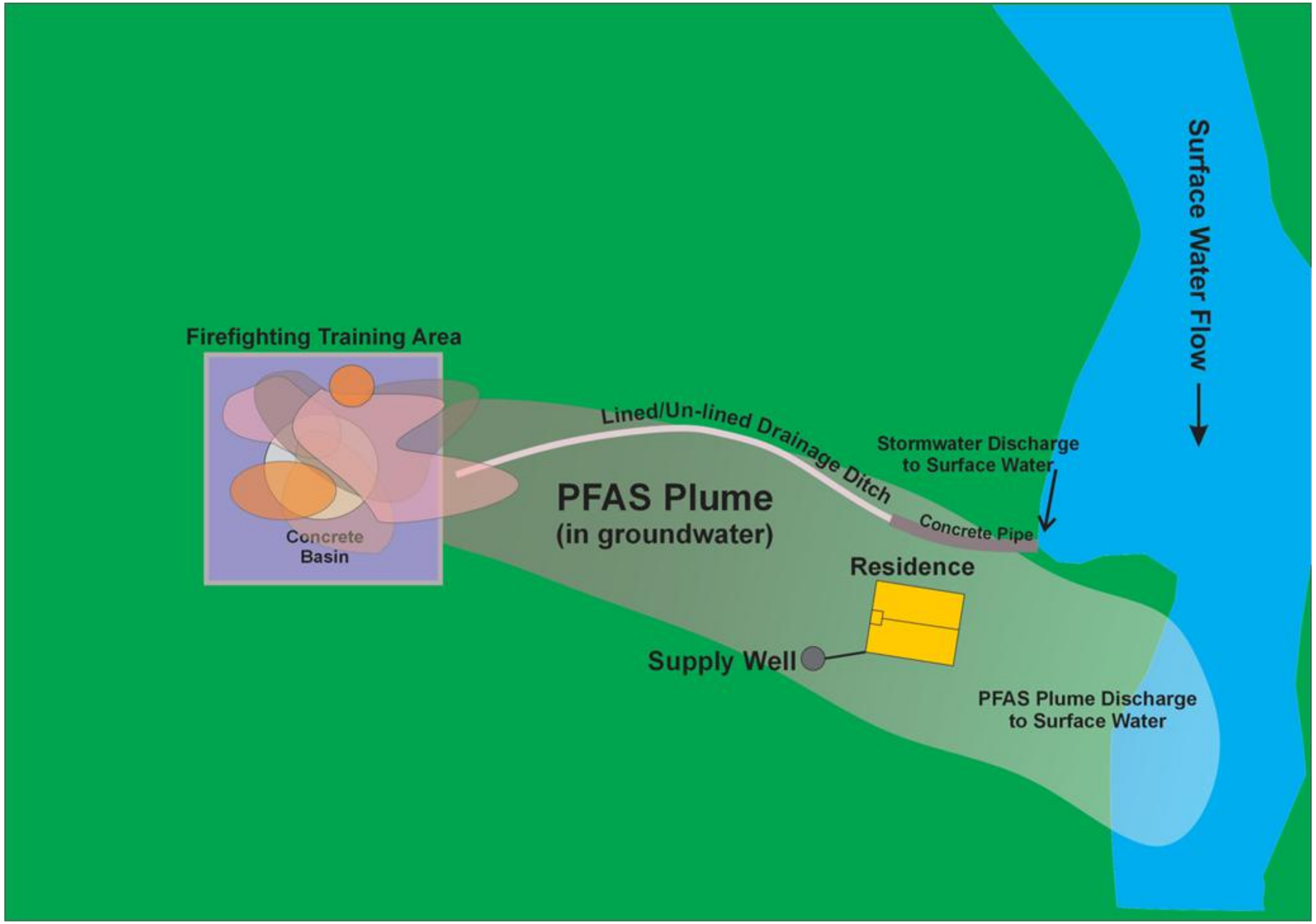
Source Zone Characterization



Source Zone Characterization

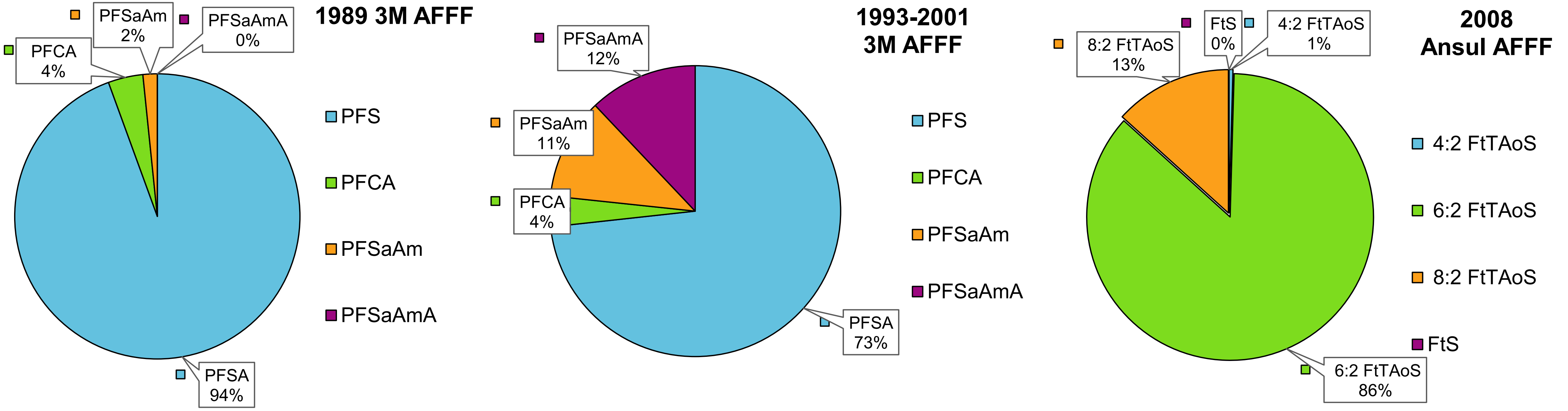
Source area

- Area of contaminated media that continues to contribute mass to the PFAS plume
- Area results from a number of cumulative releases over time
- Defined on horizontal and vertical planes
- Likely includes concrete pad and surrounding surface soil



Class B AFFF Contains Highly Diverse Mixtures

AFFF product chemistry has changed over time



Electrochemical Fluorination (ECF) | Fluorotelomerization

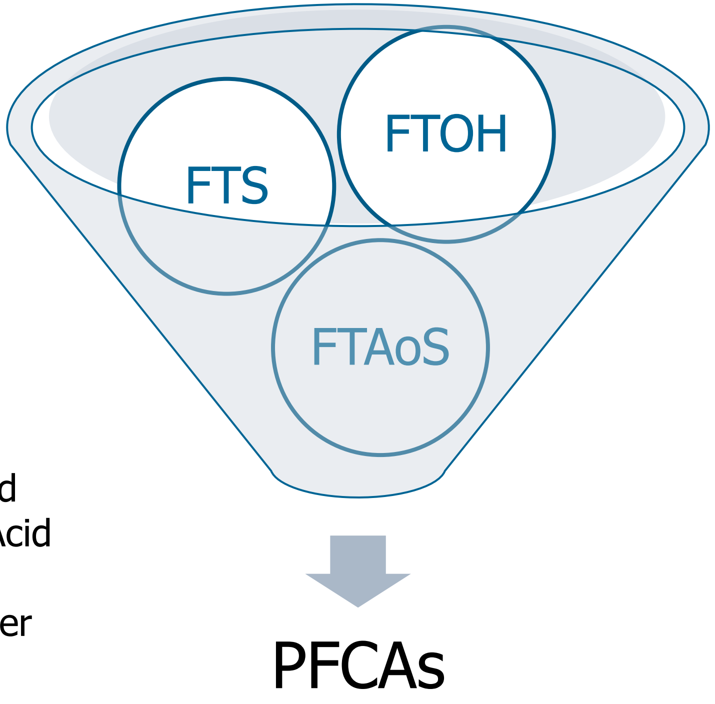
PFAS-1 Table 3-1, Types of Foam and Composition.
Figures used with permission from J. Field, Oregon State.

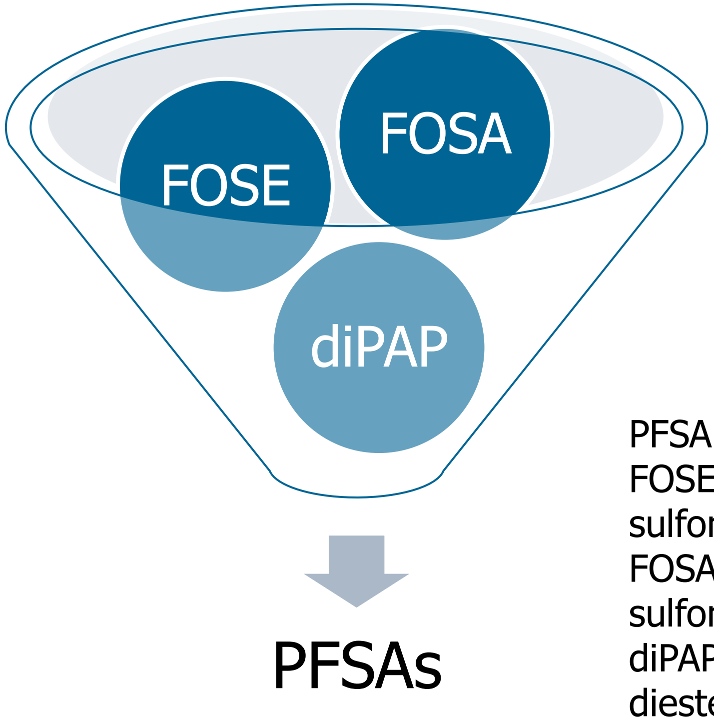
Barzen-Hanson et al. 2017. Environ Sci Technol 51: 2047-2057.
PFAS-1 Section 3.2

Source Zone Characterization

Understand AFFF source material

- Precursor composition determines fate and transport potential and final composition



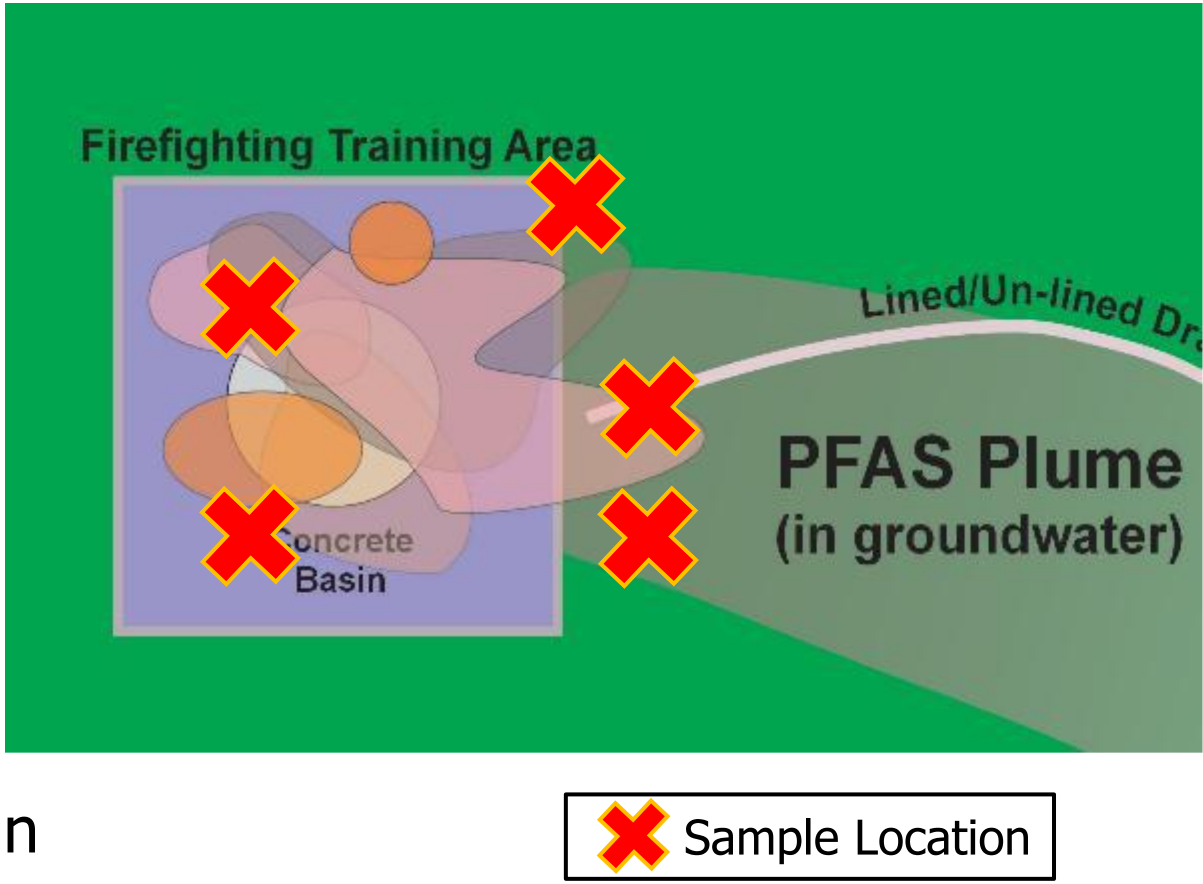


PFCA: Perfluorocarboxylic Acid
FTS: Fluorotelomer Sulfonic Acid
FTOH: Fluorotelomer Alcohol
FTAoS: Fluorotelomer thioether amido sulfonate

PFSA: Perfluorosulfonic Acid
FOSE: Perfluorooctane sulfonamidoethanol
FOSA: Perfluorooctane sulfonamide
diPAP: Polyfluoroalkyl phosphate diester

Source Zone Characterization – Sampling Plan

- Understand extent by sample placement
  - Concrete pad and apron
  - Vertical soil profiles to understand extent and distribution of infiltration
  - Sediment and concrete in drainage channels
- Understand composition through choice of analytical method
  - Different analytical methods can determine precursor composition
    - EPA Method 1633A
    - Non-target Analysis
    - Total Oxidizable Precursor (TOP) Assay/Total Organic Fluorine (TOF)
- Results inform potential source control design



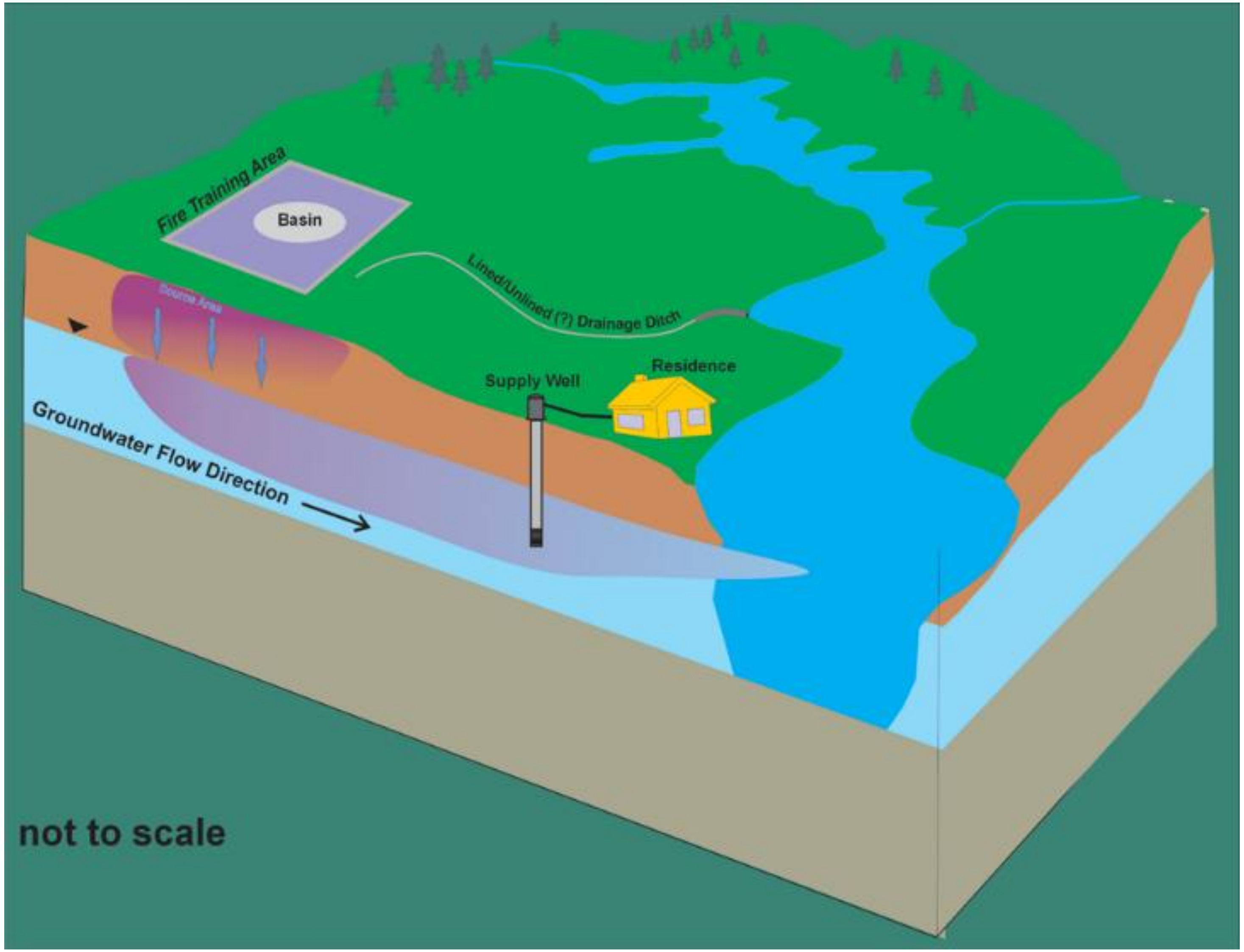
Knowledge Check!

Check In!

AFFF composition can vary due to:

A. Manufacturing process that produced the PFAS
B. The AFFF supplier that produced the formulation
C. When the AFFF supplier produced the formulation
D. All of the above

Vadose Zone



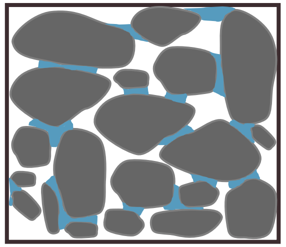
Fire Training Area
Basin
Lined/Unlined (?) Drainage Ditch
Supply Well
Residence
Groundwater Flow Direction
not to scale

PFAS Behavior in the Vadose Zone

- Surfactant behaviors
  - Air-Water interfacial (AWI) retention
  - Amplified relative to hydrocarbon surfactants
  - Particularly important for longer chain & sulfonates (PFOS vs PFBA)
- Interactions with Soil
  - Organic carbon is only part of the story
  - pH
  - Divalent cations
  - Remedial history
- Source strength considerations
  - Typical Dilution Attenuation Factor (DAF) not representative

Shallow Source Area

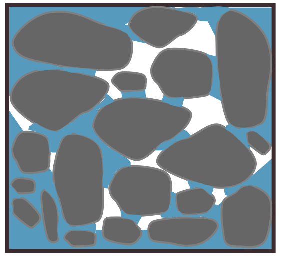
Long chain PFAS partition to interfaces & Significant retention



- Underlies source zone
- Persistent case in arid environments

Recharge

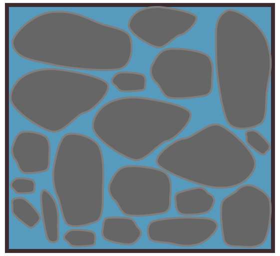
Partitioning into aqueous phase & Competitive sorption



- Transient condition
- Frequency dependent on climate
- Persistent case in humid environments

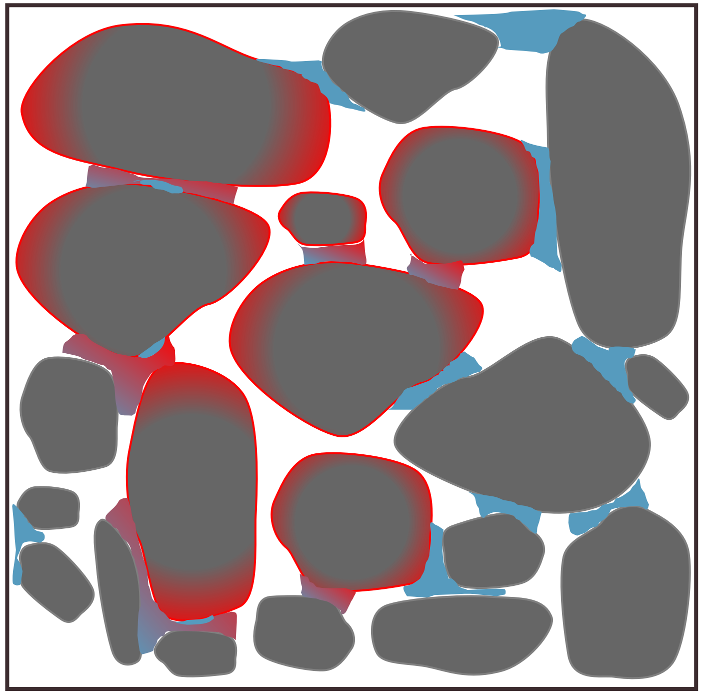
Saturation AWI~0

AWI collapse, Mass release, & Colloid transport

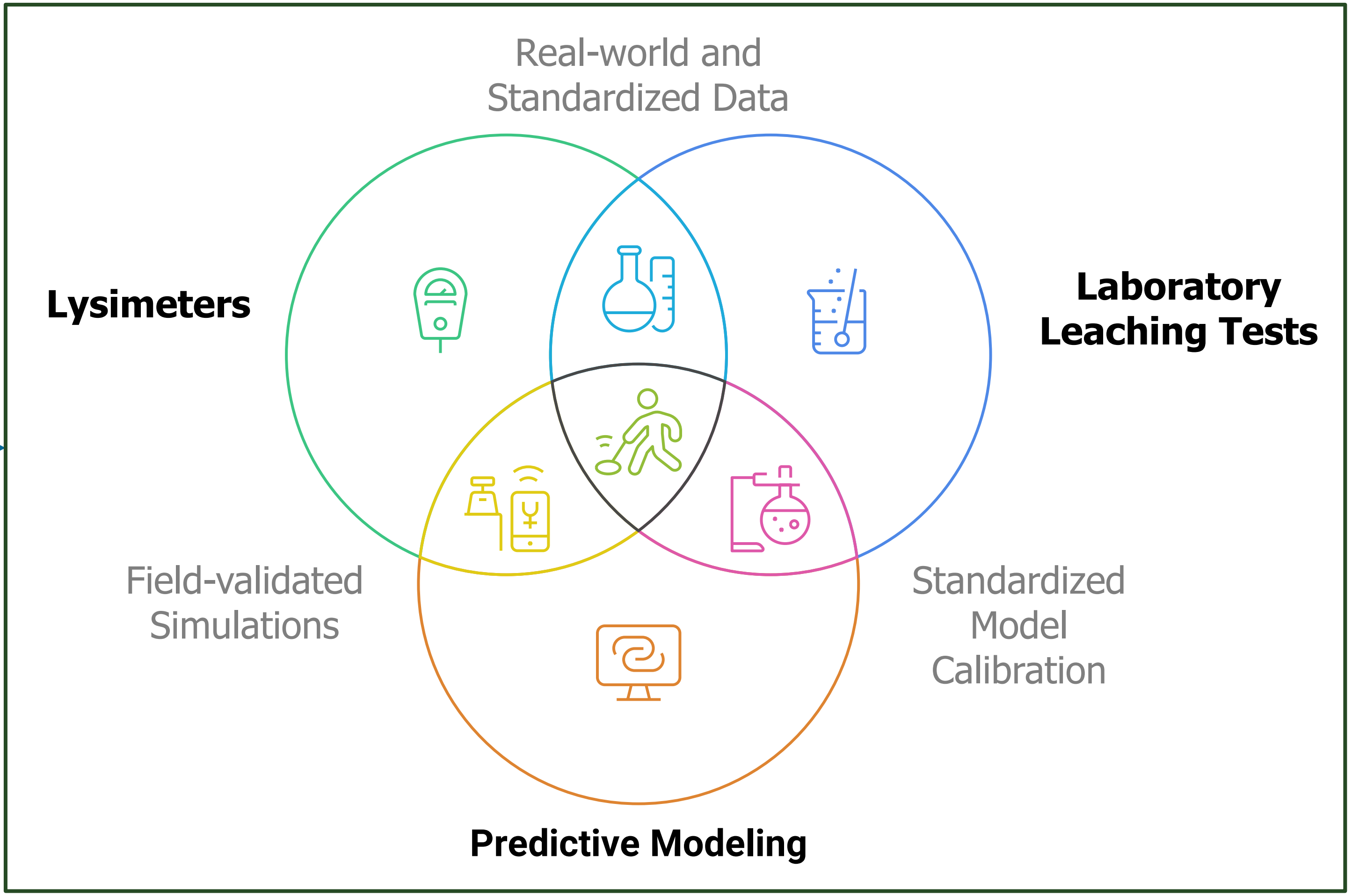


- Transient condition may be seasonal and brief
- Hysteresis (matrix diffusion through newly connected pores)

Sampling Plan→ Source Strength Evaluation



What soil concentration is expected to yield a leachate concentration protective of groundwater?



PFAS-1 Section 1.3.1.2 & 1.5.1, Section 5 (Leaching Models & Methods, respectively)

Image created with Napkin.ai 2/2/26 using the search "..show visual overlapping functionalities ..."

Leaching and Lysimeter Tests

Leaching Tests

- Do not account for PFAS retention at the air-water interface
- Do not represent the soil-to-leachate ratio encountered under field conditions
- Can address kinetic desorption (LEAF)
- SPLP derived Kd[1]

Lysimeter Porewater

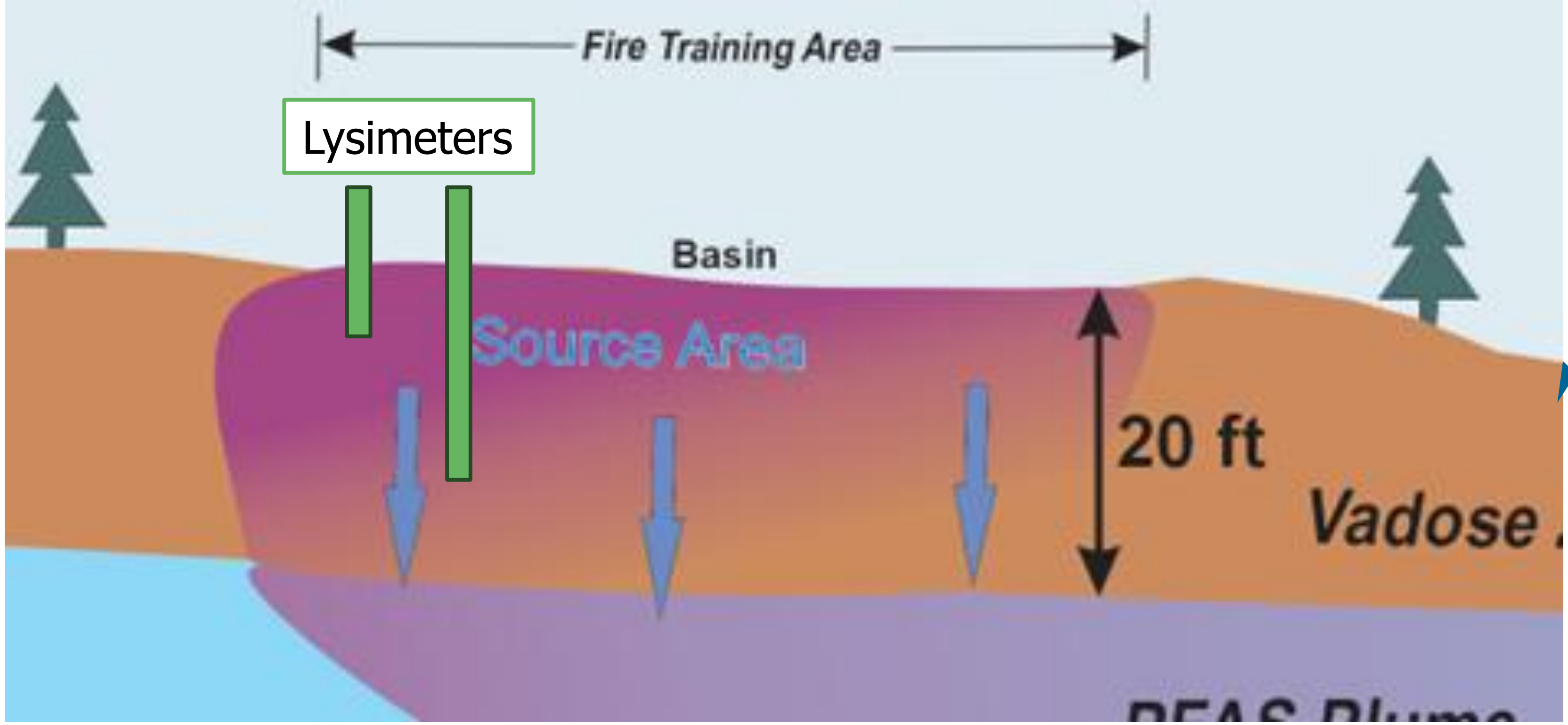
- Represent a single time result → consider this from season to season
  - Relative to soil moisture
- Limitations include:
  - Very shallow groundwater
  - Bedrock
  - Very arid environments
  - Insufficient co-located soil sample data

BOTTOM LINE

- Soil concentration alone does not account for retentive properties → misleading for source strength
- Conservative DAF likely overestimates true source strength
- Lysimeters can improve interpretation, if feasible

[1] *NJDEP. 2025. "PFAS SPLP Calculator." https://dep.nj.gov/srp/guidance/rs/*
(See also PFAS-1 Section 1.5.1)

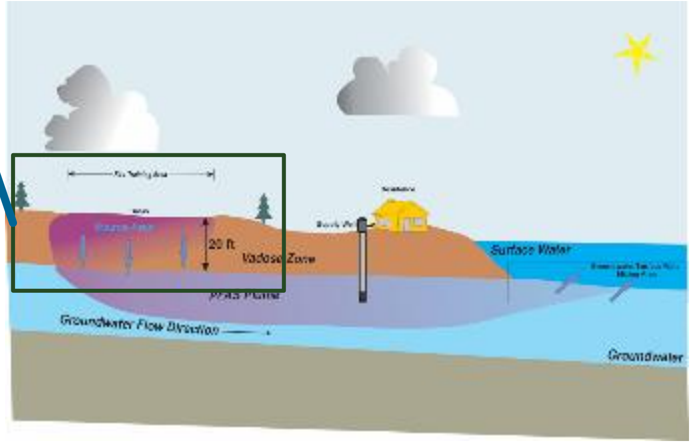
Vadose Zone Characterization*



How many lysimeters are needed?

- Range of depths
- Range of permeabilities
- Range of concentrations

- Lysimeter installation within the source zone.
- Shallow (below the root zone)
- Deep (above the capillary fringe)
- Soil samples coincident with suction cup (splits)
    - Laboratory leaching tests
    - Total PFAS
    - Characterization (model support)



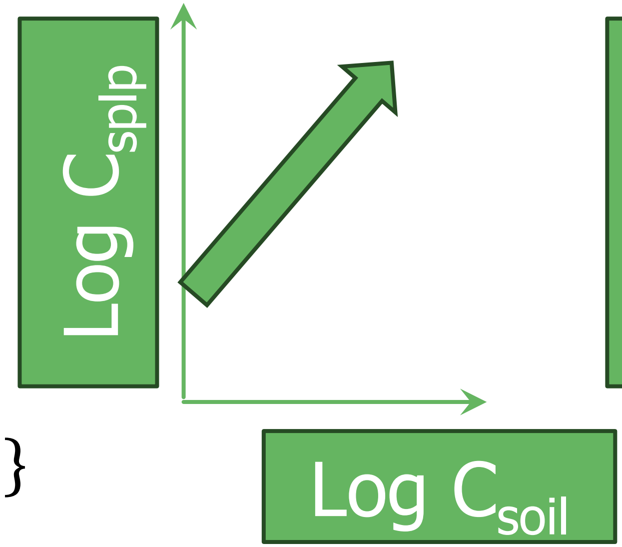
*Our CSM is conducive to lysimeter sampling; this may not always be the case!

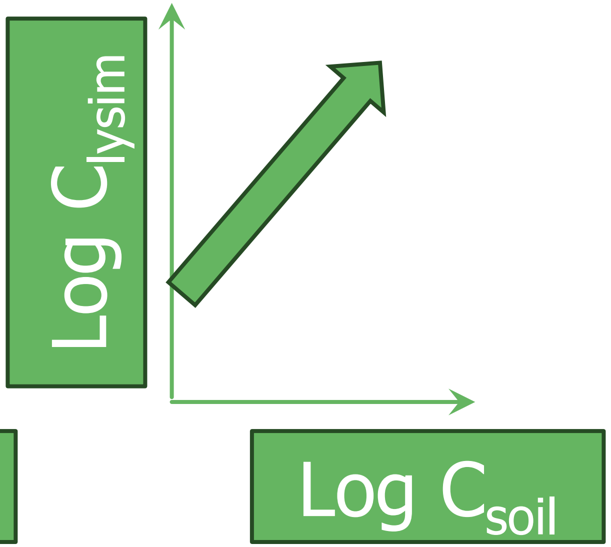
Example site source strength evaluation

Eqn 1: $PW_{PGW} = DAF * PSL$

Eqn 2: $^{*}DAF = 1 + (\frac{Kid}{IL})$

Eqn 3: $d = (0.0112 * L^2)^{0.5} + d_a\{1 - \exp\left[\frac{(-LI)}{(Kid_a)}\right]\}$





Characterization Data (CSM)

- K = aquifer hydraulic conductivity (meters per year [m/yr])
- i = hydraulic gradient (meters per meter [m/m])
- d = mixing zone depth (meters [m])
- I = infiltration rate (m/yr)
- L = source length parallel to groundwater flow (m)
- d_a = aquifer thickness (m)

Eqn 4: $Leachate_{PFAS} = \boldsymbol{m}C_{soil} + \boldsymbol{b}$

Eqn 5: $SSL = 10(\frac{\log PW_{pgw} - \boldsymbol{b}}{\boldsymbol{m}})$

SSL: Soil Screening Limit; PW: Porewater; PGW: Protective of groundwater; PSL: Project Screening Limit

**Source of the DAF equations: USEPA 1996. Soil Screening Guidance: Users Manual, 2nd Edition. Publication 9355.4-23. July*

Knowledge Check!

Check In!

Why would you expect a PFOS SSL derived from SPLP to be higher than an SSL derived from lysimeter PW?

a) Collapse of the air-water interface under fully saturated conditions during SPLP results in mass release.

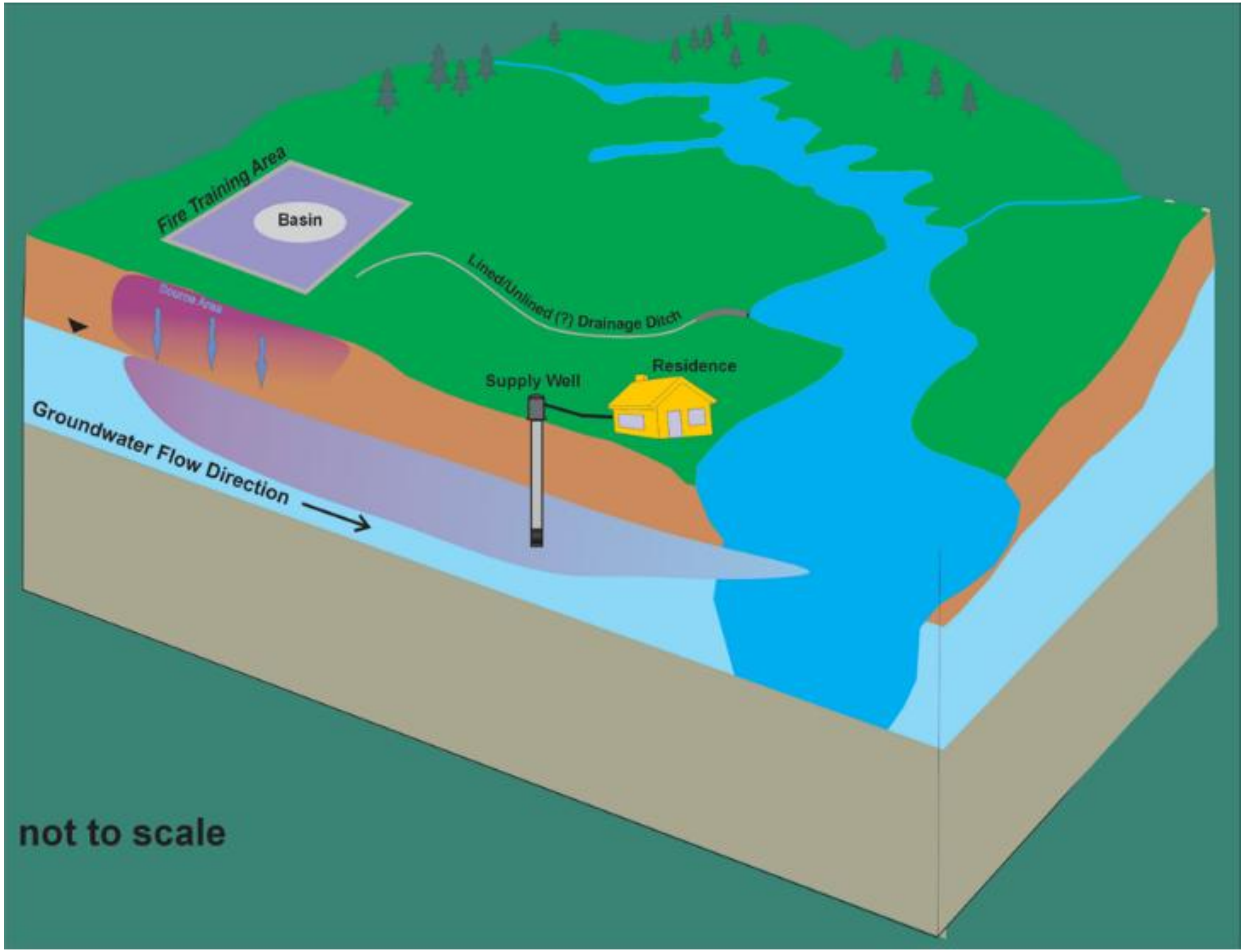
b) Lysimeters do not pull representative samples under certain conditions and SSLs derived from lysimeter PW are always biased low.

c) A long chain sulfonate like PFOS would not have a higher SPLP-derived SSL. They should be the same.

Question and Answer Break

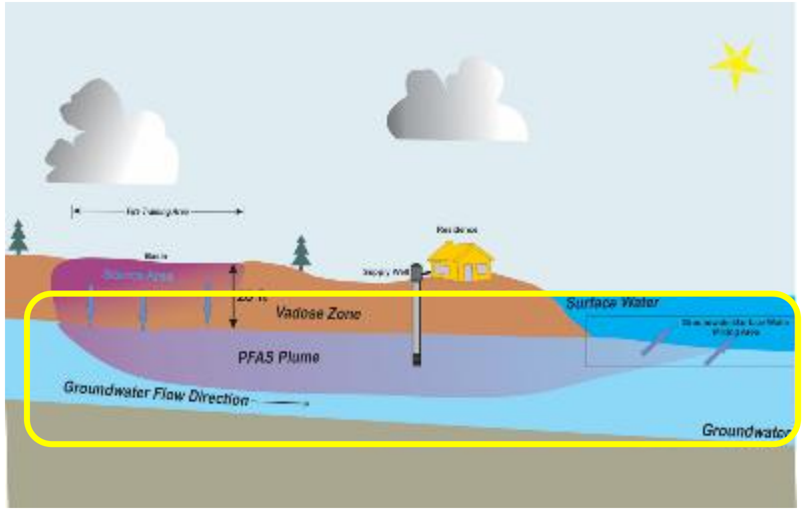
Please use the Q&A Pod to ask questions.

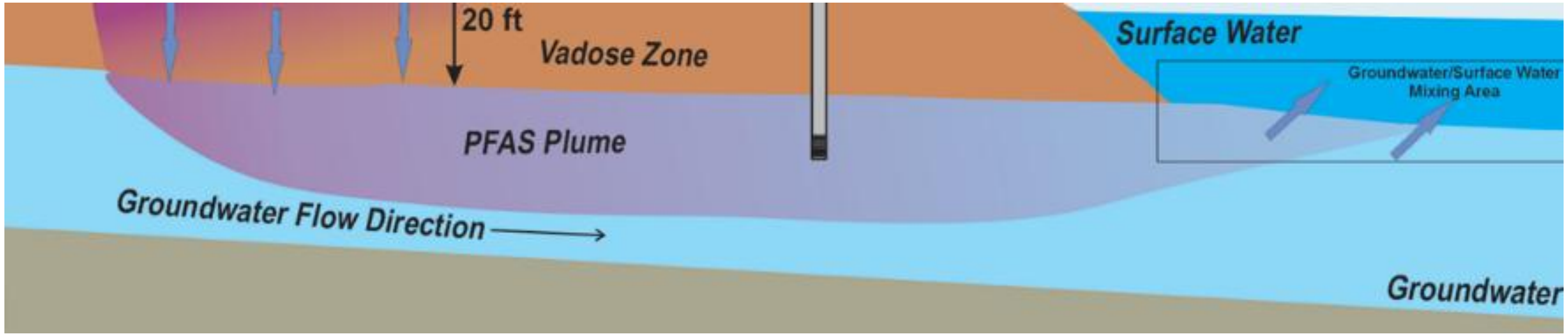
Saturated Zone



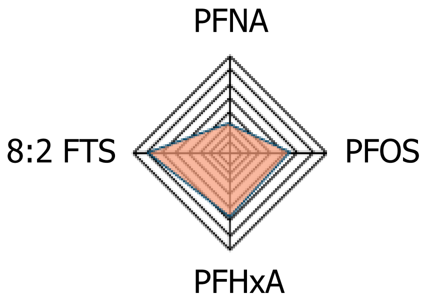
PFAS Behavior in the Saturated Zone

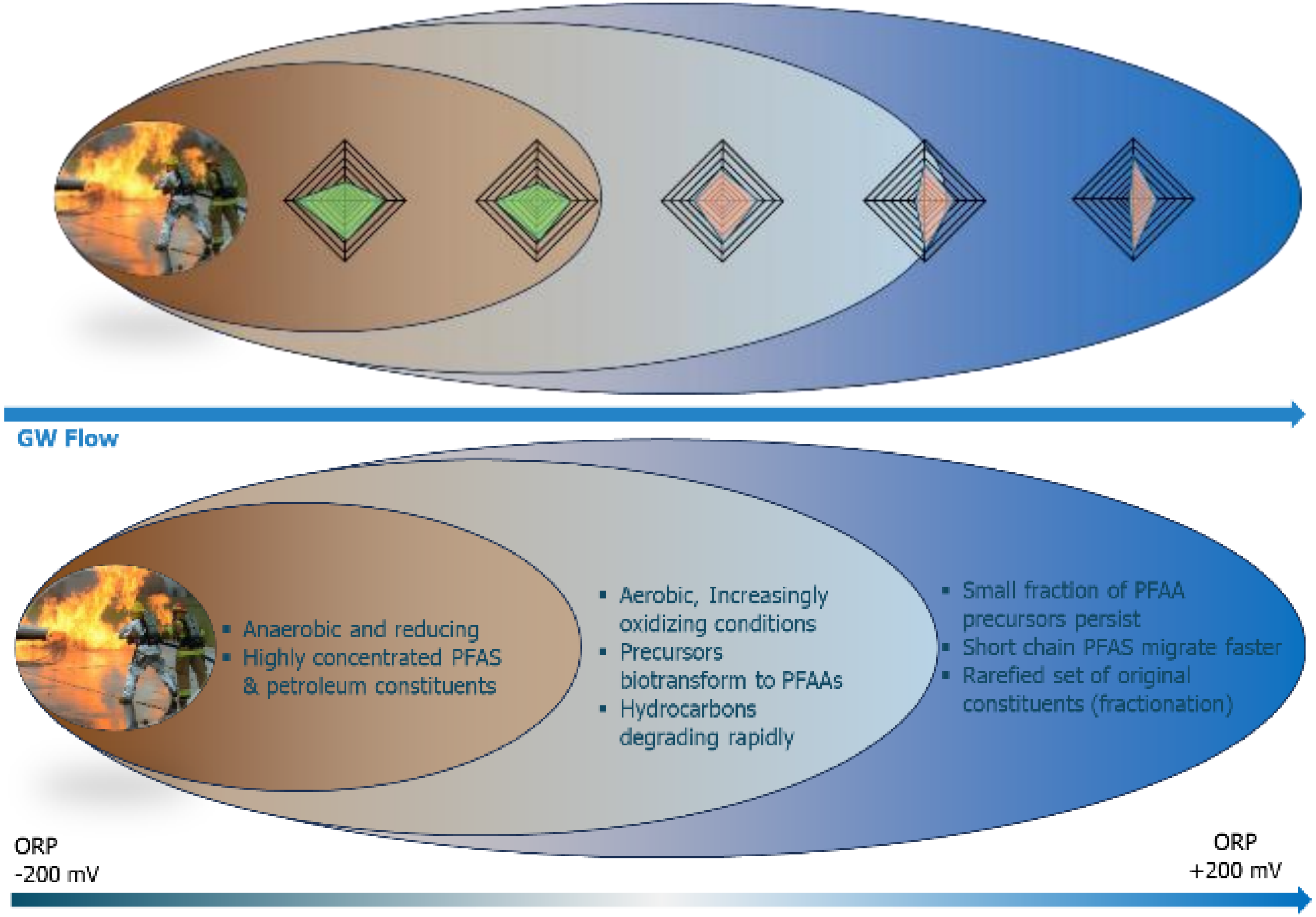
- Co-contaminants: Section 1.3.4.1
- Precursor Transformation: Section 5.4.2
- Diffusion/Back Diffusion: Section 5.3.1
- Transient Water Level: Section 5.3.3
- Differential Migration: Section 5; Section 15.1





Differential Transport



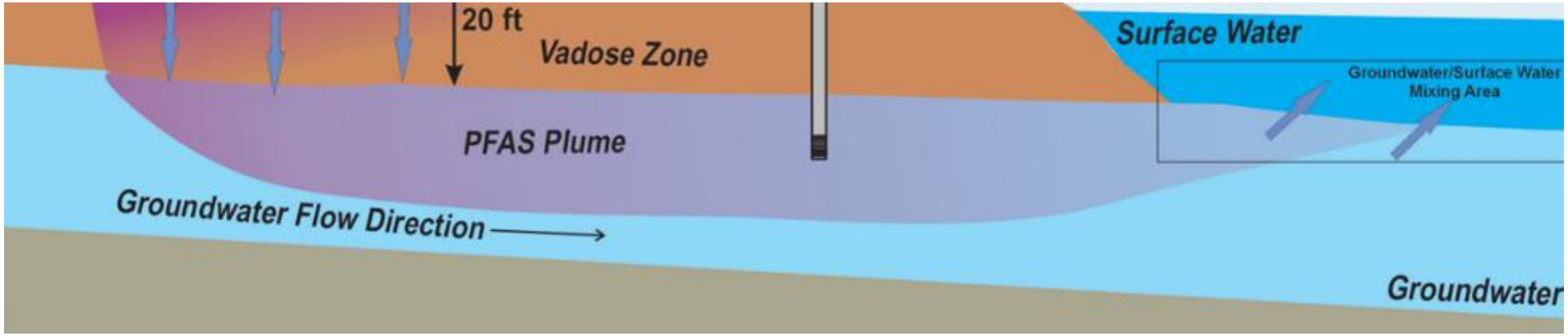


A1C Kyle Gese, Public domain, via Wikimedia Commons.

ORP – Oxidation-Reduction Potential

Sampling Plan for the Saturated Zone

- General Notes For Groundwater Sampling Plan
  - PFAS-free materials, equipment, and supplies: Section 11.1.7.2
  - Avoid coated bentonite pellets
  - Polytetrafluoroethylene (PTFE) is PFAS
  - Some concrete may contain PFAS
  - PFAS-Free water supply. Confirm water supply meets Data Quality Objectives
  - Minimize turbidity

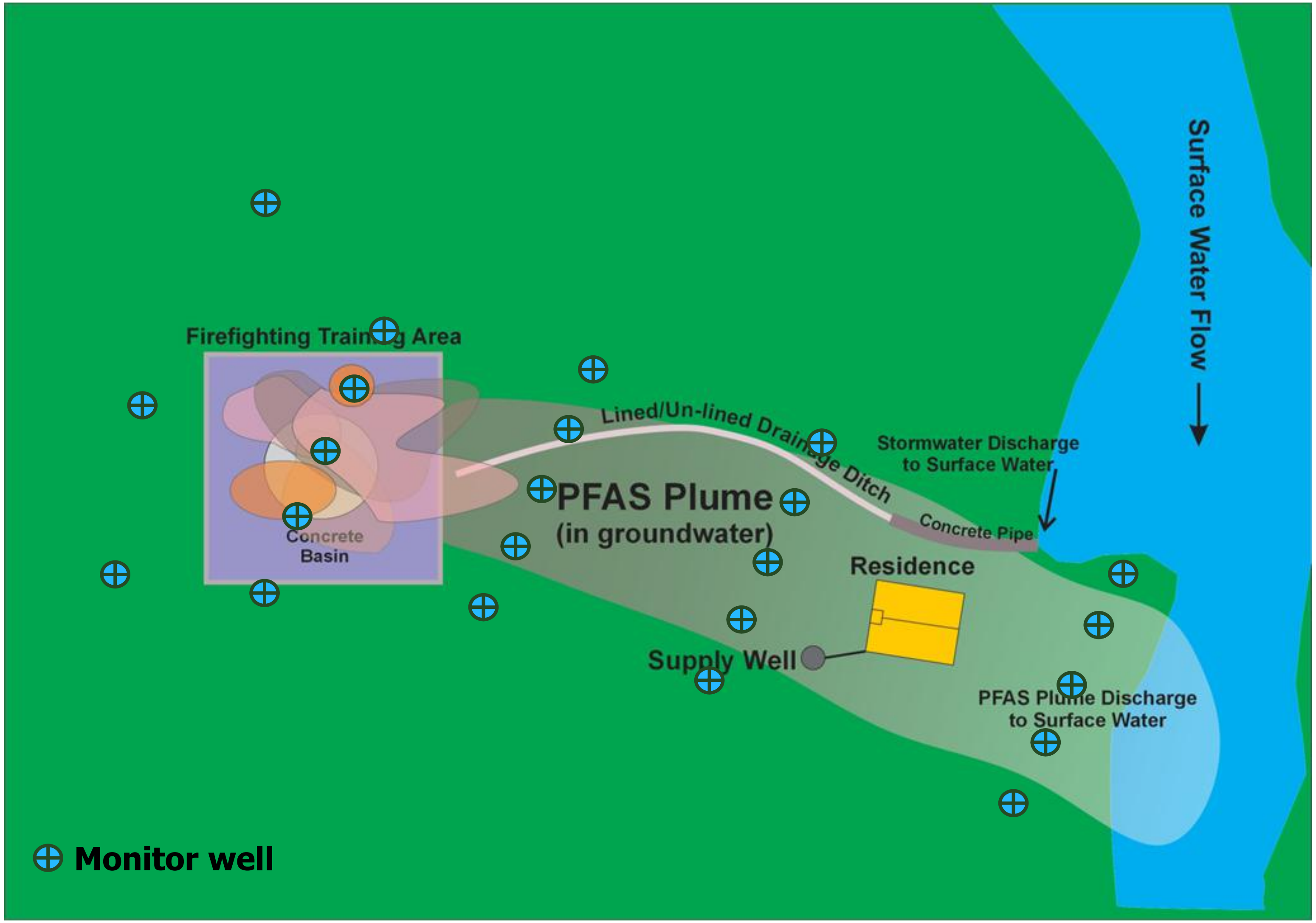


Sampling Plan for the Saturated Zone

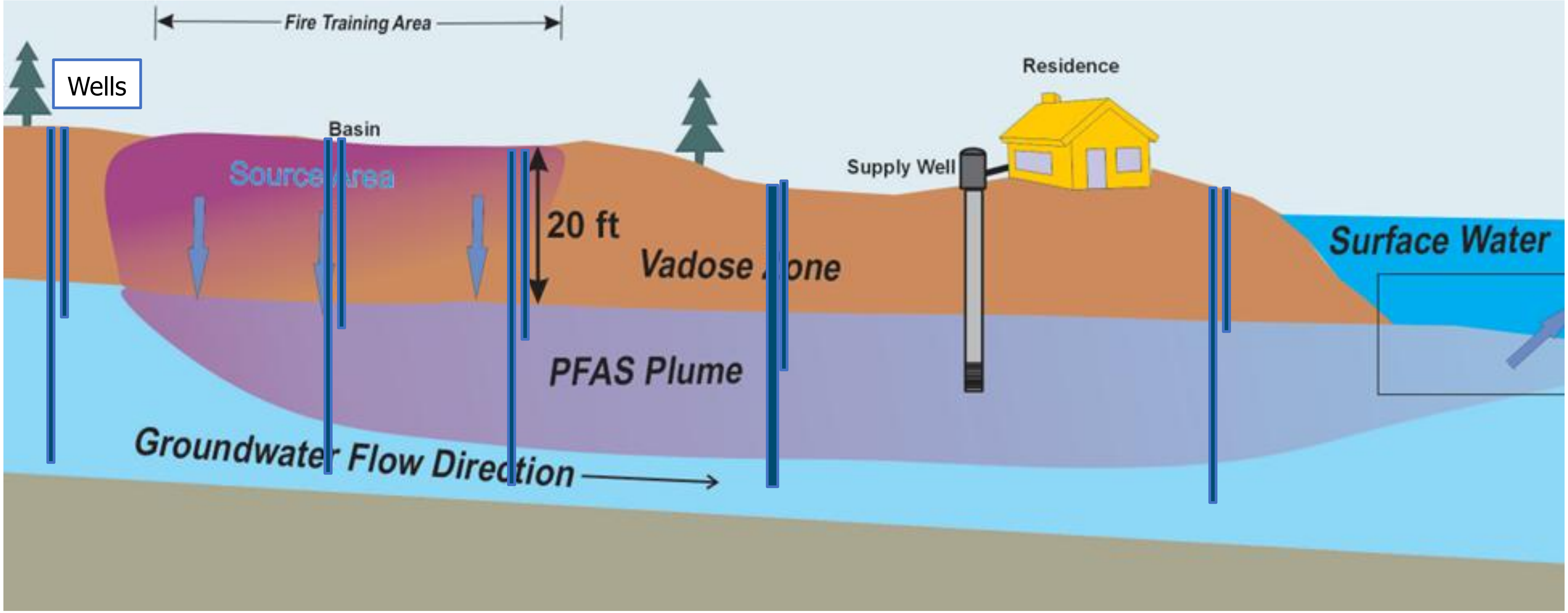
Goal of the saturated zone sampling plan → understand plume characteristics and dynamics

- Fundamentals: Characterize the Hydrogeology (Section 10.3.1.1)
  - Physical, hydraulic, hydrologic, geochemical parameters (may require aquifer testing and geotechnical sampling)
  - Assess site in context of geologic history (e.g., environmental sequence stratigraphy and geomorphology)
- Consider use of High-Resolution Site Characterization (HRSC) tools
  - Direct-Push type tools (MIP, HPT, APS) https://asct-1.itrcweb.org/
  - Geophysical tools (surface/borehole/remote sensing)
- Characterize Plume Extent and Stability (Sections 10.4.4 & 10.4.8)
  - Define source area, lateral and vertical extents
  - Consider evaluating mass flux
- Evaluate Precursor Transformation and Impact of Co-contaminants (Sections 5.2.5 & 10.4.6)

Sampling Plan for the Saturated Zone



Sampling Plan for the Saturated Zone

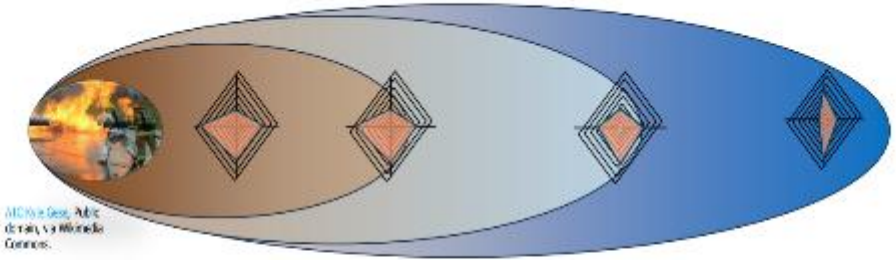


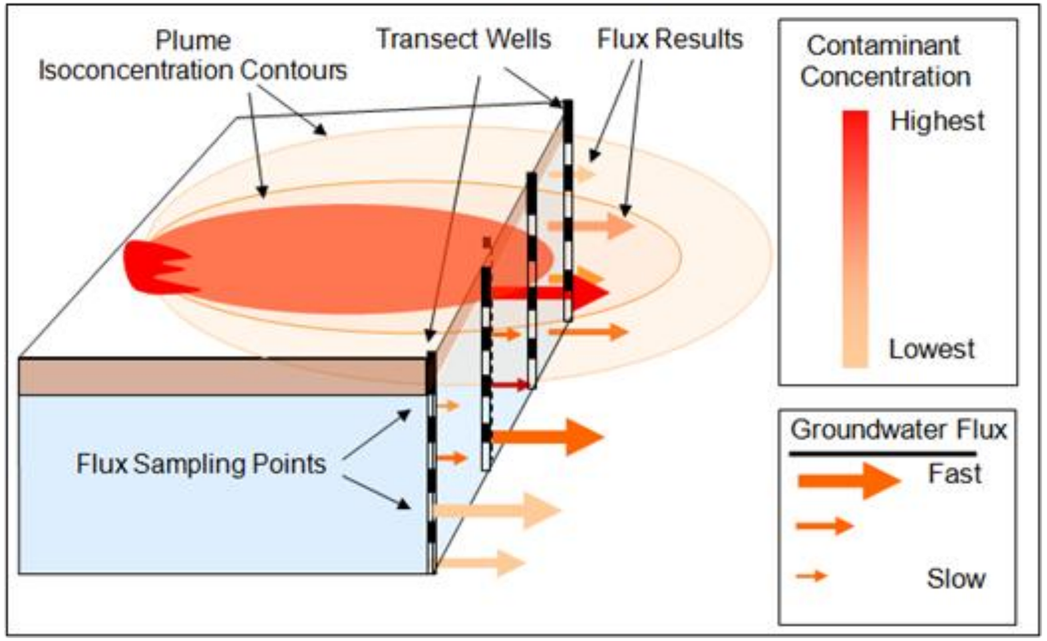
Data Evaluation for the Saturated Zone

Goals: Understanding which PFAS are migrating, where and how they are migrating, and understanding the time scales involved

- Plume Characteristics
  - Nature and extent, plume stability, mass flux
  - Co-contaminants, seasonality, impacts of extraction

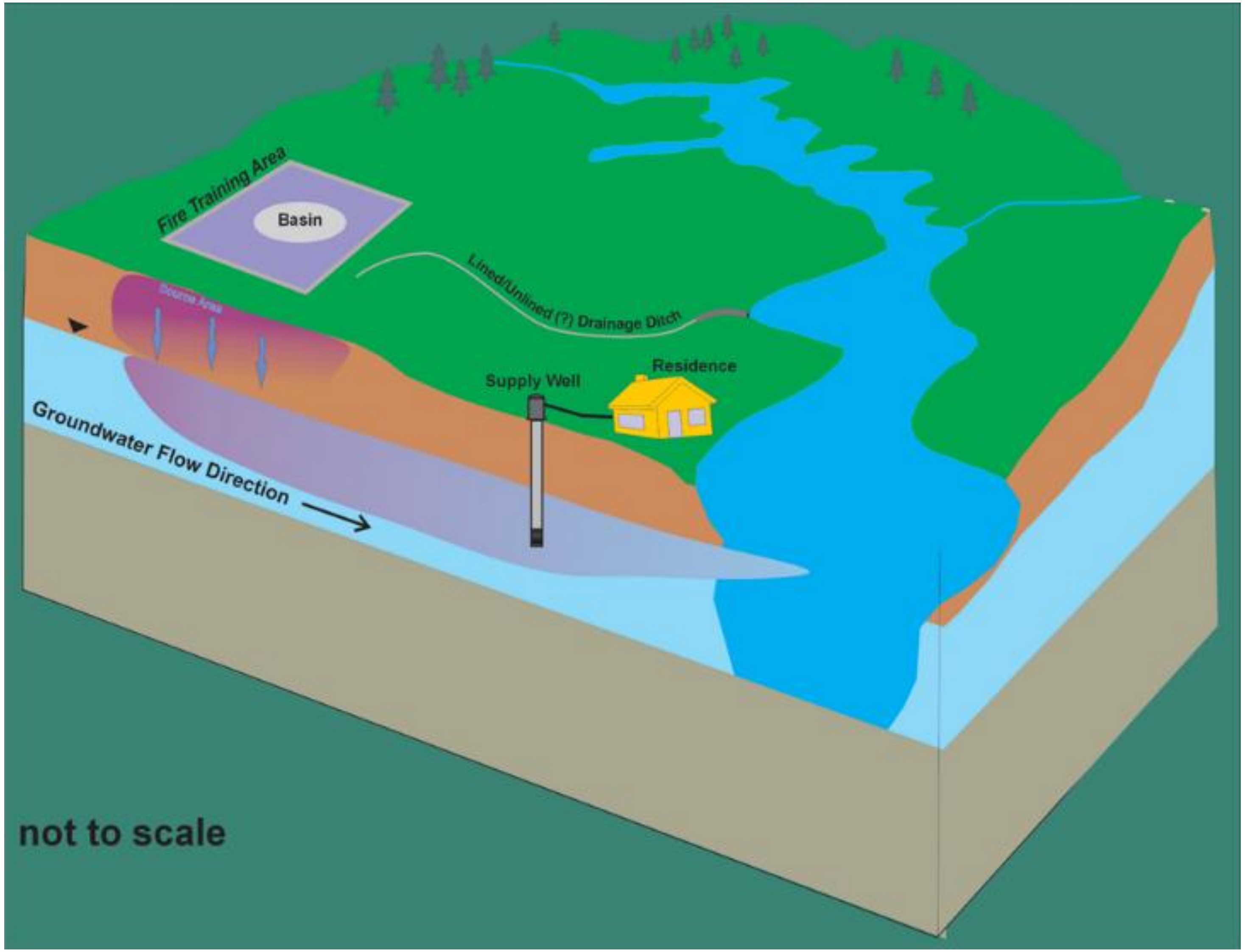
- Tools and Techniques
  - Flow modeling, contaminant fate and transport modeling
  - Forensic evaluation to understand fractionation of constituents
  - Statistical evaluations



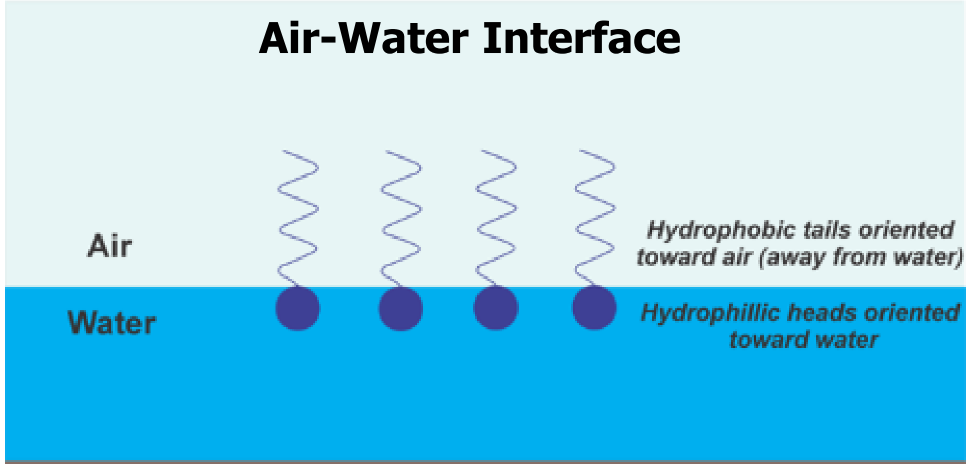


Source: (Graphic courtesy HydroGeoLogic Inc.) Figure 2-4. in ITRC Use and Measurement of Mass Flux and Mass Discharge (ITRC 2010, MASSFLUX-1).

Surface Water



Surface Water Considerations – Transport in Surface Water



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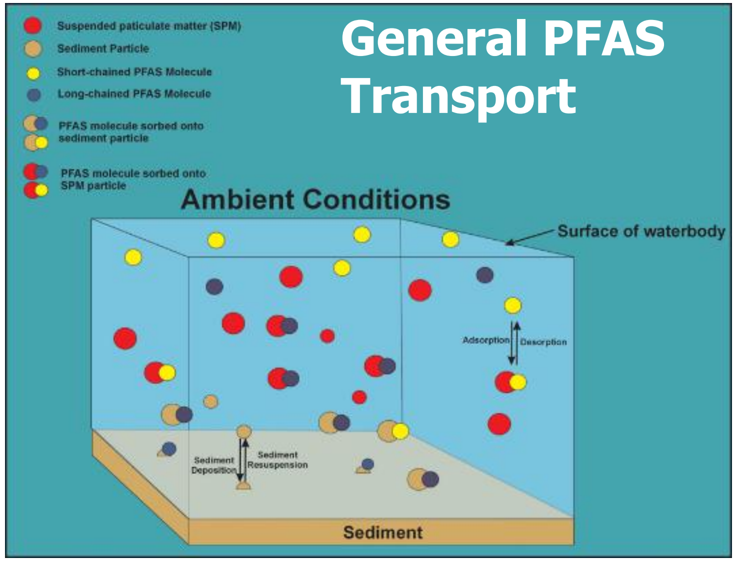
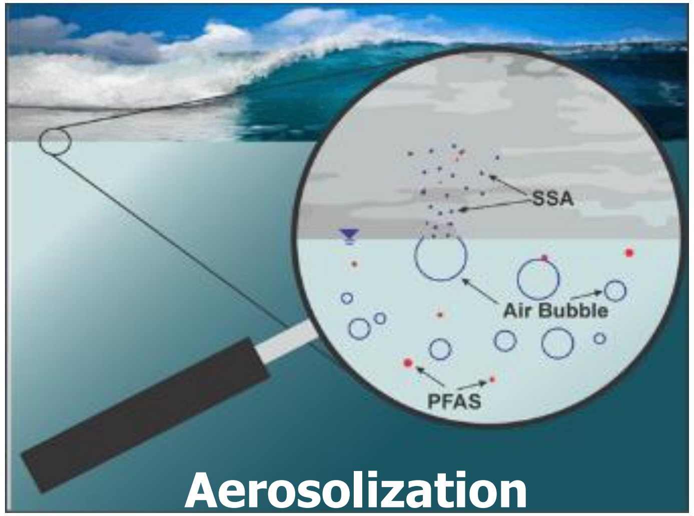


PFAS-1 Figure 1-6.



PFAS-1 Figure 1-4.

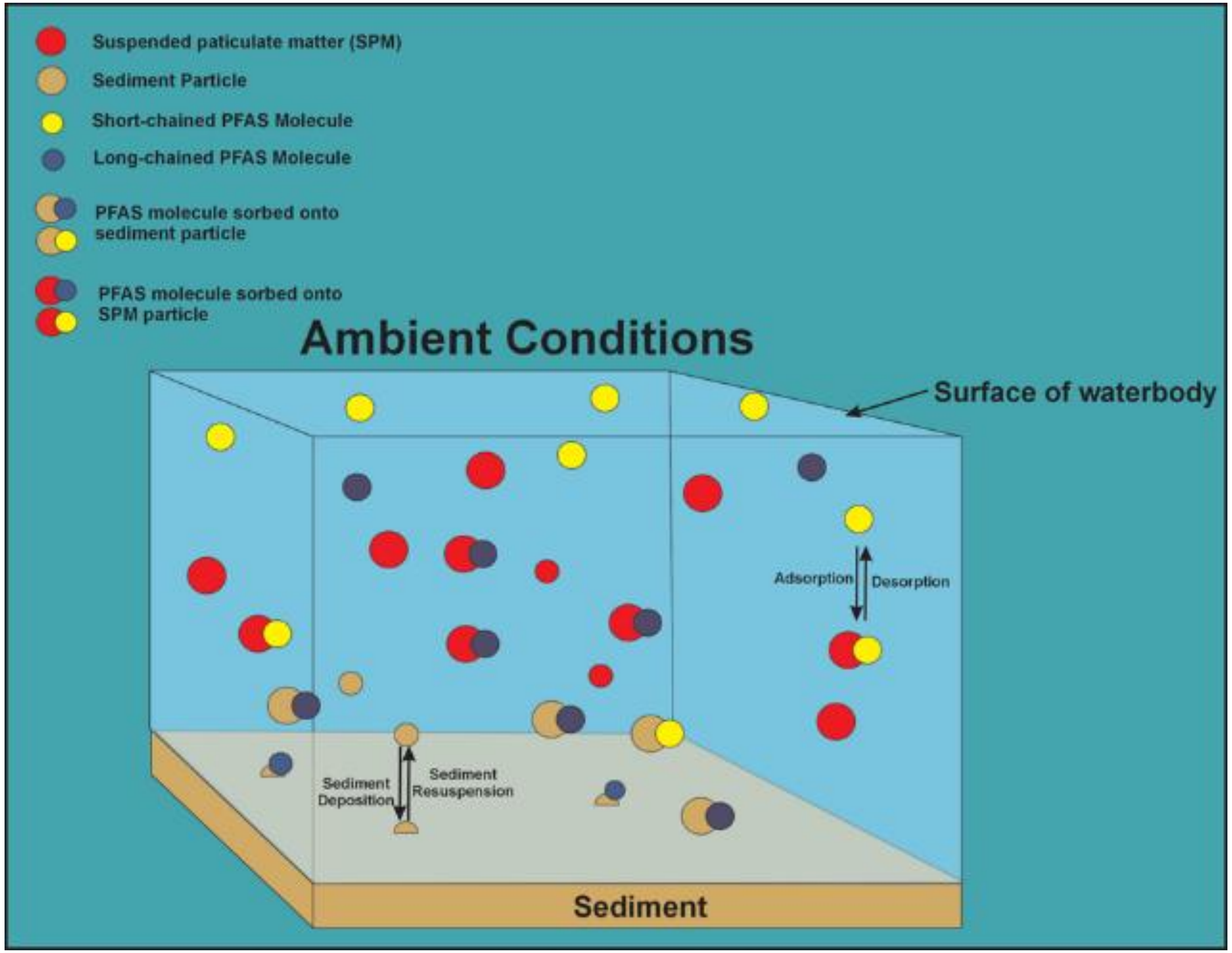
PFAS-Containing Foam

Source: Rebecca Higgins, State of Minnesota. Used with Permission.

Surface Water Considerations – PFAS Transport in Surface Water

General PFAS Transport

- PFAS found throughout the water column and sediment – dissolved and sorbed
- More likely short-chained PFAS dissolved and at/near surface
- More likely long-chained PFAS sorbed and/or in sediment and closer to bottom
- Composition/concentration of PFAS sorbed, dissolved, deposited, or suspended continuously changing



PFAS-1 Figure 1-6.

Surface Water Considerations – Foam

PFAS-Containing Foam (not AFFF)

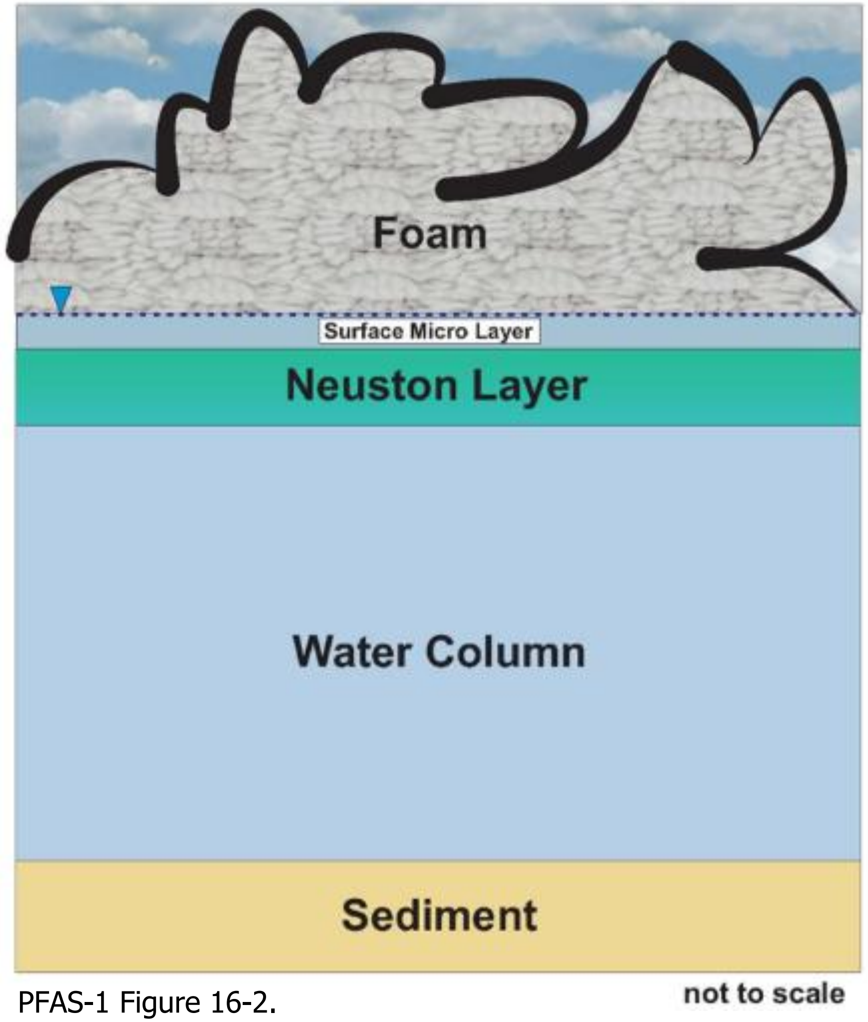
- Foam – contains **higher concentrations of PFAS than the underlying layers**; as foam is formed, it removes PFAS from the water column.
- Surface micro layer (about 50 μm thick) - includes the air-water interface. Likely **highest concentration of PFAS in water column**
- Neuston Layer – zone directly below surface micro layer. Rich in aquatic organisms
- Underlying water column

Transport as "foam islands" to a new location

Collapse of foam and **dissolution of PFAS** back into water column

PFAS in foam potentially leads to **additional exposure pathways** – both human and ecological receptors

Surface Water Foam PFAS Sampling Guidance – Michigan Dept. of Environment, Great Lakes and Energy July 2019.

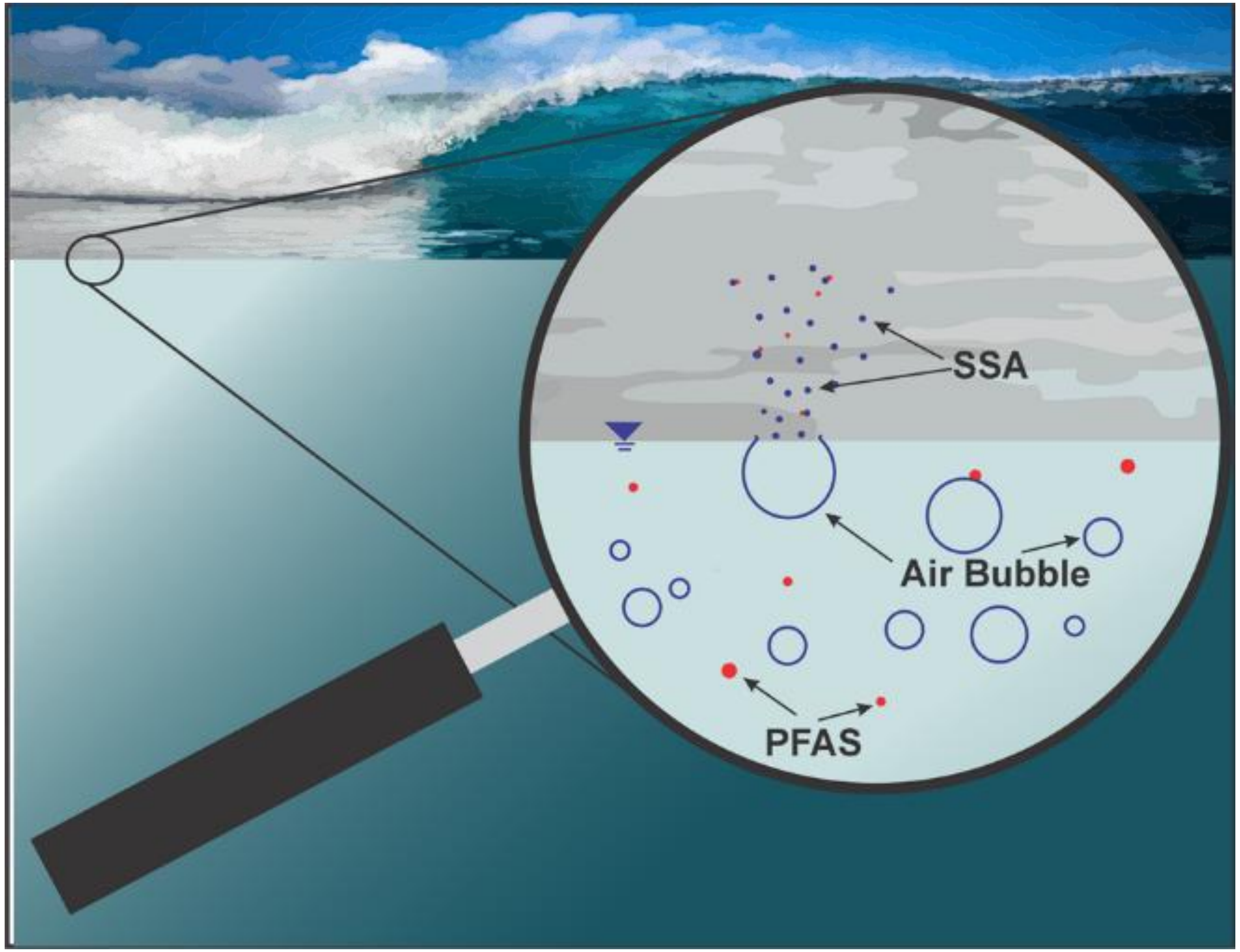


PFAS-1 Figure 16-2.

Surface Water Considerations

Aerosolization

- Wind/Wave action
- Air bubbles pushed underwater and scavenge PFAS
- Bubbles rise to the surface and burst
- Wind disperses aerosolized particles – sea spray aerosols (SSAs)
- Can be transported hundreds of miles
- Can be largest source of exposure to PFAS
- Additional Information – Section 1.3.5.3, including foam

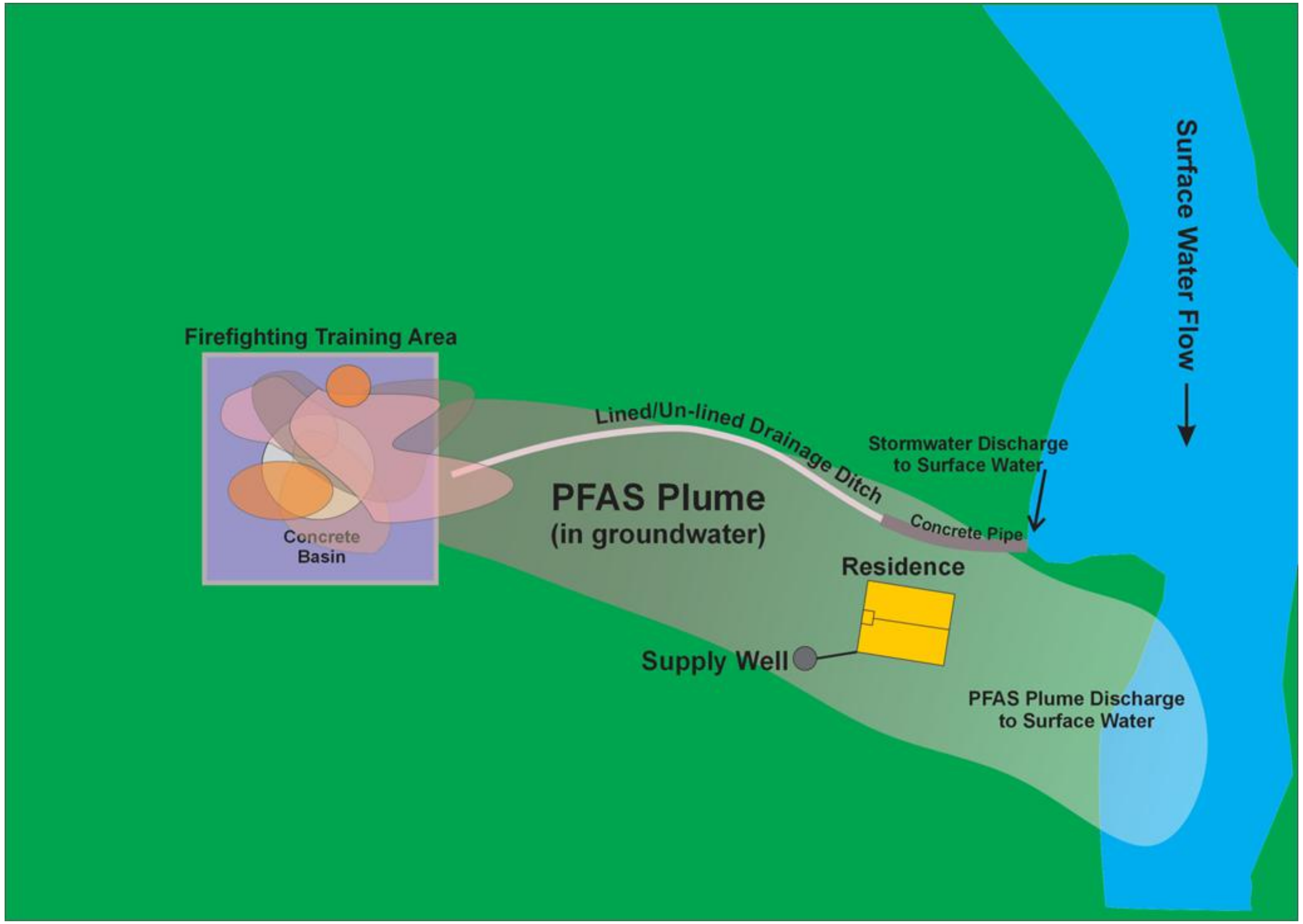


PFAS-1 Figure 1-4.

Surface Water – Case Study

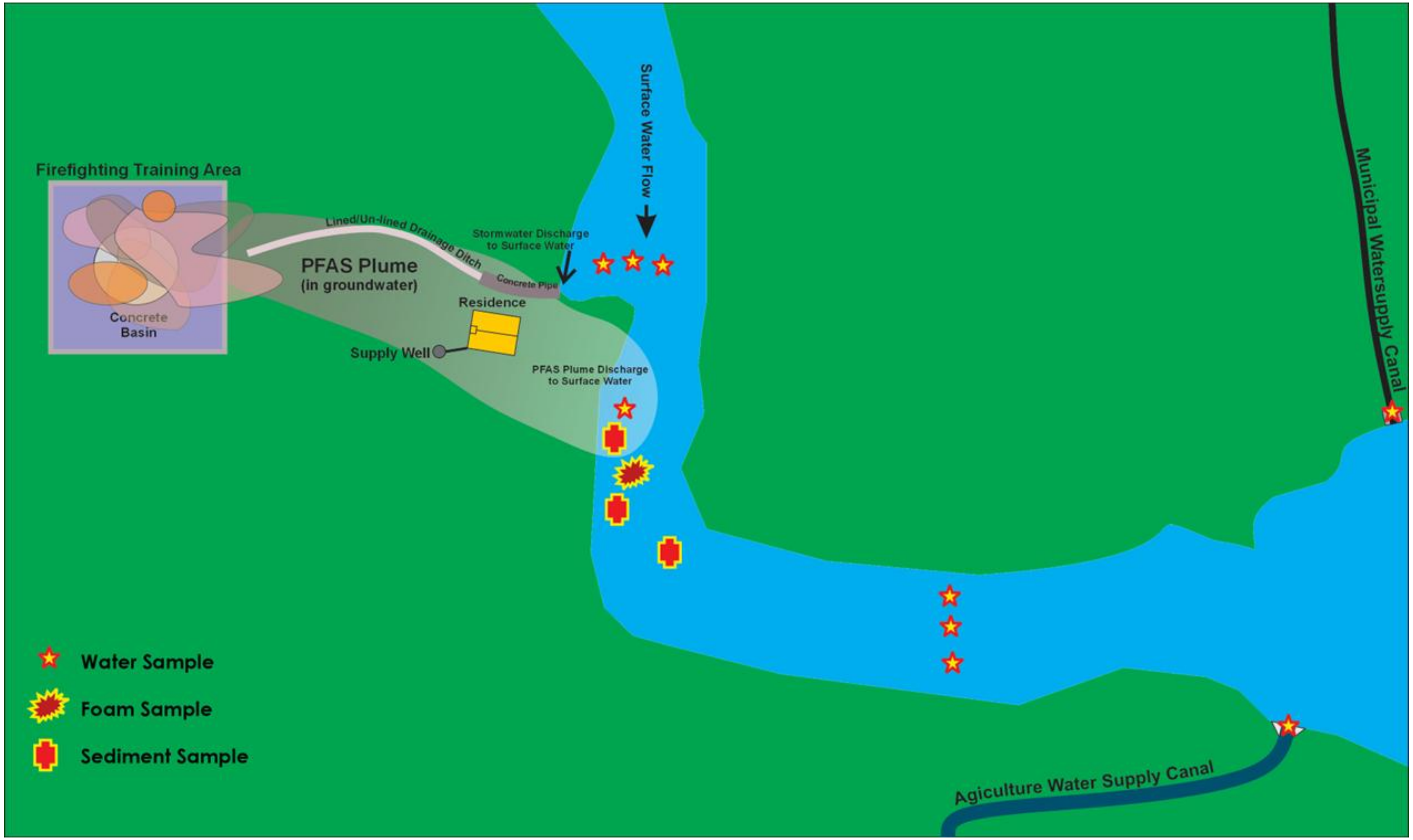
Overview

- Non-stormwater runoff period
- Impacts are only from plume in groundwater discharging to surface water
- Assess impacts on surface water quality – focusing on protection of human health, aquatic and avian species
- Evaluating Human Health – Sections 16.2 and 7.1
- Evaluating Ecological Risk – Sections 16.3 and 7.2



Surface Water – Sampling Considerations Case Study

- Low stream flow vs high stream flow
- Upstream and downstream
- Across the water column
- Across the stream
- Occurrence of foam
- Water supply intakes
- Species of concern (Section 16.3)



Knowledge Check!

Check In!

On a surface water with PFAS-containing foam, where are the highest concentrations of PFAS found?

A. The surface micro layer
B. The foam
C. The Neuston Layer
D. The deeper water column

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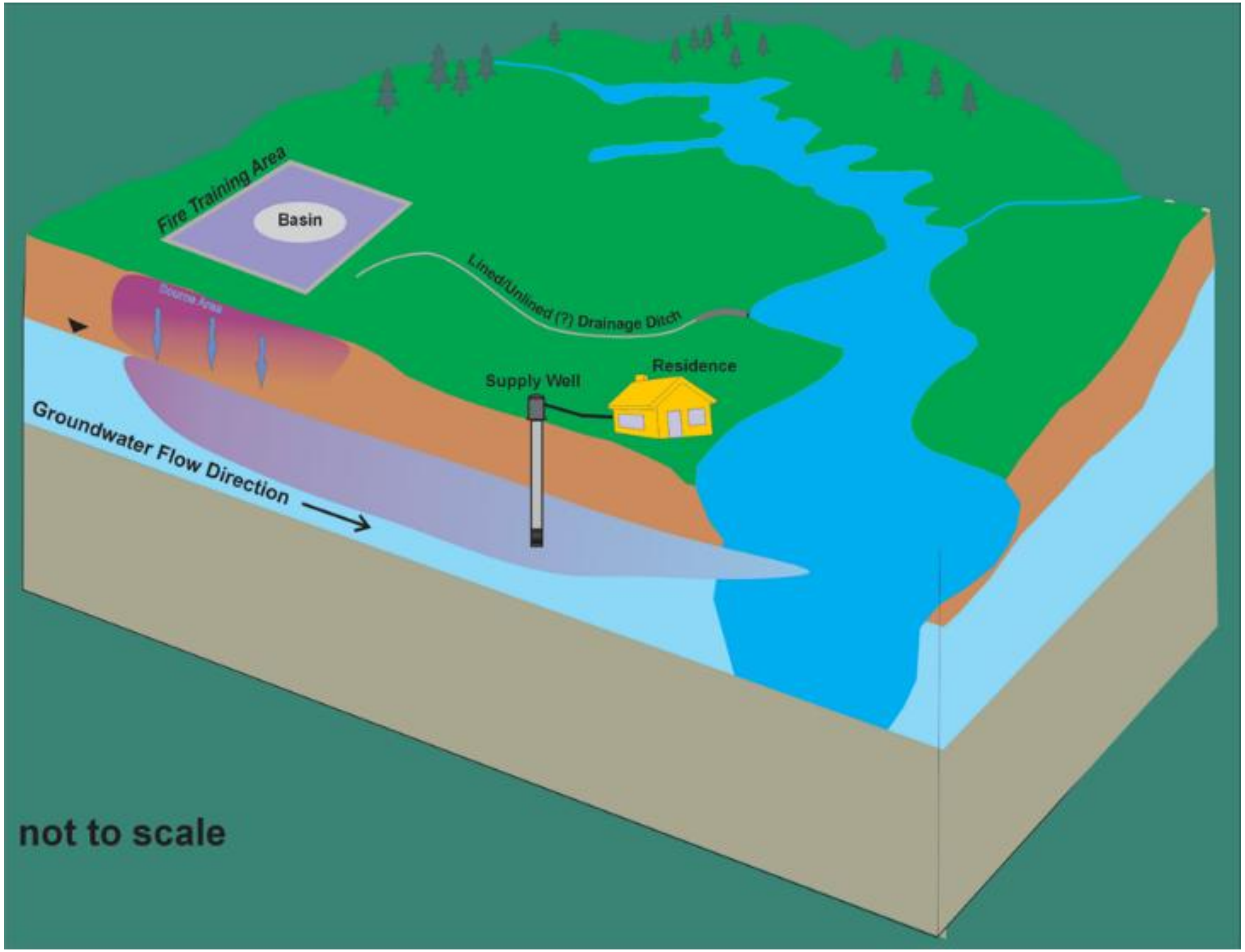
Stormwater



PFAS Behavior in Stormwater

Considerations for stormwater are similar to those for surface water

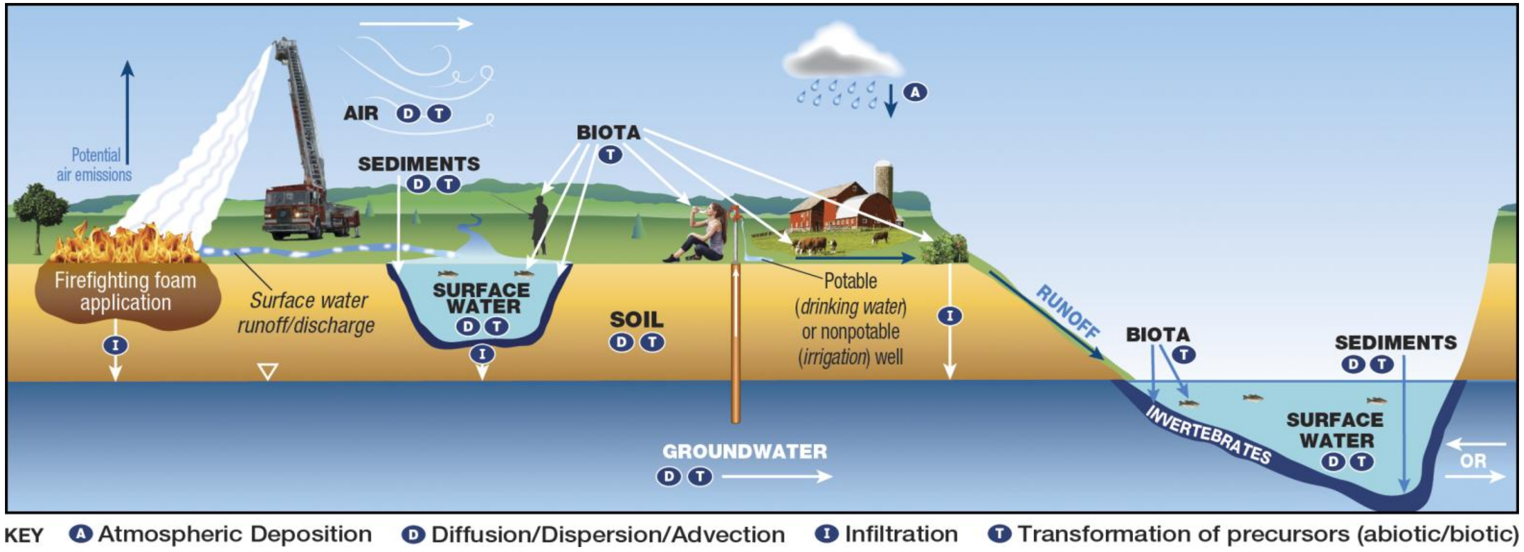
- Foam formation, aerosolization, impacts of interfaces, suspended solids

Aspects to consider

- Inherent variability (intensity, frequency, duration)
- Stormwater runoff
- Impact of runoff on receiving waters

PFAS sources

- Atmospheric
- Site related
- Concrete as a residual source



PFAS-1 Figure 2-21. Source: Adapted from figure by L. Trozzolo, TRC. Used with permission.

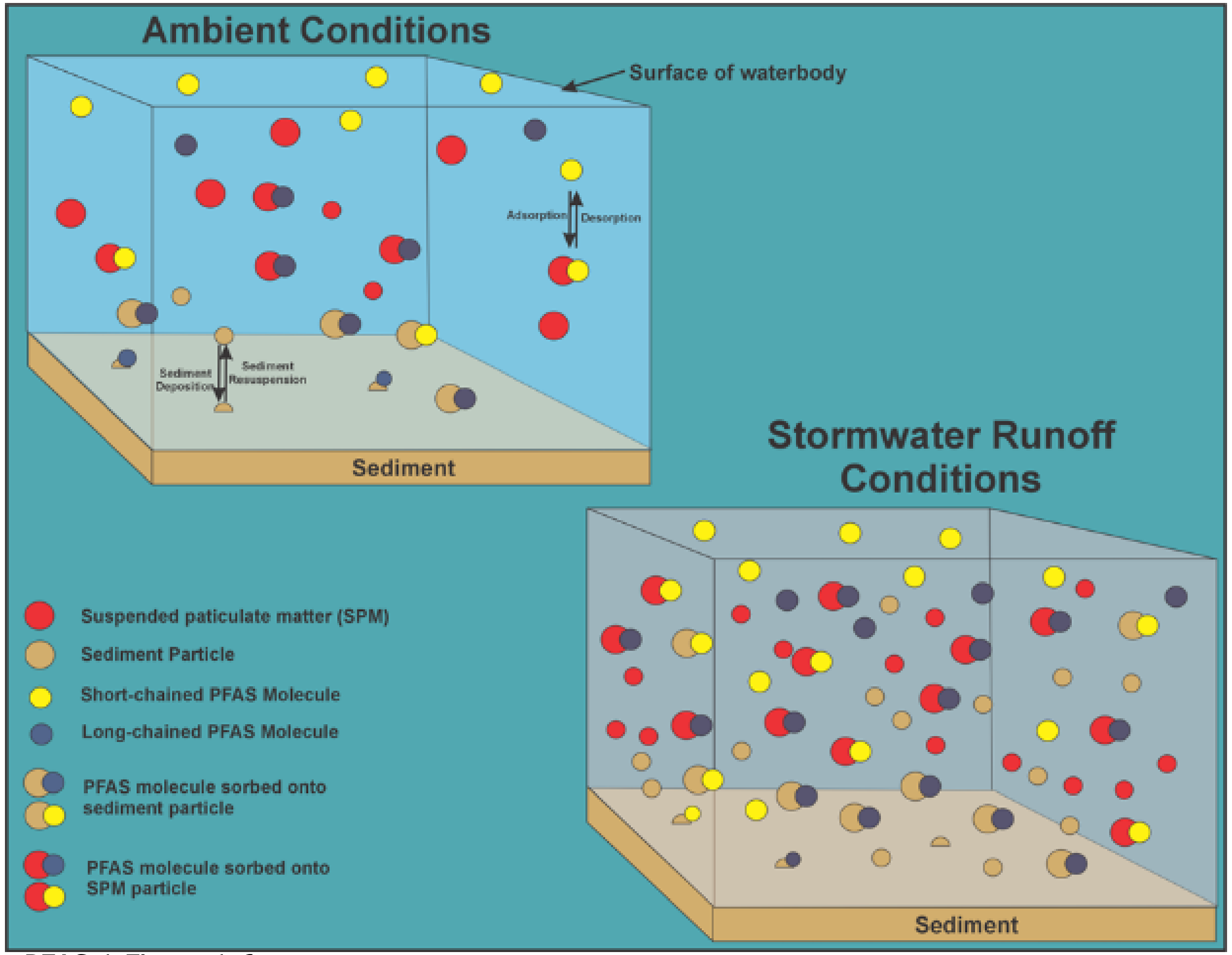
Sampling Plan for Stormwater – Case Study

Sampling should address

- Suspended solids and dissolved organic matter provide additional sites for PFAS sorption
- Importance of first flush
- Increased velocity increases transport distance
- Increased turbulence increases mixing

Additional considerations

- Concentrations of PFAS may be lower, but total mass flux may be greater
- Analysis of solids portion of the water sample
- Foam formation potentially increased
- Foam can act as a source and may become more mobile
- Rain may also be PFAS source to water

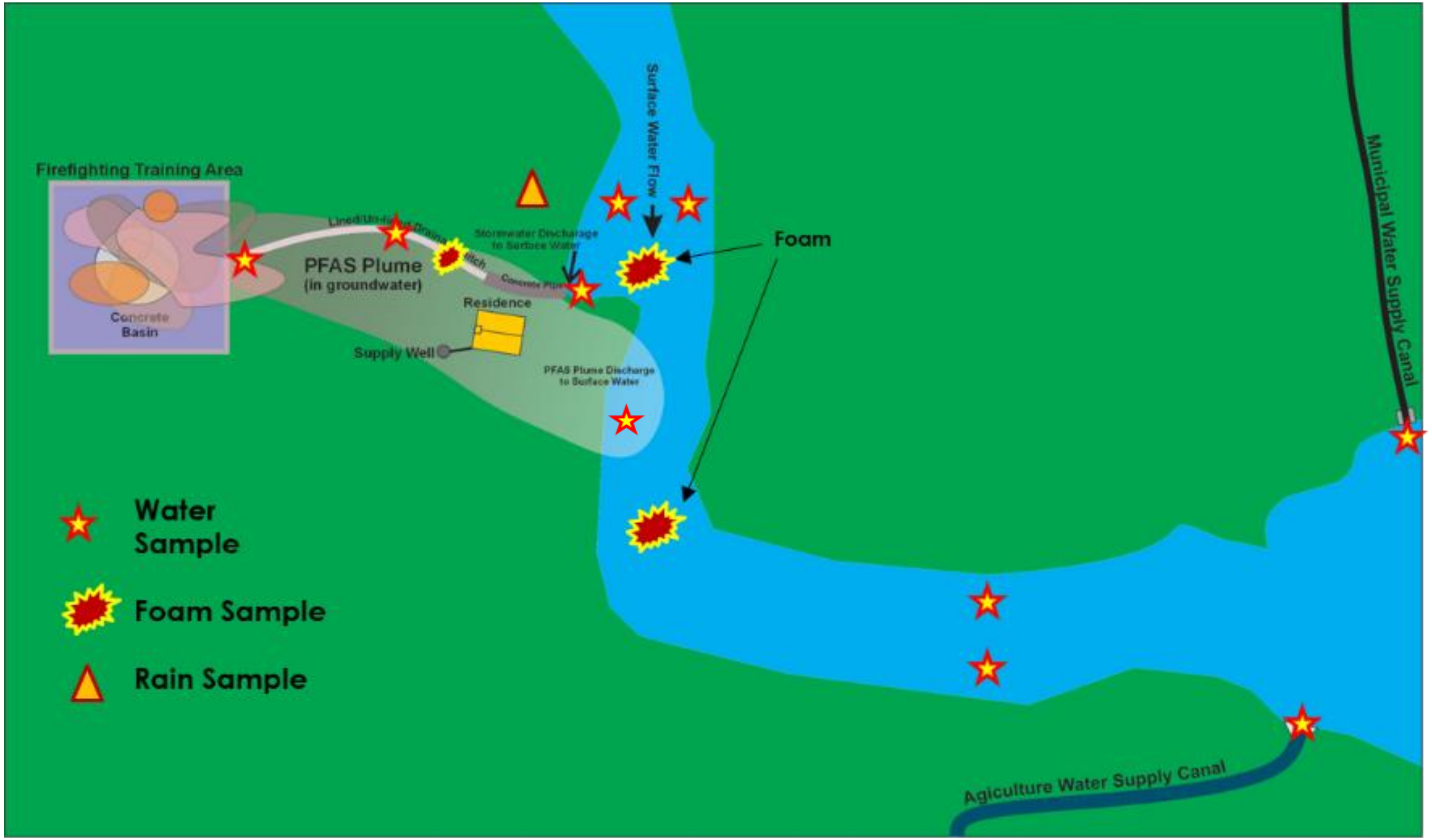


PFAS-1 Figure 1-6.

Sampling Plan for Stormwater – Case Study

Sample Locations:

- Upstream (baseline)
- Downstream
- Runoff from Source Area
- Mid-Points
- Discharge at Outfall
- Foam
- Supply Intakes
- Rain Sample

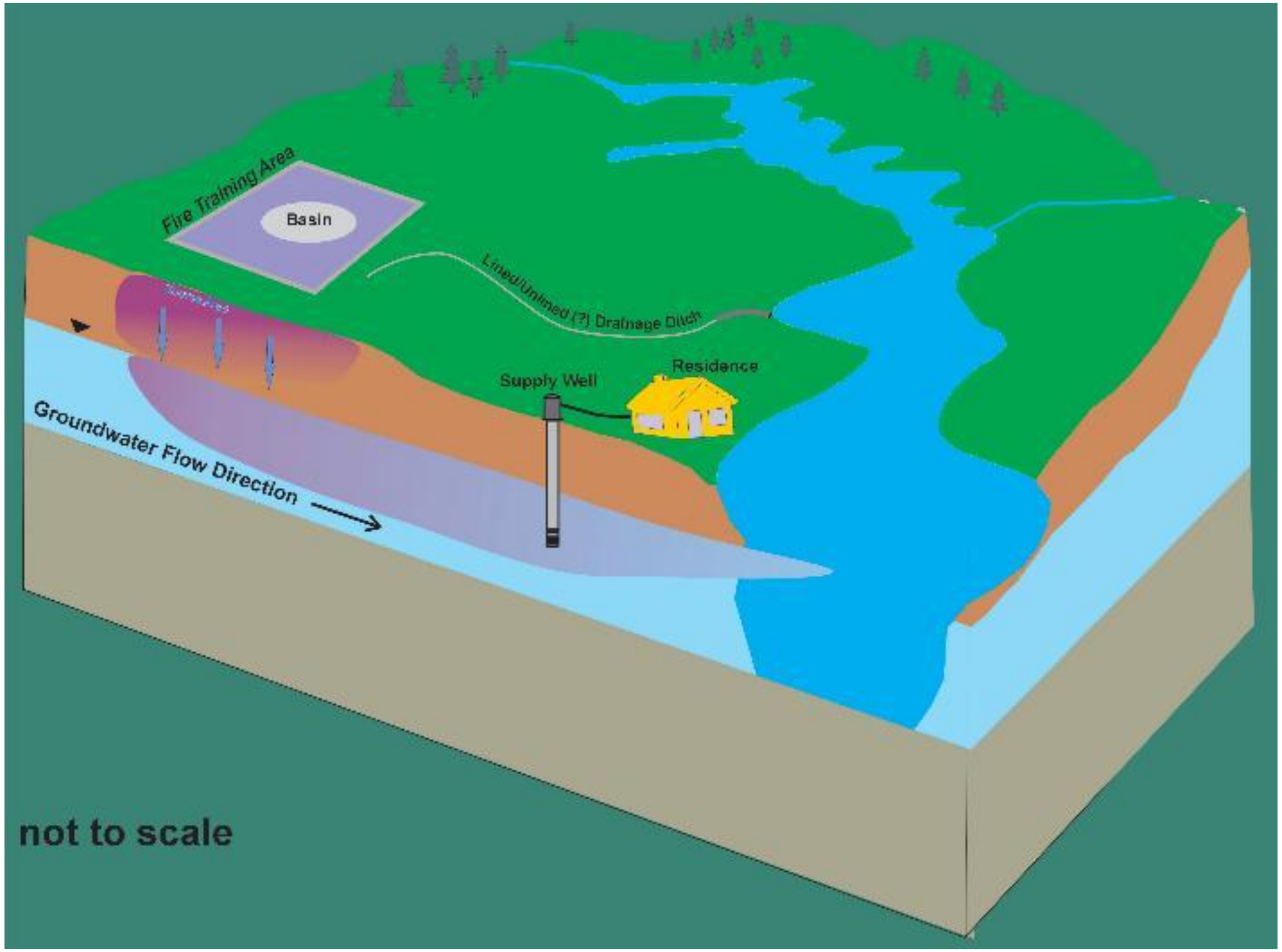


Data Evaluation for Stormwater

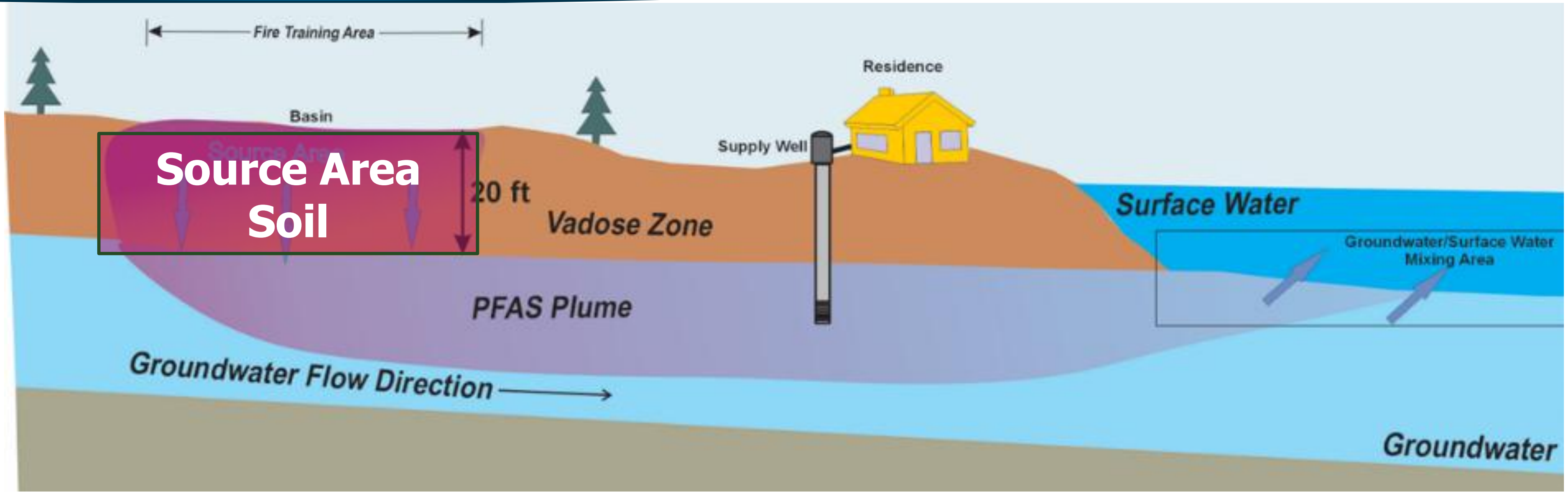
Goals: Understanding how stormwater may/may not transport PFAS and the factors effecting the fate of PFAS in stormwater

- Concentration vs Mass Loading
  - Which is more important to the project objectives?
  - High concentrations (ng/L) at low rates (L/min) compared to low concentrations at high rates.
- Understanding First Flush at Site
  - Concentrations during first flush vs concentrations during latter periods
  - Assess mass migration related to first flush vs remainder of event
- Seasonality
- Potential Residual Source(s)

Considerations for PFAS Remediation

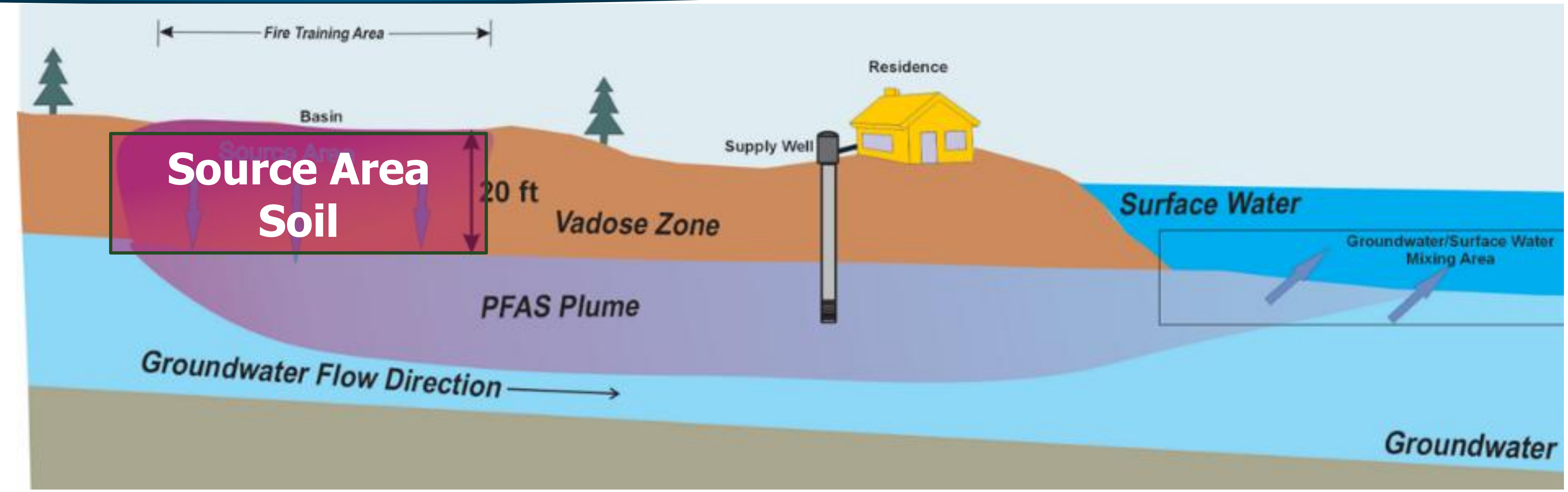


Considerations for Soil Remediation



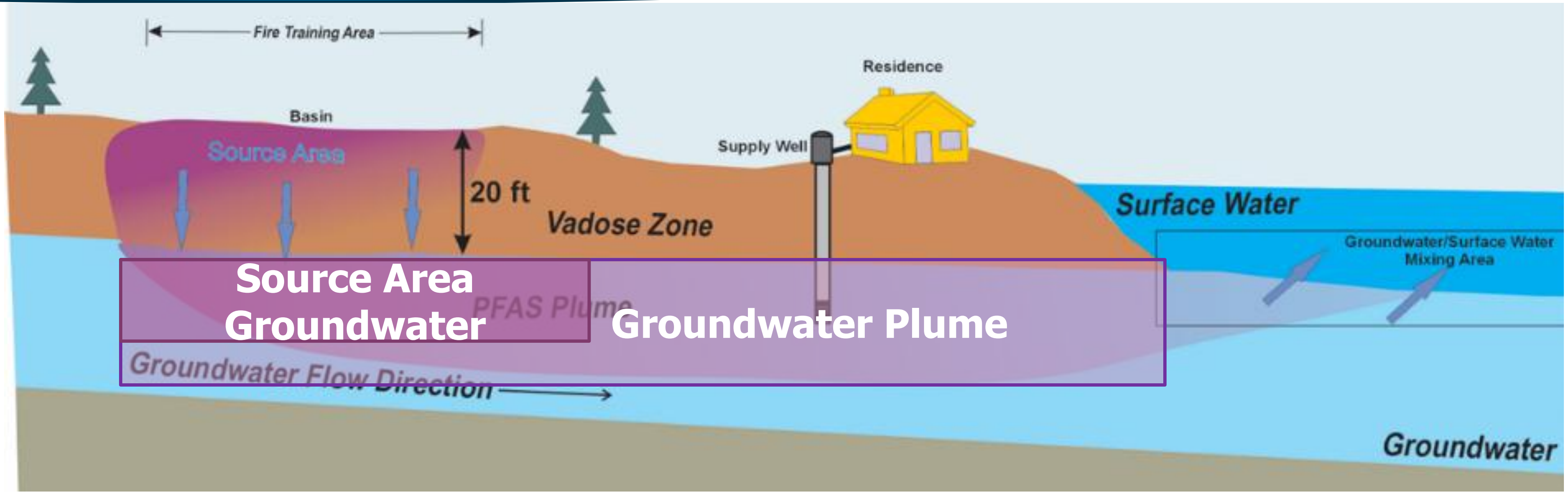
PFAS Fate & Transport	PFAS Remediation – Soil
• PFAS source strength (total PFAS, precursors) • PFAS composition (regulated/non-regulated, precursors) • Partitioning, retention & phase distribution	• Remedy selection, potential impact of remedy on unregulated PFAS, remedy resilience • Mass balance and products of incomplete destruction (destruction technologies, e.g., incineration/thermal) • Selection and dosage of amendment (sorption/stabilization) or reagent (soil washing)

Considerations for Soil Remediation (cont'd)



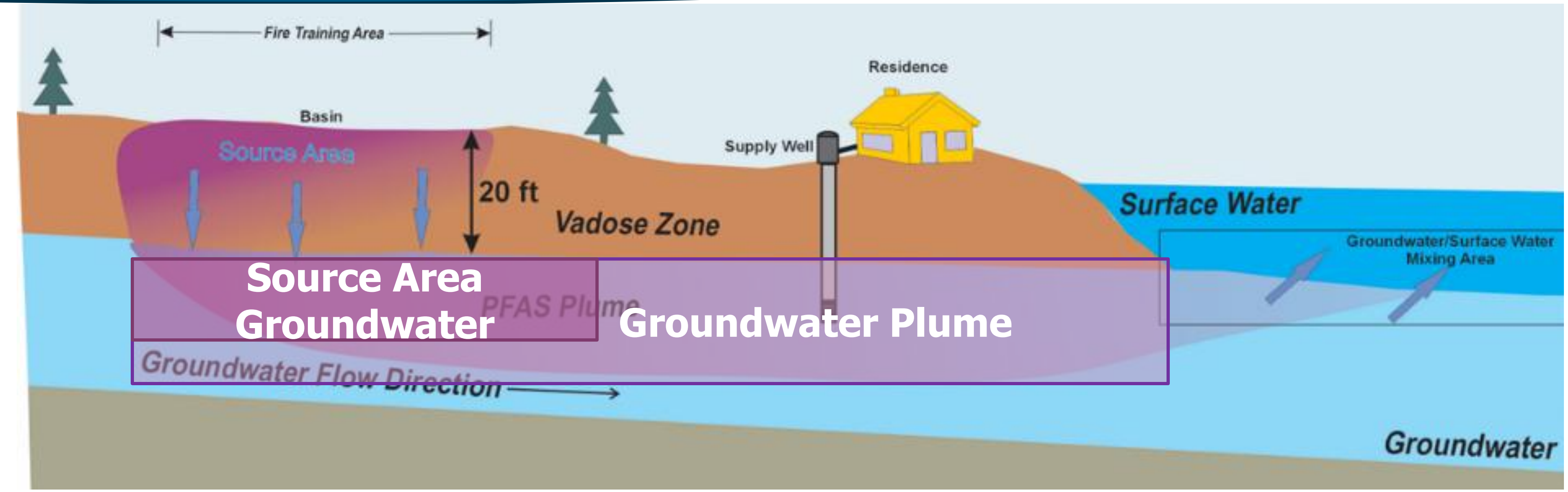
PFAS Fate & Transport	PFAS Remediation – Soil
• Interaction with co-contaminants • Precursor transformation • Leaching potential	• Long-term stability/performance (sorption/stabilization) • Final disposal considerations (e.g., landfill)

Considerations for Groundwater Remediation



PFAS Fate & Transport	PFAS Remediation – Groundwater
• PFAS composition (regulated/nonregulated, precursors) • Co-contaminants • PFAS source strength (total PFAS, precursors) • Vadose zone leaching (composition/evolution, magnitude, duration, etc.) • Precursor transformation	• Remedy selection, potential impact of remedy on unregulated PFAS, remedy resilience • Sorption media selection, pre-treatment, system design (ex-situ treatment, e.g., GAC, IX) • Source & plume longevity (in-situ sorption, MNA evaluation, long-term plume management)

Considerations for Groundwater Remediation (cont'd)



PFAS Fate & Transport	PFAS Remediation – Groundwater
• Partitioning, retention & phase distribution • Diffusion/back diffusion • Colloidal transport	• Feasibility of Pump & Treat • Plume evolution, migration & longevity, mass flux, "clean-up" timeframe (in-situ sorption, MNA evaluation, long-term plume management)

PFAS Webinars

- PFAS Introductory Training
- PFAS Chemistry Explained
- PFAS & Biosolids: Sources, Occurrence, Transport, and Treatment
- PFAS - Practical Approaches for PFAS Fate & Transport Evaluation
- PFAS Sorption Based Technologies for Separation & Concentration of PFAS from Water

PFAS Trainings

Questions

Please use the Q&A Pod to ask questions.

Feedback Form: https://www.clu-in.org/conf/itrc/PFAS-fate-transport/